

Second Edition

Principles of Risk Analysis

Decision Making Under Uncertainty



Charles Yoe



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Preface

Risk Analysis or Risk Management? Changing the name to “Risk Management” will surely sell more books. If nothing else has changed since the first edition, risk management has become the sexier term. This discipline is growing up, though, and it is fair, now, to speak of risk analysis science. So, I have danced with the language that got me here, and this remains the *Principles of Risk Analysis*. The book is growing up, too.

The content has been edited and updated, of course, several chapters have changed, and four chapters have been added. You will now find [Chapter 10](#), “The Risk Assessor’s Toolbox,” is a major new addition. It provides an introduction to about four dozen tools that can be used in qualitative and quantitative risk assessments. I would like to think everyone will find something of value in this chapter. It began as an e-book resource in one of my classes, and then one day it looked like something of potential value to risk assessors.

I am especially excited about [Chapter 19](#), “Decision Making Under Uncertainty.” That seems like a no-brainer chapter, given the title of this book, but it has some backstory. I have worked a lot with government agencies that are making a genuine effort to improve decisions and decision outcomes as a result of their use of risk analysis science. What I have heard and seen again and again is increasingly skilled and sophisticated risk assessment generating lots of good data and risk characterizations under uncertainty. The major problem that attends this trend is that decision makers, including risk managers, do not know how to handle the uncertainty.

The risk literature is rife with sophisticated treatments of uncertainty, none of which are within the grasp of most real decision makers. There is a real need for some practical and useful methods for considering and addressing uncertainty in the decision-making process. [Chapter 19](#) is a first attempt at a consolidated approach to offer such methods. I would love to hear the methods that work best in your experience because we really do want to improve decisions and decision outcomes.

[Chapter 21](#) is new, and it may be a personal indulgence of a long-held belief. If we are going to improve decisions and decision outcomes we have to stop dumping data and start telling effective stories in our risk assessments and other risk management documentation efforts. Very often, we need stories that motivate people to take action more than we need thick reports that convince them. Before you close this book convinced that I have gone mad at least flip through [Chapter 21](#). There is a place for the science and evidence of risk analysis but it may be in technical appendices. One of the interesting things about risk analysis science is that it occupies a niche at the confluence of science and values. I think there is not only room for but a great need for effective stories that can motivate change in risk management and other risk behaviors. Finally, you will find eight examples of risk assessment work that illustrate the gamut of complexity and quantitation of risk assessment in [Chapter 22](#).

There is no chapter untouched from the first edition as befits a publication on an evolving science. I hope you will find this book useful, especially those of you who will be part of the next generation to carry this new science of ours forward.



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1 The Basics

1.1 WHAT IS RISK?

Risk is a measure of the probability and consequence of uncertain future events. It is the chance of an undesirable outcome. That outcome could be a loss due to fire, flood, illness, death, financial setback, or any sort of hazard, or a potential gain that is not realized because a new product did not catch on as hoped, your investment did not produce expected benefits, the ecosystem was not restored, or any sort of opportunity is missed. What usually creates the “chance” is a lack of information about events that have not yet occurred. We lack information because there are facts we do not know, the future is fundamentally uncertain, and because the universe is inherently variable. Let’s call all of this “uncertainty” for the moment.

Given the presence of a hazard or an opportunity, there are two important components to a risk: an undesirable outcome or consequence and the chance or probability it will occur. Risk is often described by the simple equation:

$$\text{Risk} = \text{Consequence} \times \text{Probability} \quad (1.1)$$

Consider this expression a mental model that helps us think about risk rather than an equation that defines it. What this expression is conveying is not so much that this is the manner in which all risks are calculated (they are not) as much as that both of these elements must be present for there to be a real risk. If an event of any consequence has no probability of occurrence, there is no risk. Likewise, if there is no consequence or undesirable outcome, then there is no risk.

A hazard is the thing that causes the potential for an adverse consequence. An opportunity causes the potential for a positive consequence. If a population, an individual, or some asset of interest to us is not exposed to the hazard or opportunity, then there will be no consequence and no risk. The range of possible consequences, loss of life, property damage, financial loss or gain, improved environmental conditions, product success, and the like is vast, but even similar types of consequences can vary in frequency, magnitude, severity, and duration.

It is not likely that many risk professionals would agree with such simple definitions. There are any number of alternative definitions in use or found in the literature. Some purists prefer to define risk entirely in terms of adverse consequences, ignoring the chance of gains that may not be realized. These risks of loss are sometimes called pure risks. Some definitions specify the nature of the consequences. The U.S. Environmental Protection Agency (EPA), for example, “considers risk to be the chance of harmful effects to human health or to ecological systems resulting from exposure to an environmental stressor” (EPA 2010).

Storms, hurricanes, floods, forest fires, and earthquakes are examples of natural hazards. When humans and human activity are exposed to these hazards there are risks with consequences that include loss of life, property damage, economic loss, and so on. There are human-made hazards by the scores: tools, weapons, vehicles, chemicals, technology, and activities. They can pose risks to life, property, environment, economies, and the like. Health hazards comprise their own category and include pathogens, disease, and all manner of personal health difficulties and accidents that can arise. These risks of adverse consequences are traditional examples of risk.

Less widely accepted as risks, among the risk analysis community's members, are potential gains or rewards. Would anyone say they risk a promotion or an inheritance? Probably not, as this is not the traditional use of the word. Nonetheless, when there is some uncertainty that the gain will be realized, it qualifies as a risk under the definition used here. The International Organization for Standardization (ISO 2018) defines risk as the effect of uncertainty on an organization's objectives. This is clearly broad enough to include uncertain opportunities for gain. Risks of uncertain gain are often called speculative risks.

THE LANGUAGE IS MESSY

The language of risk is relatively young and still evolving. The seeds of risk analysis are sown across many disciplines, and each has found it useful to define the terms of risk analysis in a way that best serves the needs of the parent discipline. The EPA, for example, identifies 19 variations on the meaning of risk in their *Thesaurus of Terms Used in Microbial Risk Assessment*, which eponymously takes a narrow focus on the concept of risk (EPA, 2007).

Frank Knight (1921) is credited with the first modern definition of risk. Kaplan and Garrick (1981) attempted to unify the language with their famous triplet. There is not yet any one universally satisfactory definition of risk nor of many of the other terms used in this book (ISO, 2018). ISO 31000, for example, offers quite a different lexicon than the one used in this book. There is more agreement on the practice of risk analysis than there is on its language.

For those who prefer to think of risks only as adverse consequences, it takes only a small convolution of thought to say that not realizing the gain/promotion/inheritance is the adverse consequence. In any event, loss and uncertain potential gains are considered risks throughout this book. Know that some would prefer to distinguish and separate risks and rewards more carefully.

Thus, we have pure risks, which are losses with no potential gains and no beneficial result, and speculative or opportunity risks, which are generally defined as risks that result in an uncertain degree of gain. They are further distinguished by the fact that pure risk events are beyond the decision maker's control, the results of uncontrollable circumstances, while speculative risks are the result of conscious choices made in decision making. These two types of risks lead to two distinct risk management strategies: risk avoiding and risk taking. Risk managers select options that will enable them to reduce unacceptable levels of pure risk to acceptable or tolerable levels. Risk

managers also choose to take risks when they select an alternative course of action to pursue potential gains. So, risk managers function as risk avoiders when they decide how best to reduce the adverse consequences of risk and as risk takers when they decide how best to realize potential gains in the future. Uncertainty makes all of this necessary; there is no risk without uncertainty.

A FEW PROPOSITIONS ABOUT RISK

- Risk is everywhere
- Some risks are more serious than others
- Zero risk is not an option
- Risk is unavoidable

Therefore, we need risk analysis to:

- Describe these risks (risk assessment)
- Talk about them (risk communication)

There is very little we do that is risk free, although risks certainly vary in the magnitudes of their consequences and the frequencies of their occurrences. A leaky ballpoint pen is not in the same class of risks as an asteroid five miles in diameter colliding with Earth.

Risk is sometimes confused with safety. In the past, we have tried to provide safety, and getting to safety has been the goal of many public policies. The problem with a notion like safety is that someone must decide what level of chance or what magnitude of consequence is going to be considered safe. That is a fundamentally subjective decision, and subjective decisions rarely satisfy everyone. Risk, by contrast, can be measurable, objective, and based on fixed criteria.

Safety has been defined in a number of legislative and administrative frameworks* as a “reasonable certainty of no harm,” a phrase extended in some contexts to include “when used as intended.” The very language chosen suggests the uncertain existence of a residual risk, and if there is a residual risk, then safety in any absolute sense is a psychological fiction. In fact, the act of calling something safe is a risk management decision.

An alternative to looking for safety and providing margins of safety is to look objectively for risk. That means we have to be able to objectively describe these risks for ourselves and others. Then, we need to be able to communicate that information to one another. Finally, we need a means of determining when a risk is not acceptable and needs to be avoided or managed to some level we can tolerate. This is basically the risk analysis process.

Because uncertainty gives rise to risk, the essential purpose of risk analysis is to help us make better decisions under conditions of uncertainty. This is done by separating what we know about a decision problem from what we do not know about it. We use what we know and intentionally address those things we do not know

* The Food Quality Protection Act of 1996 is one such example.

in a systematic and transparent decision-making process that includes effective assessment, communication, and management of risks.

Many people in many different disciplines figured this all out a while ago. They also articulated these ideas in the language of their own disciplines, and that has given birth to a wonderfully chaotic language of risk. Many of these discipline-based uses of risk analysis have deep enough roots that practitioners are sometimes reluctant to consider other views of this new composite discipline. There may be emerging consensus about some ideas, but there is little or no universal agreement about the language of risk analysis. That makes it difficult for anyone trying to understand the essence of risk analysis to get a clear view of just what this is all about.

Risk analysis is a framework for decision making under uncertainty. It was born spontaneously, if not always simultaneously, in many disciplines. It has evolved by fits and starts rather than by master design. Its practice is a wonderful mess of competing and even, at times, contradictory models. Its language borders on a babel of biblical proportions. And still it has begun to become something we can all recognize.

Many practitioners do not even recognize the term “risk analysis.” They would call this framework for decision making under uncertainty “risk management.” They could argue, effectively, that it includes risk assessment and risk communication. The language of risk is quite messy and not likely to be reconciled any time soon.

This book makes no pretense toward unifying, standardizing, or exemplifying the language, definitions, or models of the science of risk analysis. What it does modestly attempt is to distill the common elements and principles of the many risk tribes and dialects into serviceable definitions and narratives. There is more that unites risk analysis and risk management than divides it. Once grounded in the basic principles of risk analysis, or, if you prefer, risk management, the reader should feel free to venture forth into the applications and concepts of the many communities of practice to use their models and speak their language. Now, with this simple understanding of risk and this caveat in mind, let’s consider a few more important questions.

1.2 HOW DO WE IDENTIFY A RISK?

It is precisely because the language is so messy that it is important to be able to identify a risk clearly. There are five essential steps to a good risk identification process:

- Identify the trigger event.
- Identify the hazard or opportunity for uncertain gain.
- Identify the specific harm or harms that could result from the hazard or opportunity for uncertain gain.
- Specify the sequence of events that is necessary for the hazard or opportunity for uncertain gain to result in the identified harm(s).
- Identify the most significant uncertainties in the preceding steps.

1.2.1 TRIGGER

Something initiates the need for risk identification. It could be a discrete event like a study authorization or a flood, information obtained from stakeholders, the

accumulation of scientific knowledge, an intentional search for risks, and the like. It helps to note the event that triggers a specific risk coming to light.

1.2.2 HAZARD OR OPPORTUNITY

A hazard is anything that is a potential source of harm to a valued asset. Hazards include all natural and anthropogenic events capable of causing adverse effects on people, property, economy, culture, social structure, or environment. Hazards can be readily fit into categories of hazards like biological, chemical, physical, and radiological agents. Examples of hazardous events include terrorism, infrastructure failure, crimes, fires, hurricanes, wars, explosions, seismic events, hydraulic fracturing, automobile accidents, and so on.

An opportunity is any situation that causes, creates, or presents the potential for an uncertain positive consequence. It is any set of circumstances that presents a good opportunity for progress, advancement, or other desirable gain to a valued asset. The gain may be personal, organizational, communal, societal, national, or global. Opportunities include potential financial gain through new products, ventures, and behaviors, they also include such things as cost savings, ecosystem improvements, reduced traffic congestion, and so on.

LOSS RISK

Trigger: Congressional authorization

Hazard: Aquatic nuisance species (ANS)

Harm: Reduced landings of commercial fisheries

Sequence: Pathway exists → ANS arrives at pathway → ANS survives passage thru pathway → ANS colonizes in commercial fishery waterway → ANS spreads and outcompetes commercial fishery

Uncertainty: Arrival time, survival through pathway; will it outcompete

SPECULATIVE RISK

Trigger: Competition among ports

Opportunity: Reduce transportation costs

Harm: Reductions not realized

Sequence: Harbor improvements → fleet composition does not change → tonnage lost to other ports

Uncertainty: Fleet composition, trade patterns, technology changes

1.2.3 CONSEQUENCE

Determining the specific harm in a risk situation must precede an assessment of the probability of that harm. Thus, consequence comes before probability in the risk identification task. If one begins with the probability, it is easy to become confused: the probability of what? Once the consequence is identified, it is easier to identify its probability. Analysts must identify the specific harm or harms that can result from

a hazard. Likewise, they must identify the disappointing and unwelcome results that can occur with an opportunity for uncertain gain.

There may be more than one undesirable outcome. If so, identify all the relevant harms to be assessed. Floods for example can result in loss of life, property damage, business loss, and other kinds of harm. Ecosystem restoration could increase habitat, improve water quality, increase ecosystem services, and offer other potential gains.

1.2.4 SEQUENCE OF EVENTS

For each harm identified, the analyst should identify the specific sequence of events that is necessary for the hazard to result in the identified harm or consequence. The likelihood of that precise sequence of events occurring will define the probability of the risk. When there is more than one pathway from the hazard to the harm, each relevant pathway ought to be identified. In a similar fashion, the sequence of events from an opportunity to an undesirable outcome ought to be identified.

1.2.5 UNCERTAINTY

The initial identification of a risk is likely to be uncertain. Some consequences, that is, harms, may be uncertain and the sequence of events that leads to them may, likewise, be uncertain. Even when the consequences and their causative events are known, there can be uncertainty about their magnitude, frequency, duration, and the like. It is the analyst's job to identify the most significant uncertainties that attend a risk so that they can be addressed in assessment and management.

This identification process provides clarity about the risk of concern. It is common practice to speak about the risk of acrylamide, the risk of dam failure, the risk of bankruptcy, and so on. This shorthand communication often leads to considerable confusion about the true nature of a risk. For risk managers, assessors, and communicators, it is essential that they are able to clearly and unambiguously identify risks of concern with a process like that above before they revert to shorthand descriptions of risks.

1.3 WHAT IS RISK ANALYSIS?

Risk analysis is an emerging science, and it is a decision-making paradigm. Terje Aven (2018) makes a powerful argument for risk analysis as a new emerging science. Although it is rapidly developing it is not yet widely regarded as a science unto itself. As a paradigm, it is capable of producing knowledge about risks and risky activities in the real world. As a science, it also produces knowledge about concepts, theories, frameworks, methods, and the like to understand, assess, communicate, and manage risks. This latter knowledge set makes risk analysis as much a science as statistics is, for example. The risk analysis paradigm presented in this text is frequently referred to as risk management, especially by those who practice enterprise risk management.

PILLARS OF RISK ANALYSIS SCIENCE

1. The Scientific Basis
2. Concepts
3. Risk Assessment
4. Risk Perception and Communication
5. Risk Management
6. Solving Real Risk Problems and Issues

Source: Aven (2018).

The traditional scientific method is often not applicable for decision making, especially when uncertainties are large and social values are prominent. Risk analysis is a process for decision making under uncertainty that consists of three tasks: risk management, risk assessment, and risk communication, as shown in [Figure 1.1](#). We can think of it as the process of examining the whole of a risk by assessing the risk and its related relevant uncertainties for the purpose of efficacious management of the risk, facilitated by effective communication about the risk. It is a systematic way of gathering, recording, and evaluating information that can lead to recommendations for a decision or action in response to an identified hazard or opportunity for gain.

Risk analysis for real world problems is not pure science; it is not certain; it is not a solution; it is not static. We may be uncertain about one or more aspects of the consequence of the risk(s) of concern to us or its likelihood of occurring.

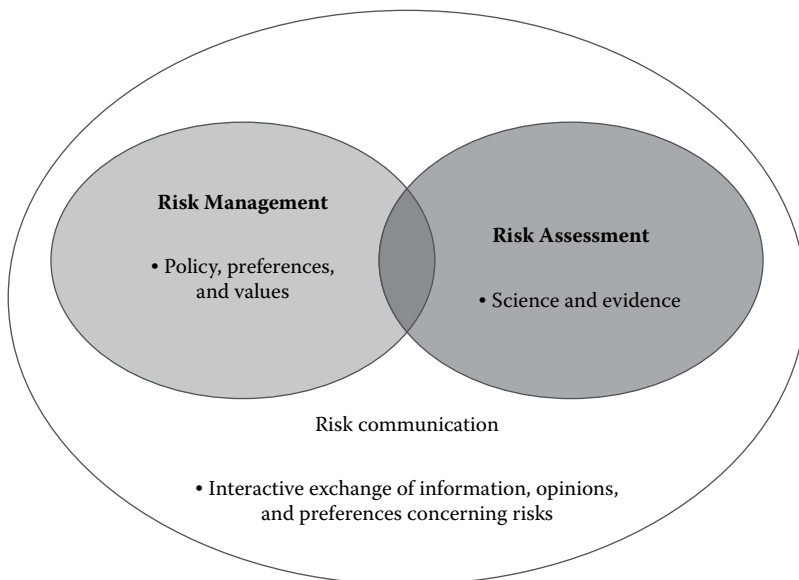


FIGURE 1.1 Three tasks of risk analysis.

More troubling, we may be unsure of what to do about the risk or how effective our risk management efforts will be. Risk analysis should address all these things as a paradigm for decision making under conditions of uncertainty. Thus, we draw a distinction between the science of risk analysis that advances the field and the risk analysis paradigm that is applied to real world problems.

I speak the dialect of the community of practice (CoP) that raised me in risk. That would be the public sector, with stewardship responsibilities for public health and safety and natural resources. If your CoP prefers to use risk management as the overarching term to organize and label its risk work, I honestly believe you can substitute risk management for risk analysis without doing any significant harm at all to the discipline of risk. Do not let that distinction get in your way of learning. Risk management takes center stage as an organizing concept in the chapter on enterprise risk management.

People tend to not be terribly analytical when making decisions. Human reasoning is fallible. Risk analysis influences our thinking by making it more analytical. This simultaneously limits the “damage” our fallible human reasoning can inadvertently do when making decisions. Risk analysis is a useful and an evolving way to think about and solve risky and uncertain problems. It is “science-based” decision making. This is true in part because the uncertainty is sometimes substantial, but also because risk analysis honors social values. In fact, it is not a stretch to think of risk analysis as the decision-making interface between science and values.

What makes risk analysis a science and a paradigm? That question will be answered in some detail throughout this book. But let’s consider a few features that distinguish it.

First, it is based on good science. Scientific facts, evidence, and good analytical techniques are hallmarks of risk analysis. In best practice, risk analysis relies on the best available science. Risk analysis separates what we know (the science) from what we don’t know (the uncertainty), and it focuses appropriate attention on what we don’t know and how that might affect decision outcomes and, therefore, the decision itself. It aspires to get the right science into the decision process and then to get that science right. The risk assessment task is always based as much as possible on sound evidence, whether that evidence is qualitative or quantitative, known with certainty or shadowed by uncertainty. Done well, risk analysis uses the best available analytical techniques and methods.

Second, risk analysis considers social values. As important as science is, it is not the sole basis for decision making. Social values enter the risk analysis process through the risk management task. Risk analysis incorporates both good science and social values when making decisions under uncertainty.

Third, risk analysis addresses uncertainty explicitly. Few, if any, decisions are ever made with complete information and certainty. Lacking complete information and facing sometimes considerable uncertainty rarely absolves us of the need to make a decision. Risk analysis has evolved explicitly for these kinds of decision problems. It is a paradigm that copes well with soft data and that tolerates ambiguity both in

analysis and decision making. Risk assessors address uncertainty in the assessment of risks, risk managers address it in their decision making, and risk communicators convey its significance to interested parties as appropriate.

Fourth, the purpose of this paradigm is to begin to make good decisions by finding and defining the right problem. If the problem is not properly identified, little that follows will aid a successful solution. Risk analysis seeks the needed information from a variety of sources. In the process of doing so, it involves many people in its efforts to identify and resolve that which we do not know about the problem.

Fifth, because of its focus on uncertainty, risk analysis is well suited to continuously improving decisions. As uncertainty is reduced over time and problems are better understood, new and better solutions may come into view. Risk analysis is flexible and can be updated. Every risk management decision is conditional on what is known and what is not known at the time the decision is made. Risk analysis has an eye on uncertainty, and this enables it to deal with a future-focused vision of the next solution as well as the current one. Reducing that which is not yet known about a situation and ever-changing social values ensures that many risk management decisions are part of an evolutionary decision-making process.

Risk analysis provides information to decision makers; it does not make decisions. It is neither a magic bullet, nor a black box. The risk analysis paradigm helps establish the balance between the expediency of decision making and having all the information. It does not remove subjectivity and judgment from decision making. If anything, it shines a light on these things and forces us to consider what is not known with certainty.

Risk analysis is defined here as a process with three tasks. These tasks are discussed in considerable detail in subsequent chapters. For now, let us content ourselves with some informal characterizations of these tasks.

1.3.1 RISK MANAGEMENT

Risk management is a process of problem identification, requesting information, evaluating risks, and initiating action to identify, evaluate, select, implement, monitor, and modify actions taken to alter levels of unacceptable risk to acceptable or tolerable levels. The goals of risk management are often said to include scientifically sound, cost-effective, integrated actions that reduce risks while taking into account economic, environmental, social, cultural, ethical, political, and legal considerations. More informally, risk management is the work one has to do to pose and then answer the following kinds of questions:

1. What's the problem?
2. What information do we need to solve it, that is, what questions do we want risk assessment to answer?
3. What can be done to reduce the impact of the risk described?
4. What can be done to reduce the likelihood of the risk described?
5. What are the trade-offs of the available options?
6. What is the best way to address the described risk?
7. Is it working? (Once implemented)

Risk management is discussed at length in [Chapter 3](#) and a description of enterprise risk management is provided in [Chapter 6](#).

REWARDS

When the definition of risk is expanded to include uncertain potential gains, it challenges the conventional language. In particular, risk management must include modifying risks as well as mitigating them. Some of the informal questions posed must be altered somewhat.

- What's the opportunity?
- What information do we need to attain it, that is, what questions do we want risk assessment to answer?
- What can be done to increase the positive impact of the opportunity risk described?
- What can be done to increase the likelihood of the desired outcomes?

The other questions remain the same for either risk of loss or opportunity risk.

The alternating emphasis on potential gains could become tedious and cumbersome if constantly continued. Alternative discussions of potential gains will be restricted to only the most critical topics. If you find the language confusing at times, for a potential gain it may help to consider failure to attain the gain as a loss.

1.3.2 RISK ASSESSMENT

Risk assessment is a systematic process for describing the nature, likelihood, and magnitude of risk associated with some substance, situation, action, or event that includes consideration of relevant uncertainties. Risk assessment can be qualitative, quantitative, or a blend (semiquantitative) of both. It can be informally described by posing and answering the following questions that build on the Kaplan and Garrick triplet (1981):

1. What can go wrong?
2. How can it happen?
3. What are the consequences?
4. How likely is it to happen?

1.3.3 RISK COMMUNICATION

Risk communication is the open, two-way exchange of information and opinion about risks intended to lead to a better understanding of the risks and better risk management decisions. It provides a forum for the interchange of information with

all concerned about the nature of the risks, the risk assessment, and how risks should be managed. Risk communication may be informally characterized by its own set of questions (Chess and Hance 1994):

1. Why are we communicating?
2. Who are our audiences?
3. What do our audiences want to know?
4. How will we communicate?
5. How will we listen?
6. How will we respond?
7. Who will carry out the plans? When?
8. What problems or barriers have we planned for?
9. Have we succeeded?

1.3.4 RISK SEMANTICS

Even a brief review of the literature will reveal a staggering range of definitions for these tasks. As with the definitions of risk, the discipline of origin and the nature of the risk have a powerful influence over the words used to define these tasks. However, once the words are distilled to their essence, the ideas represented by the questions above capture the spirit of most definitions in use today. The differences are, in my opinion, more semantic than substantive, but semantics are very important to some people. Any good risk analysis approach will identify hazards and opportunities, characterize the risks, recognize and address uncertainty, summarize conclusions, recommend options, and document the basis for all recommendations and decisions.

1.4 WHY DO RISK ANALYSIS?

In a word, “uncertainty” is the reason we do risk analysis. There is very little in life that is risk free, and risk is everywhere. Even in a certain world, decision making would not be a seamless process. We would still argue values, priorities, and trade-offs, for example; but it would be much easier than it is now. In the uncertain world in which we live, the circumstances of our lives, the problems we face, and the evidence we need, as well as the outcomes of our decisions are often unknown. We have come to realize the value found in managing, assessing, and communicating about risks to make better decisions and to better inform the affected public and stakeholders about the nature of the risks they face and the steps we take to manage them.

There are also other compelling reasons. Our decision-making processes and approaches to problems used in the past have paid amazing dividends. We have done much to make the world less risky through modern medicine, engineering, finance, environmental management, and the like. Even so, substantial and persistent problems remain. New risks appear all the time. Clearly, as well as our decision processes have served us in the past, they have not been sufficient to rid the world of risks. So, we do risk analysis to intentionally make our lives less risky, to wisely take risks when warranted and, hopefully, to reduce unacceptable risks to levels that we can at least tolerate.

Traditional approaches to decision making have relied on such things as precedent, trial and error, expert opinion, professional judgment, compromise, safety assessment, standards, precaution, inspection, zero tolerance, ignorance, and a host of other somewhat structured decision-making strategies. These traditional approaches have proven insufficient, as recurring problems and unrealized opportunities persist. They have been unable to detect and resolve many current problems. They have been slow to effectively deal with the growing complexity and rapid pace of change in society. Few of these traditional approaches have effectively integrated science and social values in decision making. They do not deal especially well with uncertainty.

Science-based risk analysis activities have been shown to be effective in reducing risks, and they are becoming the standard operating procedure for many public- and private-sector organizations. Risk analysis adds value to decisions by improving the quality of our thinking before a decision is made. Uncertainty is ubiquitous, and every organization develops its own culture of uncertainty. At one extreme, this culture is dominated by risk analysis; at the opposite extreme, we are oblivious to what we do not know. Intentionally considering the relevant uncertainty in a decision problem improves decision making.

One of the principal reasons we do risk analysis is to help provide and ensure a safer living and working environment for people. Risk analysis has also been used extensively to help protect animals, plant life, ecosystems, infrastructure, property, financial assets, and other aspects of modern society. Risk analysis has become essential to economic development. The Technical Barriers to Trade (TBT) and Sanitary Phytosanitary (SPS) Agreements of the World Trade Organization, for example, establish risk assessment as a legitimate means for establishing protective trade practices when the life, health, and safety of a sovereign nation's people are at risk. Risk analysis and risk assessment are being used more and more frequently by domestic and international organizations.

1.5 WHO DOES RISK ANALYSIS?

Many risk analysis practices have been around for centuries. However, it is only in the last half century or so that the practice of risk analysis has started to become more formalized and structured. Government agencies use risk analysis as the basis for regulation, resource allocation, and other risk management decisions. Private industry, sometimes following government's lead and sometimes leading government, is also making more frequent and widespread use of risk analysis, although it may be more common for them to refer to the overarching concept as risk management. To understand who is using risk analysis it is helpful to begin with a brief history of its evolution.

1.5.1 A BRIEF HISTORICAL PERSPECTIVE ON RISK ANALYSIS

Risk analysis was not possible until we were able to think intentionally about the facts of what can go wrong, how it can happen, its consequences, and the probabilities of those consequences occurring. Anyone who wants to know the history of risk analysis needs to read *Against the Gods: The Remarkable Story of Risk* (Bernstein 1996).

If there is not time to read this book, then read Covello and Mumpower's (1985) *Risk Analysis and Risk Management: An Historical Perspective*. These are simply the best single works of their genres done on the subject. This section owes a great debt to each.

We have always faced problems and have solved them, more or less successfully, since we have walked the planet. The authors cited in the previous paragraph detail this history delightfully. It was the possibility of risk assessment, however, that opened the door for risk analysis, and risk assessment has been made possible by the confluence of many events throughout history. These include the development of probabilistic thinking, which enables us to thoughtfully consider the "chance" dimension of risk, and the evolution of science, which enables us to analyze and understand the "undesirable outcomes" that can occur. Our ability to think about and to understand probability and consequences in risk scenarios made risk assessment possible.

The rise of decision sciences, especially in the last century, has enhanced the role of the manager in the analysis of risk. Our growing interest in finding effective ways to deal with uncertainty in the universe has magnified the importance of both the assessment and management tasks. The fact that we still face many old as well as a growing number of new and emerging problems not solved by our old decision-making paradigms has opened the door for risk analysis at this point in time. Growing emphasis on the involvement of the public and stakeholders in public policy decisions has created a role for risk communication. So, let us begin a brief look at the historical development of our ability to think about probability and the development of scientific methods to establish and demonstrate causal links and connections between adverse effects and different types of hazards and activities.

Undoubtedly, risk assessment began when some unknown *Homo sapiens* picked up something, ate it, fell sick, and died. "Don't eat that!" must have been the mental note all those around him made. Risk analysis had begun.

History is filled with scientific footnotes that suggest aspects of risk assessment. The Asipu in 3200 BCE (Covello and Mumpower 1985) plied the Tigris-Euphrates Valley offering guidance for risky ventures. Centuries later, Hippocrates (460–377 BCE) studied the toxicity of lead. Socrates (469–399 BCE) experienced the risks of hemlock, and Aristotle (384–322 BCE) knew that fumes from charcoal could be dangerous. Pliny (23–79 CE) and Galen (131–201 CE) explored the toxicity of mercury in their medical studies. The point being, we humans have long been engaged with aspects of risk, especially identifying those things that can do us harm.

Fast forward to the later Renaissance period in Europe where gambling, always a popular pastime, piqued an interest in the more formal study of probability. If anyone succeeded in figuring out the odds of various games of chance, it was not documented until Girolamo Cardano (1500–1571) wrote *Liber de Ludo Aleae* (Book on Games of Chance). This is one of the earliest works to explore statistical principles of probability. His book, which focused on chance, is the first to express chance as a fraction. Odds began to appear soon after.

Blaise Pascal's (1623–1662) wager is broadly considered to be one of the first examples of decision science. Pascal undertook the age-old question of God's existence: God is, or God is not? Which way should we incline, and how shall we

live our lives? Considering two states of the world (God is, God is not) and two alternative behaviors (live as a Christian, live as a pagan), Pascal used probability and concluded that the expected value of being a Christian outweighed the expected value of paganism.

The use of basic statistics is also relatively new to humans. John Graunt (1620–1674) undertook a study of births and deaths in seventeenth-century London to learn how many people may be available for military service. He used raw data in new ways, including sampling and statistical inference, that formed the basis for modern statistics. He published his famous life expectancy tables in 1662 and changed data analysis forever.

Risk management made a formal appearance in Edward Lloyd's 1687 London coffeehouse. By 1696, Lloyd's list of ship arrivals and departures along with conditions abroad and at sea was a risk management standard for everyone in the British maritime industry. Ships' captains compared notes on hazards in one corner of the coffeehouse, and it grew into the headquarters for marine underwriters, a precursor of the modern insurance industry. Flower and Jones (1974) report that London's insurance industry would help protect you from house-breaking, highway robbery, death by gin-drinking, death of horses, and would provide assurance of female chastity—no doubt the great risks of the day!

Jacob Bernoulli (1654–1705) began to integrate ideas about information and evidence into the growing body of thought on probabilities. He noted we rarely know a probability before an event (*a priori*) but can often estimate a probability after an event (*a posteriori*). This, he noted, implies changing degrees of belief as more information is compiled; so, the past is only part of reality. Thomas Bayes (1701–1761) extended this work and wrote of using new information to revise probabilities based on old information. The world was beginning to discover tools and to think that perhaps uncertainty can be measured and variability described. Many others, Laplace, Chebyshev, Markov, von Mises, and Kolmogorov, to name a few, followed, and the quantitative universe was gradually being revealed.

Meanwhile, our knowledge of disease and our powers of scientific observation were also making great leaps. Edward Jenner (1749–1823) observed that milkmaids got cowpox but not smallpox. John Snow (1813–1858) figured out that cholera was transmitted by contaminated water, by studying what today we might call a GIS (geographic information system) map of a cholera outbreak. The microscopic world was beginning to come into focus.

The Industrial Revolution marked a change in the public sector's role in the management of risks. Concerns about occupational disease and the need to protect workers and the public from toxic chemicals gave rise to the field of public health. Toxicology was one of many emerging sciences, and the idea of a “no observed adverse effects level” (NOAEL) was born in the twentieth century. This is the dose of a chemical at which there are no statistically or biologically significant increases in the frequency or severity of adverse effects between the exposed population and its appropriate control. This was clearly a firm step in the direction of risk analysis, combining science with a value judgment.

Early efforts to determine a safe level of exposure to chemicals were based on laboratory animal tests to establish a NOAEL. To leap the uncertain hurdles of

extrapolating from animals to humans and from the high doses of a chemical given to animals to the low doses to which humans were exposed, the scientific community approximated a safe level by dividing the NOAEL by an uncertainty or safety factor to establish the acceptable daily intake (ADI):

$$\text{ADI} = \text{NOAEL}/\text{uncertainty factor} \quad (1.2)$$

In the 1950s, the U.S. Food and Drug Administration (FDA) used a factor = 100 to account for the uncertainty.

More formal notions of risk were finding their way into the public-sector mentality. The Delaney Clause was a 1958 amendment to the Food, Drug, and Cosmetic Act of 1938 that was an effort to protect the public from carcinogens in food. It is often cited as an effort to establish a zero tolerance for policy purposes. When scientific methods were a bit cruder than they are now, it was easier to equate an inability to detect a hazard with a notion of zero risk.

As science improved, it became clear that zero risk was not a policy option, and the notion of *de minimis* risk took root. A *de minimis* risk is a risk so low as to be effectively treated as negligible. Mantel and Bryan (1961) suggested that anything that increases the lifetime risk of cancer by less than 1 in 100 million was negligible. The FDA later relaxed this to 1 in 1 million. The EPA proposed to adopt a uniform “negligible risk” policy for all carcinogenic residues in food in 1988. The Occupational Safety and Health Administration (OSHA) regulated all carcinogens in the workplace to the lowest level feasible. The point to be taken for our purposes is that society was beginning to get used to the idea that we would have to live with some nonzero level of risk.

Risk assessment per se began with radiation biology in the middle of the twentieth century. The Japanese survivors of World War II atomic bomb blasts made the dangers of radiation eminently clear. This new technology raised concerns about how the incidence of human cancer is influenced by exposure to small doses of radiation.

The National Academies of Science (NAS) in the United States struggled with this radiation question, and the first formal risk assessment, “Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants,” NUREG 75/014, better known as the Rasmussen Report, was prepared for the Nuclear Regulatory Commission (Nuclear Regulatory Commission, 1975). This was, among other things, a study of core meltdowns at nuclear power plants that used a no-threshold model to estimate cancer deaths following a nuclear reactor accident.

NATIONAL FLOOD PROGRAM

Risk analysis was creeping into the public consciousness in a number of ways, although no one called it by that name at the time. In 1936, the U.S. government passed the Flood Control Act of 1936, which established a national flood control program. This program assesses, communicates, and manages risk. Following hurricanes Katrina and Rita, the U.S. Army Corps of Engineers renamed this program Flood Risk Management.

Government agencies eventually began doing risk assessment routinely, and the early pioneers of risk assessment describe a rather ad hoc process. In the 1980s the National Research Council was asked to determine whether organizational and procedural reforms could improve the performance and use of risk assessment in the federal government. In 1983 they published their response, *Risk Assessment in the Federal Government: Managing the Process*, better known as *The Red Book* because of its cover (National Research Council, 1983). This is one of the seminal publications in risk assessment, and it identifies the four steps of risk assessment as:

1. Hazard identification
2. Dose-response assessment
3. Exposure assessment
4. Risk characterization

This has been the foundation model for risk assessment that has been modified and evolved many times since.

Risk assessment came before the U.S. Supreme Court in two cases during the Carter administration. The Industrial Union Department, *AFL-CIO v. American Petroleum Institute*, 448 U.S. 607 (1980) case considered whether quantitative cancer risk assessments could be used in policy making. One federal agency, OSHA, said no, while the EPA and FDA said yes. The majority opinion established that risk assessment is feasible and that OSHA must do one before taking rule-making action to reduce or eliminate the benzene risk. Later, in the *American Textile Manufacturers Institute v. Donovan*, 452 U.S. 490 (1981) case, the Supreme Court reaffirmed the Benzene case finding and added that safe does not mean zero risk. With this last hurdle cleared, risk assessment moved more confidently into the government's policy arena.

Internationally, risk assessment was also growing in credibility. The General Agreement on Tariffs and Trade's (GATT) Uruguay Round on multilateral trade negotiations (1986–1994) was instrumental in the global spread of risk analysis. Specifically, two agreements—on Sanitary and Phytosanitary Measures (SPS) and on Technical Barriers to Trade (TBT)—paved the way for risk assessment in the World Trade Organization (WTO).

THREE SISTERS

The SPS agreement has influenced the international standards of the *Codex Alimentarius* (for food), the World Organisation for Animal Health (OIE), and the International Plant Protection Convention (IPPC), all of whom have adopted risk analysis principles for their procedures.

The SPS agreement (1995) recognizes the right of governments to protect the health of their people from hazards that may be introduced with imported food by imposing sanitary measures, even if this means trade restrictions. The agreement

obliges governments to base such sanitary measures on risk assessment to prevent disguised trade protection measures.

Following the lead of the WTO, many regional trade agreements, including the North American Free Trade Agreement (NAFTA), incorporate risk analysis principles into their agreements. Both the Food Agricultural Organization (FAO) and the World Health Organization (WHO), two United Nations agencies, lend extensive support to the use of risk analysis principles globally.

The Committee of Sponsoring Organizations of the Treadway Commission (COSO) published its “Enterprise Risk Management—Integrated Framework” in 2004. It defined enterprise risk management (ERM) as a “...process, effected by an entity’s board of directors, management, and other personnel, applied in strategy setting and across the enterprise, designed to identify potential events that may affect the entity, and manage risk to be within its risk appetite, to provide reasonable assurance regarding the achievement of entity objectives.” The International Organization for Standardization undertook an effort to write a new global guideline for the definition and practice of risk management internationally. That guideline “Risk Management—Principles and Guidelines” was completed and released in 2009 (ISO 31000). It was updated in 2018.

In recent years many nations have begun to make extensive use of risk analysis in their regulatory and other government functions. Risk analysis is now well established in both the private and public sectors around the world.

1.5.2 GOVERNMENT AGENCIES

Government agencies are widely adopting risk analysis principles to varying extents. Some agencies have begun to redefine their missions and modes of operation in terms of risk analysis principles. Risk analysis has become their *modus operandi*. Other agencies have added risk analysis principles to their existing methodologies and tools for accomplishing their mission (see accompanying text box). *Risk-informed decision making* is a term often used to describe the use of risk analysis in some government agencies. States and local governments are adopting risk analysis approaches at varying rates. Natural and environmental resource agencies as well as public health and public safety agencies tend to be the first to adapt risk analysis principles at the nonfederal levels of government.

Internationally, risk analysis has proliferated in some communities of practice. Food safety, animal health, plant protection, engineering, and the environment are some of the areas in which other national governments are likely to have established the practice of risk analysis. The global economic recession that began in 2008 has propelled economic and financial regulatory agencies to move more aggressively toward risk analysis in the form of ERM.

In 2016, the U.S. Office of Management and Budget Circular No. A-123, *Management’s Responsibility for Enterprise Risk Management and Internal Control*, established the requirement for U.S. government agencies to implement an ERM capability in order to improve mission delivery, reduce costs, and focus corrective actions toward key risks.

SELECTED U.S. AGENCIES USING SOME RISK ANALYSIS PRINCIPLES

Animal and Plant Health Inspection Service http://www.aphis.usda.gov/	Food Safety and Inspection Service http://www.fsis.usda.gov/
Bureau of Economic Analysis (BEA) http://www.bea.gov/	Foreign Agricultural Service http://www.fas.usda.gov/
Bureau of Reclamation http://www.usbr.gov/	Forest Service http://www.fs.fed.us/
Centers for Disease Control and Prevention (CDC) http://www.cdc.gov/	U.S. Geological Survey (USGS) http://www.usgs.gov/
Coast Guard http://www.uscg.mil/	Government Accountability Office (GAO) http://www.gao.gov/
Congressional Budget Office (CBO) http://www.cbo.gov/	National Aeronautics and Space Administration (NASA) http://www.nasa.gov/
Consumer Product Safety Commission (CPSC) http://www.cpsc.gov/	National Marine Fisheries http://www.nmfs.noaa.gov/
Corps of Engineers http://www.usace.army.mil/	National Oceanic and Atmospheric Administration (NOAA) http://www.noaa.gov/
Customs and Border Protection http://www.cbp.gov/	National Park Service http://www.nps.gov/
Defense Advanced Research Projects Agency (DARPA) http://www.nsf.gov/	National Science Foundation http://www.nsf.gov/
Department of Defense (DOD) http://www.defenselink.mil/	National Security Agency (NSA) http://www.nsa.gov/
Department of Energy (DOE) http://www.energy.gov/	National Transportation Safety Board http://www.nts.gov/
Department of Homeland Security (DHS) http://www.dhs.gov/	National War College http://www.ndu.edu/nwc/index.htm
Director of National Intelligence http://www.dni.gov/	National Weather Service http://www.nws.noaa.gov/
Economic Research Service http://www.ers.usda.gov/	Natural Resources Conservation Service http://www.nrcs.usda.gov/
Endangered Species Committee http://endangered.fws.gov/	Nuclear Regulatory Commission http://www.nrc.gov/
Environmental Protection Agency (EPA) http://www.epa.gov/	Oak Ridge National Laboratory http://www.oro.doe.gov/
Federal Aviation Administration (FAA) http://www.faa.gov/	Occupational Safety and Health Administration (OSHA) http://www.osha.gov/
Federal Bureau of Investigation (FBI) http://www.fbi.gov/	Office of Management and Budget (OMB) http://www.whitehouse.gov/omb/
Fish and Wildlife Service http://www.fws.gov/	Office of Science and Technology Policy http://www.ostp.gov/
Food and Drug Administration (FDA) http://www.fda.gov/	

Risk Management Agency (Department of
Agriculture)

<http://www.rma.usda.gov/>

Securities and Exchange Commission (SEC)

<http://www.sec.gov/>

Superfund Basic Research Program

<http://www.niehs.nih.gov/research/supported/sbrp/>

Tennessee Valley Authority

<http://www.tva.gov/>

1.5.3 PRIVATE SECTOR

The insurance industry may represent the oldest and most explicit application of risk management in the private sector. As early as 1955, Dr. Wayne Snider, University of Pennsylvania, suggested “the professional insurance manager should be a risk manager.” By 1966, the Insurance Institute of America had created a credentialed position called “Associate in Risk Management.” In 1975, the American Society of Insurance Management changed its name to the Risk and Insurance Management Society (RIMS). In 1986, the Institute for Risk Management in London began a program of continuing education that looked at risk management in all its aspects. GE Capital used the title “Chief Risk Officer” to describe an organizational function to manage all aspects of risk that same year.

During the 1990s, several national standards began advocating that businesses should manage all risks as a portfolio across the enterprise. COSO’s “Enterprise Risk Management—Integrated Framework” was a significant step forward. By the time ISO 31000 was published in 2009, the private sector had two popular models of risk management to follow. Both of these models include the three risk analysis tasks of risk management, risk assessment, and risk communication, to varying extents. The private financial sector has also been an innovator in risk-related areas. Security has taken on a growing number of risk applications as technology has expanded the notion of and need for risk analysis. Academia has also embraced risk management in significant numbers.

Risk management spread from the insurance and financial sectors to other safety-oriented professions and businesses like engineering, construction, and manufacturing, where safety assessments have long been a part of the industry. From there it has been a short leap to every kind of private entity. Organizations in all industries have now begun a more explicit consideration of risk.

A conspicuous example of this is found in the food industry, where all links in the food chain have been devoting increased attention to food-safety risk analysis. The medical community is also increasingly involved with risk reduction. Formal risk analysis/risk management has been penetrating the private sector in increasingly large numbers. ISO 31000 marks a landmark effort to standardize many risk management notions for industry. As public policies increasingly reflect the influence of risk analysis, it is inevitable that the private-sector interest will continue to grow. A 2016 survey of more than 300 U.S.-based executives (Deloitte, 2017)

identified the following top-rated risk management successes in private industry (% of respondents):

- Avoided major compliance failures (44%)
- Expanded our senior leadership team’s participation in setting risk management priorities (42%)
- Have become more agile through risk management (36%)
- Identified and acted on an important opportunity for a new product or line of business (31%)
- Avoided major damage to reputation (31%)
- Improved risk management by implementing new methods/technologies (28%)
- Avoided a major potential financial loss (21%)
- Substantially improved relationships with one or more customers (19%)

With these kinds of results, the spread of risk management is inevitable.

1.6 WHEN SHOULD WE DO RISK ANALYSIS?

Risk analysis is for organizations that make decisions under conditions of uncertainty. [Figure 1.2](#) provides a schematic illustration of the kinds of decision contexts where risk analysis adds the most value to decision making. This value depends on how much uncertainty the organization faces and the consequences of making a wrong decision.

In the lower-right quadrant, there is little uncertainty and the consequences of being wrong are minor. This kind of decision making does not require risk analysis. Any convenient means of decision making will do here.

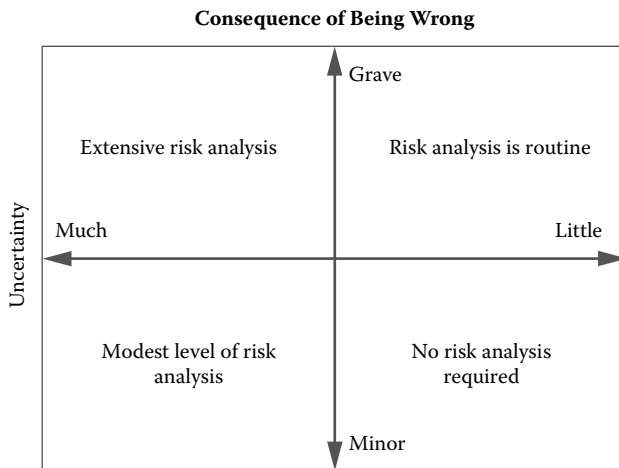


FIGURE 1.2 When to use risk analysis.

When there is a lot of uncertainty, but the consequences of an incorrect decision are minor, it would be sufficient to do a modest level of risk analysis. This may entail little more than sifting through the uncertainty to assure decision makers that the decision and its outcome are not especially sensitive to the uncertainties. In some instances, it may be sufficient to establish that one or the other factors of the “consequence \times probability” product is sufficiently small as to render the relevant risks acceptable.

When the consequences of making a wrong decision rise, so does the value of risk analysis. In an environment with relatively less uncertainty but with serious consequences for wrong decisions, risk analysis is valuable as a routine method for decision making. As the uncertainty grows in extent, risk analysis becomes the most valuable, and more extensive efforts may be warranted.

Some organizations would be wise to always be doing risk analysis. In fact, a slowly growing number of organizations define themselves as risk analysis or risk management organizations, meaning that what they do as an organization is manage risks, assess risks, and communicate about risks. Others use risk analysis as a framework, tool, or methodology for specific situations. Stewards of the public trust would be well advised to use risk analysis for decision making.

Risk analysis, as a way of doing business, is especially useful for organizations that have some or all of the following elements of decision making in common (adapted from National Research Council, 2009):

- A desire to use the best scientific methods and evidence in informing decisions
- Uncertainty that limits the ability to characterize both the magnitude of the problem and the corresponding benefits of proposed risk management options
- A need for timeliness in decision making that precludes resolving important uncertainties before decisions are required
- The presence of some sort of trade-off among disparate values in decision making
- The reality that, because of the inherent complexity of the systems being managed and the sometimes long-term implications of many risk management decisions, there may be little or no short-term feedback as to whether the desired outcome has been achieved by the decisions.

Every organization has its own unique reality. They have a history, a mission, personnel, resources, policies, procedures, and their own way of doing things. If you drop risk analysis science down into any organization, the context of that organization is going to affect the way the risk analysis paradigm is going to look and work. For example, there is no agreement on what applied risk science is even called, much less agreement on any one risk analysis model to be followed by the U.S. government agencies mentioned previously. In fact, it is probably fair to say that risk analysis looks different in every organization that uses it.

WHAT IS IT CALLED?

The EPA favors risk assessment. The FDA and Food Safety Inspection Service tend to use risk analysis. The DoD leans toward integrated risk management, while the U.S. Army Corps of Engineers is transitioning from risk-informed decision making to enterprise risk management.

Take the FDA as an example. Risk analysis is vigorously pursued in several of its centers including the Centers for Food Safety and Applied Nutrition, Veterinary Medicine, Devices and Radiological Health, and Drug Evaluation and Research. Each of these defines the terms of risk analysis differently and applies the concepts in different ways and to varying extents. They have developed their own risk-related tools and techniques. This is a strength of the paradigm. It is a remarkably flexible and robust way to think about and to solve problems, so be assured there is no one best way to practice risk analysis.

1.7 ORGANIZATION OF BOOK

This book is organized into two broad sections. The first six chapters provide a generic introduction to the science and principles of risk analysis. The next 15 chapters provide details on how to apply these principles.

There are hundreds of very good books already in print devoted to risk analysis. Most tend to focus, relatively quickly, on a rather narrow aspect or practice of the discipline. Many are written from a particular disciplinary or topical perspective, such as engineering, finance, environment, public health, food safety, water, and so on. This book avoids a narrow focus on any one field in favor of distilling principles, integrating topics, and stressing the application of the principles in a generic fashion. Armed with this understanding the reader can return to any CoP to apply these principles.

Risk analysis can become complex. Some books can become overwhelming for those new to risk analysis because they introduce so many ideas so fast. This text focuses narrowly on the most basic principles of the emerging science of risk analysis, that is, risk, uncertainty, risk management, risk assessment, and risk communication.

Like good risk analysis, this book proceeds in an iterative fashion. Each of the next five chapters unpacks and explains important concepts introduced in this chapter. [Chapter 2](#) takes up the notion of uncertainty in more detail. Uncertainty is the primary reason for risk analysis, and its pervasiveness is what has caused the use of risk analysis to spread so quickly in recent years. It is important for risk managers, risk assessors, and risk communicators to have a sound and common understanding of uncertainty.

[Chapter 3](#) develops the risk management component and the job of the risk manager. In best practice, every risk analysis task begins and ends with risk management. The tasks of risk management are presented in a generic fashion, free from any particular preexisting risk management model. [Chapter 4](#) unpacks the risk assessment component. This is where the analytical work gets done for any risk management activity. As with the risk management chapter, the risk assessment tasks

are presented in a model free fashion. [Chapter 5](#) explores the risk communication component in greater detail. The generic tasks of both the internal and external risk communication responsibilities are presented. [Chapters 3 through 5](#) together describe the three elements of the risk analysis paradigm. [Chapter 6](#) introduces enterprise risk management (ERM). ERM has been adopted by a great many private sector organizations and is significantly increasing the footprint of risk analysis. ERM tends to avoid the use of the term “risk analysis” and instead uses risk management as the overarching term for this risk paradigm.

[Chapters 7 through 9](#) expand on the risk management task. [Chapter 7](#) emphasizes the importance of problem-identification in risk management by expanding on the nature of problems and opportunities and by offering several techniques that have proven useful in identifying them. This critical step is one of the most overlooked and underemphasized in my risk analysis experience.

[Chapter 8](#) is about brainstorming. Good risk management requires divergent thinking at various points throughout the process. Many, if not most, well-educated professionals are justifiably leery of processes, especially those that seem trendy and fashionable. When the goal is to generate ideas and different perspectives, brainstorming is a technique that works. No risk manager should be without a technique or two to draw on.

The final risk management chapter summarizes economics for risk managers. Someone is always going to care about costs. With complex decision problems, there will always be conflicting values. This chapter focuses primarily on the economic aspects of opportunity cost, trade-offs, and incentives. The ability to correctly identify all the relevant costs and to understand how trade-offs are made at the margin is an indispensable skill for risk managers in any field. The success of a risk management decision often depends, critically, on the incentive effects of the decision.

The risk assessment task is emphasized in [Chapters 10–17](#). Many essential details will be found in them. [Chapter 10](#) introduces the reader to dozens of tools and techniques that comprise the risk assessor’s toolbox. These include qualitative and quantitative tools. The subject of [Chapter 11](#) is modeling. It begins by considering different types of models and then focuses on a 12-step model-building process that can be followed for any kind of quantitative model. This section builds on the work of others and my own experience in building risk assessment models.

The next five chapters address varying aspects of probability, all essential to decision making under uncertainty. A review of basic probability concepts used by risk assessors is found in [Chapter 12](#). It presents a pragmatic distinction between the frequentist and subjectivist views of probability without taking an advocacy position. This is followed by a discussion of probability essentials, that is, where they come from and what the most important axioms and propositions are. All of this is done with an eye on why you need to know this to do risk assessment.

[Chapter 13](#) is, I hope, one of the more useful chapters in this applications part of the text. It begins by describing the different functions that can be used to present probability distribution information. The real heart of the chapter is devoted to helping risk assessors—whether experienced or inexperienced—choose the right probability distribution to represent their knowledge uncertainty or the natural variability in the world they are modeling. The method presented has been pieced together over a

number of years of experience, where at times I was the only person who cared about the distribution and at other times the acceptance of a model stood on the credibility of the distribution(s) chosen.

[Chapter 14](#) introduces the topic of characterizing uncertainty through expert elicitation with a focus on probability elicitation, a specific form of expert elicitation that is growing rapidly. One of the most common uncertainties encountered stems from a lack of data about quantities of critical interest to our risk assessments. Experts are increasingly being used to fill in gaps in dose-response curves, to estimate probabilities of failure and unsatisfactory performance, to forecast the likelihoods of future events from sea level rise to terrorist attacks, and virtually anything you can imagine. The problem is that even experts are not so reliable at estimating subjective probabilities. Thus, it is important to have a good grasp of the issues that can arise in subjective probability elicitation. That grasp can be found in [Chapter 14](#).

The Monte Carlo process may be the most commonly used approach to probabilistic risk assessment. Every good risk assessor needs to know a little about this process and how it works. [Chapter 15](#) provides the reader with a peek behind the Monte Carlo process curtain. It will also help you think about how many iterations you need and whether you should generate them using Monte Carlo or Latin Hypercube sampling techniques.

[Chapter 16](#) builds on the work in earlier chapters to present an especially useful bundle of risk assessment tools called probabilistic scenario analysis. This chapter begins by defining scenarios and describing some of the most common types used in risk assessment. It then focuses on tree structures as one of the more useful tools for structuring scenarios. Once the probability tools and techniques of the earlier chapters are layered on top of the scenario tools, the risk assessor has a very powerful suite of tools to use to assess risk.

Techniques for addressing uncertainty are woven throughout the chapters of this text. [Chapter 17](#), however, discusses sensitivity analysis, which can be described as the uncertainty “table stakes” for every risk assessment. Exploring the significance of the uncertainty encountered in a decision problem for the decision-making process through sensitivity analysis is the absolute bare minimum standard for any risk assessment. A variety of qualitative and quantitative sensitivity analysis techniques are presented or summarized.

[Chapters 18 and 19](#) focus on decision makers. [Chapter 18](#) focuses on presenting and understanding the results of a risk assessment. This content could just as easily be considered an expansion of either the risk management or risk assessment tasks. It could also be considered part of the risk communication task because communication of complex quantitative and probabilistic information to decision makers and the general public remains a substantial hurdle in the risk analysis process.

[Chapter 19](#) reverts back to an important risk management task, namely decision making under uncertainty. This might entail making a decision when some decision criteria are uncertain or could mean not knowing what to do even when the decision criteria are understood. Although it offers an overview of some decision theory approaches, it is its practical suggestions that are likely to be most useful to readers.

Chapters 20 and 21 expand on some risk communication challenges. Chapter 20 is about developing risk communication messages for the public. Beginning with a basic communication model, it quickly differentiates the challenges of communicating about risk, especially during the high-anxiety circumstances of a crisis. Message development and message mapping are introduced as useful entry points into this rich field of risk communication. Chapter 21 addresses the value of effective story telling when communicating the results of risk assessments and risk management actions. If risk analysis does not lead to effective action, then the battle is not won. Data may be effective in convincing people, but risk analysis is science in action, and it takes compelling stories not ponderous reports to inspire people to action.

The final chapter, Chapter 22, presents examples of risk assessments. Eight examples are offered to illustrate some of the ideas discussed throughout the text. Appendix A provides an introduction to Palisade Corporation's DecisionTools® Suite software that was used in the preparation of this book. Files used in the creation of this book and additional exercises as well as a free student version of the software are available at <http://www.palisade.com/bookdownloads/yoe/principles/>.

1.8 SUMMARY AND LOOK FORWARD

Risk is the chance of an undesirable outcome. That outcome may be a loss or the failure to attain a favorable situation. In a certain world there is no risk because every outcome is known in advance. It is uncertainty that gives rise to risk.

Safety is a subjective judgment, while risk analysis is, in principle, an objective search for the risks in any given situation. Risk analysis is the framework or, if you prefer, the science used to manage, measure, and talk about risk. It has three components: risk management, risk assessment, and risk communication. Risk analysis is now possible because of the confluence of many scientific developments. Its use in the United States and internationally is growing steadily, and applications are found in a wide variety of fields.

The language of risk analysis is evolving. It would be comforting to think that it is evolving toward some consensus definitions and a common terminology. That is not yet the case, and this book makes no attempt to resolve the language differences. What it does do is attempt to distill the principles common to the many different dialects of risk that are spoken in the fields of applied risk analysis. There is a growing tendency among some in both the public and private sectors to refer to the risk analysis paradigm as risk management. This text will use risk analysis to represent the emerging science and to describe the use of risk analysis science as applied to real world problems. Do not let that semantic debate get in the way of your understanding. Use the term you prefer.

The next chapter gets to the root cause of risk analysis, that is, uncertainty. A primary role of the risk analyst is to separate what we know from what we do not know and then to deal honestly, intentionally, and effectively with those things we do not know. The job of the risk analyst is to be an honest broker of information in decision making. Knowledge uncertainty and natural variability, two fundamental concepts essential to understanding risk analysis, are the focus of Chapter 2.

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2 Uncertainty

2.1 INTRODUCTION

Because risk analysis focuses on decision making under uncertainty, it is important to understand what uncertainty is. At the most basic level, when we are not sure, then we are uncertain. Uncertainty arises at two fundamentally different levels. First, there is the macro-level of uncertainty. We all make decisions in a changing and uncertain decision environment. This means the systems, processes, social values, ways forward, and outcomes of concern to us may be uncertain. Second, there is the micro-level of uncertainty. This is the uncertainty that pertains to specific decision contexts and their relevant knowledge, data, and models. These latter uncertainties receive most of the attention in risk assessment.

If there was no uncertainty about facts, there would be no question about whether or when a loss would occur and how big it would be. Likewise, we would always know how an opportunity would turn out. Even so, uncertainty about what we should do in the face of these situations would still arise because of differing values. Uncertainty is the reason for risk analysis. Risk assessors have to understand uncertainty because they are, in a sense, the first responders to uncertainty. It is the assessors who identify data gaps, holes in our theories, shortcomings of our models, incompleteness in our scenarios, and ignorance about some quantities and variability in others. It is an important part of the risk assessor's* job to address the uncertainty in individual assessment inputs.

Think of the assessor's job as separating what we know from what we do not know about a decision problem context and then being intentional about assessing the significance of the things we do not know for decision making. There are usually things we know with certainty. We can measure distances, count dollars, we know atomic structures of chemicals; our physical world is loaded with facts. But every decision problem comes with a "pile" of things we do not know. The risk assessor, along with the risk manager, has to identify that pile and what is in it.

It is the risk manager's job to decide how to handle the uncertainty that remains in decision making. Measures of decision criteria may be uncertain, the outcome of a risk management option may be unknown. Addressing these uncertainty issues is the risk manager's responsibility. There may also be uncertainty that arises with the risk management task. Even when all the decision criteria are clear, the risk manager may not know what to do because of conflicting values. This uncertainty also belongs to the risk manager. Risk managers need to understand uncertainty because they are the final arbiters of it in the decision-making process.

The risk communicator has the responsibility of understanding the uncertainty and its relevance for decision making so that they can explain it and its significance to others. That task requires risk communicators to understand input, output, and

* The possessive case used for risk assessors and risk managers will always be in the singular form for the sake of simplicity. It should be understood, however, that both can be multiple in numbers at times.

outcome uncertainty well enough to make it understandable by diverse audiences among the public and stakeholders interested in a risk management decision.

There is another important distinction to make about things that are uncertain. Uncertainty is relevant if it could impact a decision in at least a subtle way. Relevant uncertainty may make one option less appealing than another or it might make a particular stakeholder uneasy. Relevant uncertainty can be categorized as instrumental or noninstrumental. The ability to distinguish between the two is essential to both good risk assessment and good risk management. Instrumental uncertainty can alter the decision that is made or the outcome of that decision. Noninstrumental uncertainty refers to uncertainty that would not alter a decision if it was reduced. Noninstrumental holes in our data or gaps in information may be relevant in some way, but they would not affect the decision to be made if they were filled. Good risk assessors and risk managers are able to focus on identifying, reducing, or otherwise characterizing the instrumental uncertainty encountered in decision making.

This chapter focuses, in a conceptual way, on the pile of things we do not know and specifically on the instrumental uncertainty in that pile of things. In order to know how best to address the things we do not know, the assessor must first understand the nature of those things in the pile of unknowns (see [Figure 2.1](#)). The

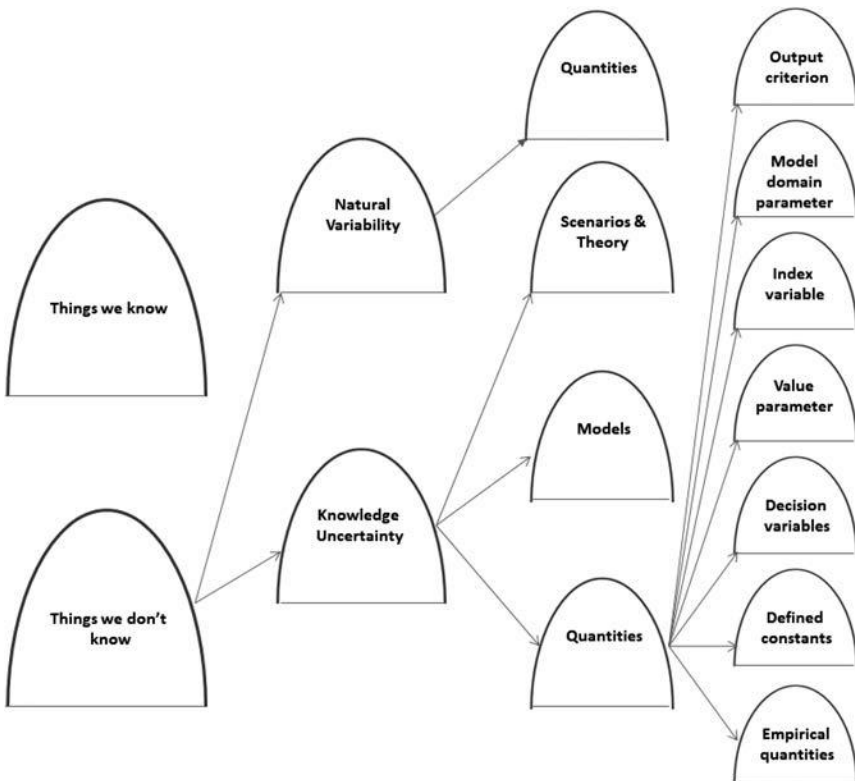


FIGURE 2.1 Separating what we know from what we do not know and sorting out the unknowns.

original pile of unknowns, or uncertainty, is then sorted into two distinct sources of not knowing: natural variability and knowledge uncertainty. Natural variability generally refers to empirical quantities. Knowledge uncertainty is divided into three main piles: scenarios and theory, models, and quantities. The quantities, in their turn, are separated into types of quantities first proposed by Morgan and Henrion (1990). This conceptual sorting activity enables us to choose most appropriately from the various tools, techniques, and methodologies available for addressing uncertainty in the assessment and management tasks.

This chapter begins by considering the macro-level of uncertainty that is sometimes overlooked in risk analysis. Then it focuses on the micro-level uncertainty issues that occupy so much of the risk assessor’s concerns. At that point in the chapter we will reengage the structure shown in [Figure 2.1](#).

An important distinction will be drawn between knowledge uncertainty and natural variability, and the many piles illustrated in [Figure 2.1](#) will be explored and discussed. The causes of uncertainty in empirical quantities are considered to round out the discussion of uncertainty as depicted in the figure.

Before beginning we offer an important clarification of the language. People often speak of uncertain values, and this is, strictly speaking, not correct. The values themselves are not uncertain; it is the assessor and the manager who are uncertain about what a factual value is or what a value that reflects a preference should be. Even so, this text will join in the use of that terminology to avoid the repeated verbosity of explaining that these are values people are uncertain about.

2.2 UNCERTAINTY FROM 75,000 FEET

Uncertainty is an emerging constant in modern decision making. We all operate in an uncertain environment. Growing social complexity and an increasingly rapid pace of change are normal parts of the decision-making landscape, and they contribute a great deal to the uncertain environment in which we operate. Risk analysis offers a viable alternative to clinging to a deterministic style of decision making in this uncertain environment.

TOP FIVE GLOBAL RISKS

In terms of likelihood

1. Extreme weather events
2. Natural disasters
3. Cyberattacks
4. Data fraud of thefts
5. Failure of climate-change mitigation and adaptation

In terms of impact

1. Weapons of mass destruction
2. Extreme weather events
3. Natural disasters
4. Failure of climate-change mitigation and adaptation
5. Water crises

Source: The Global Risks Report 2018.

The world grows more complex. Think of complexity, as used here, in a social sense. It refers to such things as the size of a society, the number of its parts, the distinctiveness of those parts, their interconnectedness, the variety of specialized social roles that it incorporates, the number of distinct social personalities present, and the variety of mechanisms for organizing these into a coherent, functioning whole. Augmenting any of these dimensions increases the complexity of a society (Tainter, 1996). The level of complexity in our social, economic, and technological systems is increasing to a point that is too unsettled and rapidly changing to be wholly understood or predicted by human beings.

For over 99% of human history we lived as low-density foragers or farmers in egalitarian communities of no more than a few dozen persons and even fewer distinct social roles. In the twenty-first century we live in societies with millions of different roles and personalities. Our social systems grow so complex as to defy understanding. Consequently, our systems of problem solving have grown more complex.

We face an increasingly rapid pace of change in almost every arena. Scientific breakthroughs make things that once were impossible to conceive commonplace. Much of this change is driven by rapid advances in technology. For example, the risk of conflict is exacerbated by weaponized robotics and artificial intelligence. Cyberspace is an entirely new domain for conflict. Technology changes social values and beliefs as well as the way we live and work. The ways we communicate have changed forever and continue to change in ways that are difficult to forecast. Change is too rapid and at times too turbulent to be wholly understood or predicted.

Social, economic, and technological connectivity around the globe accelerates at a dizzying pace. Social movements are often global in their pervasiveness. We are increasingly a global economy. Fashions are designed in New York and approved in London, patterns are cut in Hong Kong, clothes are made in Taiwan and shipped in containers on vessels that call around the world, and then the clothes are sold across Europe and North America. Computer viruses spread in hours; human viruses spread in weeks. We are indelibly connected.

With government deficits and debts rising in the more established economies of the world, there is relentless pressure on costs in all public decision making. Patterns of competition are becoming unpredictable. It is getting harder and harder to understand and anticipate who the competition is for a job, for U.S. grain, for land use, and so on. For businesses and government agencies alike, customer/client profiles are changing rapidly and unpredictably. We see quickly increasing and diversified customer demands. There is a growing role for one-of-a-kind services and production, and rapid sequences of new tasks in business and government are becoming more routine. A media explosion is just one of the consequences of an increase in the number and speed of communication channels. Big data is transforming the ways that businesses operate.

As a result of these and other changes, we have entered a world where irreversible consequences, unlimited in time and space, are now possible. This is or should be extremely important to risk managers in both the public and private sectors. Decades after the accident at Chernobyl, some of its victims haven't even been born yet. Some

of the wicked problems* risk managers face can have a long latency period. Many of the United States' landscape-scale ecosystem restoration problems—like those in the Florida Everglades, Coastal Louisiana, and the Columbia River basin—as well as such global concerns as greenhouse gases, climate change, and sea level rise provide clear examples of problems that took decades to emerge and be recognized. The implications of the solutions being formulated may similarly take decades to be understood.

A new phenomenon of “known unawareness” has entered our lexicon. . In November 2006, Donald Rumsfeld summarized this truth to scattered laughter when he said: “There are known knowns. These are things we know that we know. There are known unknowns. That is to say, there are things that we now know we do not know. But there are also unknown unknowns. These are things we do not know we do not know” (Profita, 2006). No one is laughing anymore. As a society we are beginning to realize that despite all we know, the unknown far outweighs what is known. Knowledge is as much to create more questions as it is to provide definitive answers.

Clearly, scientists now know much more about BSE (bovine spongiform encephalopathy or mad cow disease) than when it was first found in cattle in 1986. Even now, decades after the disease's discovery, its origins, its host range, its means of transmission, the nature of the infectious agent, and its relation to its human counterpart new variant Creutzfeldt–Jakob disease remain mostly unknown. We have begun to suspect that there are some risks for which there may be no narrative closure, no ending by which the truth is recovered and the boundaries of the risk established.

Although most of us live and work in nations, our interactions and our risks are increasingly global in nature. The interconnected nature of the global system produces cascading risks at the domestic level. Failing government in Syria produces civil conflict that transfers economic, social, and political pressures into neighboring countries as well as nations around the world. Terrorism threatens the lives of innocent citizens around the world. An oil spill in the Gulf of Mexico reverberates around the world. It becomes increasingly difficult to affix responsibility for problems and their solutions. Who is destroying the ozone, causing global warming, spreading BSE and AIDS? Where did the H5N1 or H1N1 viruses originate and how? Whose responsibility is it to fix these things?

Despite the world's rapid advances in all kinds of sciences, we are increasingly dominated by public perception. Public perception is a palpable force. In some situations, it is an irresistible one. Uncertainties and the risks they give rise to have a social context. Without social and cultural judgments, there are no risks. Nonetheless, these social and cultural judgments are not always grounded in fact. Unfortunately, they are also not always adequately considered in decision-making processes. The public is fond of equating the possibility of an undesirable outcome with the probability of such an outcome. This makes conceivable risks seem very possible, and it fuels our fears of the uncertain. It leads, paradoxically, to audiences that are alternately outraged and indifferent about the risks they face.

* Wicked problems are complex problems that lack right and wrong solutions. Instead there are many candidate solutions, and some are better and some are worse than others, but none is clearly best.

Social and cultural views can find and have found their way into public policy. This is in part because many things that were once considered certain and safe, and often vouched for by authorities, turned out to be deadly. The BSE experience in Europe, the SARS (severe acute respiratory syndrome) experience in Asia and elsewhere, the melamine contamination from Chinese products, even ordinary things like dining out or attending a concert provide vivid examples of this phenomenon. Applying knowledge of these experiences to the present and the future devalues the certainties of today. This is what makes conceivable threats seem so possible and what fuels our fears of that which is uncertain. It is also what makes criticism of a decision that masquerades as certain embarrassingly easy.

Responsibility in this more connected world has become less clear. Who has to prove what? What constitutes proof under conditions of uncertainty? What norms of accountability are being used? Who is responsible morally? Who is responsible for paying the costs? These questions plague decision makers nationally and transnationally.

We all live and operate in this uncertain reality. Social values are formed, changed, and reformed against this backdrop of macro-level uncertainty. There are so many social relationships that it is difficult to know what values the nation, a project area community, or a stakeholder group holds dear at any one point in time. Yet many organizations and individuals cling stubbornly to a deterministic approach to decision making that belies the experience of public and private sectors the world over. Decision making needs a “culture of uncertainty.” Risk analysis provides just such a culture.

The future is fundamentally unknowable. There must be recognition of the central importance of demonstrating the collective will to act responsibly and accountably with regard to our efforts to grapple with this fundamental uncertainty and the inevitable shortfalls that will occur despite every best effort to account for this uncertainty. In an uncertain world we cannot know everything, and we will make mistakes despite our best efforts to the contrary. This is the challenge that invites risk analysis to the fore.

2.3 THE UNCERTAINTY ON YOUR DESK

The uncertainty that has received the most attention in risk analysis is not the macro-level uncertainty we see from 75,000 feet, nor is it the resulting uncertain environment in which we make decisions. It is the uncertainty that plagues our specific decision contexts. Anyone involved in real problem solving and decision making knows we rarely have all the information we need to make a decision that will yield a certain outcome. For any decision context, we can always make a pile of the things we know and a pile of the things we do not know. For risk analysis, we need to be able to take that pile of things we do not know and sort through it to better understand the nature and causes of the uncertainties we face. It is the nature and cause of the uncertainty that dictates the most appropriate tool to use on it. The first and most important distinction to make in our pile of unknowns is how much of the uncertainty is due to knowledge uncertainty and how much is due to natural variability.

2.3.1 KNOWLEDGE UNCERTAINTY OR NATURAL VARIABILITY?

You're headed for Melbourne, Australia, in November and are unsure how to pack because you do not know what the weather is like there at that time of year. For simplicity, let's focus on the daily high temperature. You do not know the mean high temperature for Melbourne in November. This is a parameter, a constant, with a true and factual value. That you do not know this fact makes the situation one of knowledge uncertainty. A true value exists and you do not know it. You are uncertain about a fact.

Suppose you learn from the Bureau of Meteorology, Australia, that this value is 21.9°C (71°F). The knowledge uncertainty has been removed. Now a new problem emerges. Even though you know the average temperature is 21.9°C, you have no way of knowing what the high temperature will be on any given day. In fact, you wisely expect the high temperature to vary from day to day.

DEFINITIONS OF UNCERTAINTY AND VARIABILITY

Uncertainty: Lack or incompleteness of information. Quantitative uncertainty analysis attempts to analyze and describe the degree to which a calculated value may differ from the true value; it sometimes uses probability distributions. Uncertainty depends on the quality, quantity, and relevance of data and on the reliability and relevance of models and assumptions.

Variability: Variability refers to true differences in attributes due to heterogeneity or diversity. Variability is usually not reducible by further measurement or study, although it can be better characterized.

Source: National Research Council (2009).

Using our very loose definition at the start of this chapter, you say you are not sure what the temperature will be on any given day, so that must be uncertainty as well. And in a very general sense it is. However, and this is an important however, this value is uncertain for a very specific, common, and recurring reason; there is natural variability in the universe.

This natural variability is usually separated out from other causes of uncertainty in order to preserve the distinction in its cause for reasons that will soon be apparent. Hence, we'd say you are no longer uncertain about the mean high temperature, but you still do not know the high temperature on any given day because of natural variability. The temperature varies from its mean day to day due to variation in the complex system that produces a high temperature each day. For a more formal distinction of these two concepts, we introduce the terms *epistemic* and *aleatory uncertainty*.

Epistemic uncertainty is the uncertainty attributed to a lack of knowledge on the part of the observer. It is reducible in principle, although it may be difficult or expensive to do so. Epistemic uncertainty, what was described in the previous example as knowledge uncertainty, arises from incomplete theory and incomplete understanding

of a system, modeling limitations, or limited data. Epistemic uncertainty has also been called internal, functional, subjective, reducible, or model form uncertainty. *Knowledge uncertainty* is another easier to remember and perhaps more descriptive term used to describe this kind of uncertainty. It is used throughout this book when we refer specifically to epistemic uncertainty.

Some generic examples of knowledge uncertainty include lack of experimental data to characterize new materials and processes, poor understanding of the linkages between inputs and outputs in a system, and thinking one value is greater than another but being unsure of that. Other examples include dated, missing, vague, or conflicting information; incorrect methods; faulty models; measurement errors; incorrect assumptions; and the like. Knowledge uncertainty is, quite simply, not knowing a fact. The most common example may be not knowing a parameter or value, like cost or a benefit-cost ratio, that we are interested in for model building or decision-making purposes.

AN IMPORTANT DISTINCTION

Natural variability cannot be reduced with more or better information.

Knowledge uncertainty can be reduced with more and better information through such means as research, data collection, better modeling and measurement, filling gaps in information and updating out-of-date information, and correcting faulty assumptions.

Aleatory uncertainty is uncertainty that deals with the inherent variability in the physical world. Variability is often attributed to a random process that produces natural variability of a quantity over time and space or among members of a population. It can arise because of natural, unpredictable variation in the performance of the system under study. It is, in principle, irreducible. In other words, the variability cannot be altered by obtaining more information, although one's characterization of that variability might change given additional information. For example, a larger database will provide a more precise estimate of the standard deviation of a temperature, for instance, but it does not reduce variability in the population of daily high temperatures. Aleatory uncertainty is sometimes called variability, irreducible uncertainty, stochastic uncertainty, and random uncertainty. The term adopted for usage in this book when we refer specifically to aleatory uncertainty is *natural variability*.

Some generic examples of natural variability include variation in the actual weight of potato chips in an eight-ounce bag, variation in the response of an ecosystem to a change in the physical environment, and variation in hourly traffic counts from day to day. There is also natural variability in any attribute of a population.

Knowledge uncertainty and *natural variability* are terms used by the National Research Council (2009). It will be convenient to use the term *uncertainty* to encompass both of these ideas, so that is the convention adopted in this book. However, this is by no means the usual convention, and the reader is advised to always clarify, when possible, and to try to carefully discern, when it is not, what the user of these terms means from the context of their usage.

To complicate matters, reality is often messy. Returning to our Melbourne example, we can see that at the outset we are dealing with both knowledge uncertainty and natural variability. It takes experience for a risk assessor to be able to comfortably label the reasons that a value may be uncertain. It is not always possible and not always important to be able to separate knowledge uncertainty and natural variability. In general, the most important reasons for separating the effects of the two in a risk assessment are to select an appropriate tool for addressing them and to understand that devoting more resources to the risk assessment effort may reduce knowledge uncertainty, but it will not reduce natural variability. The only way to change the natural variability produced by a system is to change the system itself. This will not eliminate natural variability; it will produce a new form of, presumably, more favorable variability in the altered system. Risk assessment can reduce knowledge uncertainty. Risk management measures can alter natural variability.

2.3.2 TYPES OF UNCERTAINTY

To sort through and understand the nature of the things we do not know, we begin by first differentiating knowledge uncertainty from natural variability. Natural variability is most often addressed through narrative descriptions of the variability, statistics, and probabilistic methods. Natural variability tends to apply to quantities only. Knowledge uncertainty is a bit more complex and needs additional sorting. The next tier of sorting separates our knowledge uncertainty into scenarios, models, and inputs/quantities, as seen in Figure 2.2.

Figure 2.2 provides an example of the types of knowledge uncertainty that might be encountered. It presents an ecological risk example. For now, think of scenarios as the stories we tell about risks. These are the narratives that describe what we believe to be

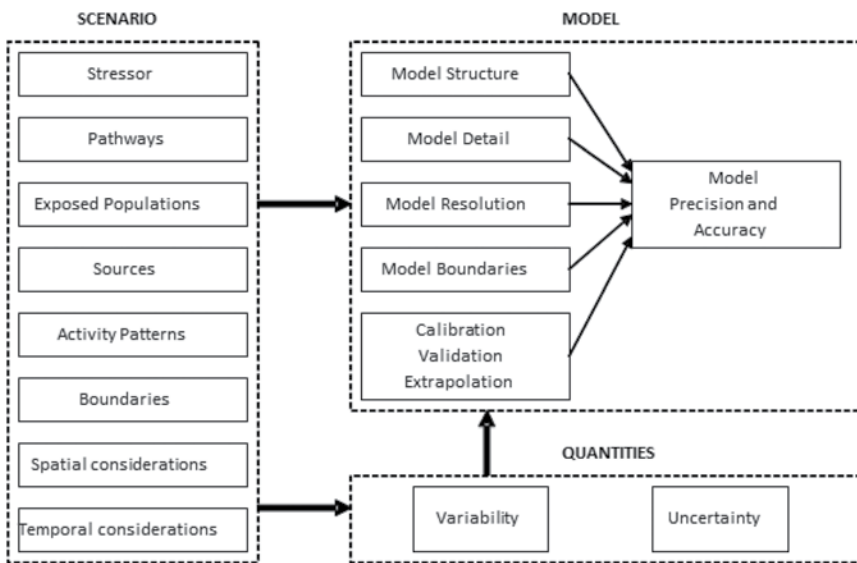


FIGURE 2.2 Sorting our knowledge uncertainty into scenarios, models, and input quantities.

true about the phenomena we study. This is where theory and knowledge of processes are most important. Models are used to give structure to scenarios and to perform calculations based on the quantities provided. Thus, we identify these three broad basic types of knowledge uncertainty you can expect to encounter in risk assessment.

Scenario uncertainty results when the elements of a scenario or their relationships are unknown or incomplete. Gaps in theory and understanding are most likely to occur in the stories we tell about what can go wrong, the consequences of it happening, how it happens, and how likely it is to happen. In the case of an ecosystem scenario, we might misunderstand the stressors that affect a habitat. Not knowing the relevant activity patterns of a locally threatened species could be another source of scenario uncertainty. We may also fail to understand all the relevant pathways in an ecosystem.

Model uncertainty reflects the bias or imprecision associated with compromises made or lack of adequate knowledge in specifying the structure and calibration (parameter estimation) of a model. Model structure typically refers to the set of equations or other functional relationships that comprise the specified scenario for the model. Model detail refers to the inclusion or omission of specific phenomena as well as the simplicity or complexity with which they are represented. Model resolution refers to the temporal or spatial scale at which information can be distinguished, for example, minutes versus hours versus years. Model boundaries describe the fidelity with which the desired scenario is captured by the model. Ideally, the precision and accuracy of the model predictions will be assessed as part of the validation exercise. In other words, how well does our model capture reality?

KNOWLEDGE UNCERTAINTY DEFINITIONS

Scenario uncertainty: Uncertainty in specifying the risk scenario which is consistent with the scope and purpose of the assessment.

Model uncertainty: Uncertainty due to gaps in scientific knowledge which hamper an adequate capture of the correct causal relations between risk factors.

Parameter/input uncertainty: Uncertainty involved in the specification of numerical values (be it point values or distributions of values) for the factors which determine the risk.

Source: WHO (2006).

Quantity or input uncertainty is encountered when the appropriate or true values of quantities are not known (knowledge uncertainty). These quantities are of enough importance to warrant additional discussion.

2.3.3 QUANTITY UNCERTAINTY

The most commonly encountered uncertainty is quantity uncertainty. Quantities can be unknown because of knowledge uncertainty or because of natural variability. Morgan and Henrion (1990) offer a very useful taxonomy for those seeking to understand

the basic types of quantity uncertainty shown in [Figure 2.1](#). Before considering their taxonomy, we need to make an important distinction. Some quantities have a true or factual value, while others do not. Instead of a true value, they have a best or most appropriate value that reflects some subjective judgment. There may be significant consternation about the best or preferred value for these kinds of quantities, but they have no true value we can discover. The search for a true value is an objective one, while the search for a best value is subjective.

In general, true values are looked up, measured, or estimated by some means. The means by which quantities with true values are estimated vary, and the best choice will depend on the cause of the value's uncertainty. Best or appropriate values are varied systematically (sometimes called parametric variation or sensitivity analysis) to examine the sensitivity of the model and its outputs to different chosen values.

TRUE VALUES

The population of a city, number of colony forming units per gram of material, percent of channel bottom that is rock, mean strength of materials in a structure, mean daily stream flow, average weight of an adult striped bass, median serving size, specificity of a diagnostic test, closing price of a stock, and contaminant concentration in a specific exposure are all quantities that have a true value.

Risk analysis can require a lot of information. Risk assessment, in particular, can involve a great deal of quantitative information that includes many parameters (numerical constants) and variables. The quantities used in risk assessment are frequently a major source of uncertainty. Having a way to think about these quantities and to talk about their uncertainty is critical to the success of any risk analysis.

Morgan and Henrion's (1990) classification of uncertain quantities includes:

- Empirical quantities
- Defined constants
- Decision variables
- Value parameters
- Index variables
- Model domain parameters
- Outcome criteria

The significance of the objective or subjective nature of the quantity uncertainty, as well as the type of quantity, will become most evident when one chooses a tool, technique, or methodology to treat the uncertainty appropriately. Look at the examples in [Table 2.1](#), then read the explanations that follow to better understand Morgan and Henrion's taxonomy of quantities. The approach used to resolve uncertainty depends very directly on what is uncertain and why it is uncertain.

TABLE 2.1
Uncertain Quantity Types and Examples

Types of Quantities	Selected Examples
Empirical quantities	Stream flow, eggs produced daily, vehicles crossing a bridge, temperature, time to complete a task, prevalence
Defined constants	Pi, square feet in an acre, gallons in an acre foot, speed of light, size of a city
Decision variables	Acceptable daily intake, tolerable level of risk, appropriate level of protection, reasonable cost, mitigation goal
Value parameters	Value of a statistical life, discount rate, weights assigned in a multicriteria decision analysis, user-day values
Index variable	A particular year in a multiyear model, the location of an egg on a pallet, a geographic grid in a spatial model
Model domain parameters	Study area, planning horizon, industry segment, climate range
Outcome criteria	Mortalities, illness rates, infrastructure failures, fragility curves, costs, probabilities, benefit-cost ratios, risk-risk trade-offs

2.3.3.1 Empirical Quantities

Empirical quantities are the most common quantities encountered in a quantitative risk assessment; they have a true value. Empirical quantities are things that can be measured or counted. This includes distances, times, sizes, temperatures, statistics, and any sort of imaginable count. They have exact values that are unknown but measurable in principle, although it may be difficult to do so in practice. A full range of methods from narrative descriptions through probabilistic methods are suitable for addressing uncertainty in these quantities.

2.3.3.2 Defined Constants

Defined constants have a true value that is fixed by definition. When these values are not known by the analyst, for example, you might not know how many square feet are in an acre or how many gallons of water in an acre-foot of water, these quantities can end up in the pile of things we do not know. Defined constants provide the perfect opportunity to point out the importance of understanding the nature of your unknowns. When you do not know one of these quantities, you do not use sensitivity analysis or probabilistic methods; instead you look them up. There are 43,560 square feet in one acre and 325,851 gallons of water in one acre-foot of water.

DECISION RULE UNCERTAINTY

What is the best endpoint for your purposes? Imprecise or inappropriate operational definitions for desired outcome criteria, for example, “risk” can be a subtle problem.

Concerned about a public health risk? Should you use the number of exposures, infections, illnesses, hospitalizations, or deaths? Which is a better criterion to base a decision on: lifetime mortality risk, annual risk of mortality, risk to children or other subpopulations, or something entirely different?

Concerned about an economic issue? Should you maximize net benefits or minimize costs? Do you want to maximize market share or profits?

There is no right answer to these questions, only better or worse ones. Someone must decide what the decision criterion or rule will be to resolve this uncertainty.

2.3.3.3 Decision Variables

This is a quantity which someone must choose or decide. Decision makers exercise direct control over these values; they have no true value. The person deciding this value may or may not be a member of the risk analysis team, depending on the nature of the variable. Policy makers may determine the values of some decision variables to ensure uniformity in decision making. An agency may decide it is unacceptable to increase the lifetime risk of cancer by more than 10^{-6} , for example. Thus, decision variable values are sometimes set by decision makers external to the risk analysis process.

In other instances, risk analysis team members may make these decisions. Examples could include determining a tolerable level of risk or design characteristics of risk management options that differentiate one option from another. Decision variables are subjectively determined. Uncertainty about them is most appropriately addressed through parametric variation and sensitivity analysis.

2.3.3.4 Value Parameters

These values represent aspects of decision makers' preferences and judgments; they have no true value. They are subjective assessments of social values that can describe the values or preferences of stakeholders, the risk manager, or other decision makers. Like decision variables, some of them may be decided by those external to the risk analysis team, while others are decided by team members.

Social values, like the monetary value of a statistical life or society's time preferences for consumption, are likely to be established corporately to ensure uniformity in decision making. Establishing decision-specific values, like assigning relative weights to different decision criteria, may be set by the team. Uncertainty about value parameters is most appropriately addressed through parametric variation and sensitivity analysis.

2.3.3.5 Index Variables

Index variables identify elements of a model or locations within spatial and temporal domains; they may or may not have a true value. Bacterial counts "24 hours after" yolk membrane breakdown, costs "ten years after" implementing a risk management solution, water quality at a cove, and defining the age and gender of a representative individual are examples of index variables. If a very specific point in time or place in space are desired, there may be a true value. Random or representative choices of index variables do not have true values and are subjectively determined: should we

look at future conditions in five years or ten? Uncertainty in index variables is most appropriately addressed through parametric variation and sensitivity analysis.

2.3.3.6 Model Domain Parameters

These values specify and define the scope of the system modeled in a risk assessment. They describe the geographic, temporal, and conceptual boundaries (domain) of a model. They define the resolution of its inputs and outputs; they may or may not have true values. Scale characteristics are chosen by the modeler and most often have no true value in nature. They reflect judgments regarding the model domain and the resolution needed to assess risks adequately. Some risk assessments, however, may be restricted to specific facilities, towns, time frames, and so forth. These may have true values. Uncertainty about domain parameters may also be considered a form of model uncertainty. If the domain is the XYZ processing plant, it is trivially specific and objective. The hinterland affected by economic activity at the Port of Los Angeles is a much more subjective determination. These kinds of quantities are most appropriately addressed through parametric variation and sensitivity analysis.

2.3.3.7 Outcome Criteria

Outcome criteria, such as illnesses, illnesses prevented, property damage, benefit-cost ratios, and the like, are output variables used to rank or measure the desirability or undesirability of possible decision outcomes. Their values are determined by the input quantities and the models that use them. Uncertainty in these values is evaluated by propagating uncertainty from the input variables to the output variables using one of several different methods. Generating the uncertainty about output criteria is the responsibility of the risk assessor; addressing it in decision making is the responsibility of the risk manager.

2.3.4 SOURCES OF UNCERTAINTY IN EMPIRICAL QUANTITIES

Empirical quantities are the most commonly encountered uncertain quantities with true values that must be measured or estimated. When good measurement data are available, there may be little or no knowledge uncertainty about the true value of a parameter or variable. Even when there is no knowledge uncertainty, we may have natural variability to address in the risk assessment. It is useful to continue the excellent conceptual framework of Morgan and Henrion (1990) to consider the different sources of uncertainty in empirical quantities. Understanding the reasons that you are uncertain about empirical quantities is essential to your ability to choose an effective treatment of that uncertainty in a quantitative risk assessment.

2.3.4.1 Random Error and Statistical Variation

Measurements are rarely perfectly exact. Even tiny flaws in observation or reading measuring instruments can cause variations in measurement from one observation to the next. Then there is the statistical variation that results from sample bias. If we take measurements on a sample, we only have an estimate of the true value of a population parameter. Classical statistical techniques provide a wide array of methods and tools for quantifying this kind of uncertainty, including estimators, standard deviations, confidence intervals, hypothesis testing, sampling theory, and probabilistic methods.

2.3.4.2 Systematic Error and Subjective Judgment

Systematic errors arise when the measurement instrument, the experiment, or the observer is biased. Imprecise calibration of instruments is one cause of this bias. If the scale is not zeroed or the datum point is off, the solution is better calibration of the instrument or data. If the observer tends to over- or underestimate values, a more objective means of measurement is needed or the observer needs to be recalibrated. The challenge to the risk assessor is to reduce systematic error to a minimum. The best solution is to avoid or correct the bias. When bias can be identified, for example, the scale added 0.1 g to each measurement, it can sometimes be corrected for, that is, by remeasuring or subtracting 0.1 g from each measurement.

IT FEELS LIKE AN EIGHT TO ME

Much data are collected outside a laboratory and under less than ideal conditions. Which box of produce do we open and inspect? Where in the stream does the investigator insert the meter to read dissolved oxygen? How do you estimate how far away a work boat is on the open water? How quickly can you count the deer in a running herd? Subjective judgments are notoriously suspect under uncontrolled conditions.

Just like with faulty instruments, the solution is better calibration. Ideally, before the fact, but calibration is better late than never.

The more difficult task concerns the biases that are unknown or merely suspected. Estimating the magnitude of these biases is very difficult and often requires a lot of subjective judgment. Bias in subjective human estimates of unknown quantities is a topic covered extensively in the literature; see, for example, O'Hagan et al. (2006).

2.3.4.3 Linguistic Imprecision

After all these years on the planet, communication is still humankind's number one challenge. We routinely use the same words to mean different things and different words to mean the same things. This makes communication about complex matters of risk especially challenging. If we say a hazard occurs frequently or a risk is unlikely, what do these words really mean? The problems can be even more pervasive than that. Tasked with measuring the percentage of midday shade on a stream, a group of environmentalists engaged in a lengthy discussion of when midday occurs and how dark must a surface be to be considered shade.

The best and most obvious solution to this kind of ambiguity is to carefully specify all terms and relationships and to clarify all language as it is used. Using quantitative rather than qualitative terms can also help. Fuzzy set theory may be an alternative approach to resolving some of the more unavoidable imprecision of language in a more quantitative fashion.

2.3.4.4 Natural Variability

Many quantities vary over time, space, or from one individual or object in a population to another. This variability is inherent in the system that produces the population of things we measure. Frequency distributions based on samples or probability distributions for populations, if available, can be used to estimate the values of interest. Other probabilistic methods may also be used.

2.3.4.5 Randomness and Unpredictability

Inherent randomness is sometimes singled out as a form of uncertainty different from all others, in part because it is irreducible in principle. The indeterminacy of Heisenberg's uncertainty principle is one example of inherent randomness. However, a valid argument could be made that this is just another instance of knowledge uncertainty because we simply have been unable to resolve this puzzle at the present time.

This cause of uncertainty identifies those uncertainties that are not predictable in practice at the current time. Examples include such things as when the next flood will occur on a stream or where the next food-borne outbreak will occur in the United States. Such events can be treated as a legitimately random process. The danger here is the personalist view of randomness that could emerge, where randomness is a function of the risk assessor's knowledge. Phenomena that appear random to one assessor may be the result of a process well known by a subject matter expert. Strong interdisciplinary risk assessment teams combined with peer involvement and peer review processes provide a reasonable hedge against this sort of problem arising. Uncertainty about such quantities can be addressed by a full range of methods, from narrative descriptions through probabilistic methods.

2.3.4.6 Disagreement

Organizations and experts do not always see eye to eye on matters of uncertainty. Different technical interpretations of the same data can give rise to disagreements, as can widely disparate views of the problem. This is not to mention the real possibility of conscious or unconscious motivational bias.

Disagreements can sometimes be resolved through negotiation and other issue resolution techniques. Allowing the disagreements to coexist is also an option. Sensitivity analysis would consider the results of the analysis using each different perspective. A common approach for some disagreements is to combine the judgments using subjective weights.

2.3.4.7 Approximation

There may be instances when it is useful to approximate values of one quantity with another quantity. This is sometimes done with microbial dose-response curves where values for one species are used to approximate values for another species. Uncertainty due to approximation is also similar to what we called model uncertainty, earlier in this chapter. The fact that the model is a simplified version of reality ensures that uncertainty will remain about the outcome criteria. We are only able to approximate the function of complex systems because of scenario, model, and quantity uncertainty. Methods for dealing with this source of uncertainty will depend on the specific limitations of the approximation.

2.4 BEING INTENTIONAL ABOUT UNCERTAINTY

Risk analysis is decision making under uncertainty. It requires risk assessors, risk managers, and risk communicators to become intentional about uncertainty. Here are 10 actions to take to become intentional about uncertainty in decision making:

1. Recognize that uncertainty exists and is relevant in your decision problem.
2. Identify the specific things that are uncertain and the sources of that uncertainty.
3. Identify the instrumental uncertainties among the uncertainty. These are the uncertainties that have the potential to affect the decision or decision outcomes.
4. Acknowledge the relevant uncertainty and make risk managers, other decision makers, and stakeholders aware of instrumental uncertainties.
5. Choose appropriate tools and techniques to address each source of instrumental uncertainty.
6. Complete the assessment and other analyses incorporating these tools and techniques.
7. Understand the results of your uncertainty analysis.
8. Identify any options for further reducing the remaining instrumental uncertainty.
9. Convey your results and the significance of the uncertainty for decision making and decision outcomes, as well as any options for reducing the residual uncertainty, to decision makers in a manner that enables them to use this information in decision making.
10. Proclaim the uncertainty and its potential impacts on decision outcomes to all appropriate stakeholders.

ROCK IN THE CHANNEL

During one proof-of-concept, risk-based estimate of costs in the early 1990s, a design engineer was asked to estimate the percentage of rock in a channel bottom with an estimated interval. He declined to do so; when pressed, he refused. His justification was that he had much more and much better data than he normally has. He was offended by the notion that he might not know how much rock was actually in the channel bottom. His point estimate proved to be off by a significant amount. He has become a supporter of interval estimates.

The process begins by recognizing uncertainty when it exists, and it almost always exists. It is not unusual for experienced professionals to underestimate the things they do not know or to overestimate the quality of their evidence. Experts are often confident, not so much because of what they actually know as what they believe to be true. Biases, mindsets, and beliefs can prevent some people from recognizing that uncertainty exists. Experts are often correct in their intuitive judgments, and this strongly reinforces those biases. Thus, the starting point for all risk work is to begin by recognizing the existence of uncertainty. This may, at times, require analysts to challenge one another. To challenge false beliefs in certainty, ask: “What is your

evidence for your beliefs about this problem?” When experts can produce evidence, it is reassuring. When they cannot, it can be enlightening.

Once the existence of uncertainty is recognized it is necessary to specifically identify what is known with certainty and what is not. The analyst’s job is to identify those uncertain things that are most important to decision making. These would be scenarios, theories and knowledge, models or quantities that if not certain could affect decision making or decision outcomes. It is not unusual to find many potential sources of uncertainty. Some of these will be more important than others, and risk assessors and other analysts need to be able to identify uncertainties that are instrumental from those that are not. Risk managers do not need to be concerned with every potential uncertainty. In some instances, instrumental uncertainties may not be identified until after the assessment is completed.

There are going to be people who need to know about the uncertainty perhaps even before you begin to address it. Consider a large public works project, where design engineers are uncertain about the existence of seismic zones in the project footprint. This could affect the work of cost estimators and others who need to know this. Acknowledging the known uncertainties early in the assessment process is an important first step in risk communication. Partners in the decision-making process are certainly going to need to know the limitations of the available data.

Matching an appropriate tool and technique to the uncertainty is an important analytical step. Some uncertainty can be addressed in a qualitative risk assessment. Other uncertainty may require a probabilistic risk assessment. Between and beyond these approaches lie many tools and techniques, some of which are described in [Chapter 10](#).

Characterizing the risks and the uncertainty that is associated with them for a decision problem requires analysts to pull together the many and disparate approaches for addressing uncertainty that may have been used and to complete the analyses. It is important for the analysts to spend sufficient time with the results of their analyses to understand them and the uncertainty that attends them well enough to explain its implications for decision making and decision outcomes to risk managers and other decision makers.

In best practice, analysts will be able to distinguish the effects of knowledge uncertainty from the effects of natural variability. This will enable the analyst to identify potential options for further reducing the uncertainty in the risk assessment and other analyses. One of the greatest challenges, and an area of risk analysis that has not yet received sufficient attention, is to convey the results, the significance of the uncertainty, and any options for reducing uncertainty to decision makers. This is the subject of [Chapter 19](#) on decision making under uncertainty.

It is the risk assessor’s responsibility to identify and address the instrumental uncertainty in their decision problems. Some of the simpler tools available include narrative descriptions of the uncertainty, clarification of ambiguous language, negotiation for differences of opinion, and uncertainty or confidence ratings for these analyses. When the relevant uncertainty could lead to dramatically different futures and a few key drivers of this uncertainty can be identified, scenario planning is a useful technique. In more quantitative analyses, assessors can use parametric variation, bound uncertain values, and use sensitivity analysis or other quantitative risk assessment methods, all of which can include both deterministic and probabilistic analysis.

It is the decision maker’s responsibility as risk manager to address instrumental uncertainty in decision making. In order to do that, risk assessors must make sure decision makers, in their risk management responsibility, understand the potential for instrumental uncertainty to affect decision making or the potential outcomes of any specific decision. Chapter 19 provides a practical approach for risk managers to follow in addressing instrumental uncertainty in decision making. It also includes a discussion of criteria that have been developed for choosing from among alternative risk management measures under uncertainty. They include:

- Maximax criterion—choosing the option with the best upside payoff.
- Maximin criterion—choosing the option with the best downside payoff.
- Laplace criterion—choosing the option based on expected value payoff.
- Hurwicz criterion—choosing an option based on a composite score derived from preference weights assigned to selected values (e.g., the maximum and minimum).
- Regret (minimax) criterion—choosing the option that minimizes the maximum regret associated with each option.

Once a decision is made the potential impacts of uncertainty on the decision’s outcomes must be vigorously proclaimed to all stakeholders with a legitimate interest in knowing how they may be affected by the decision and the uncertainty that attends it. Making this effort to be honest brokers of information, saying what we do and do not know, and stating the significance of the latter for decision making distinguishes risk analysis from other decision-support frameworks and tools. As Figure 2.3 shows, the uncertainty encountered in an assessment of a risk can be found in either its probability or consequence. It can be due to knowledge uncertainty or natural variability. It is the risk assessor’s responsibility to address significant relevant uncertainties in their assessments. Risk managers are expected to address instrumental uncertainty in their decision making.

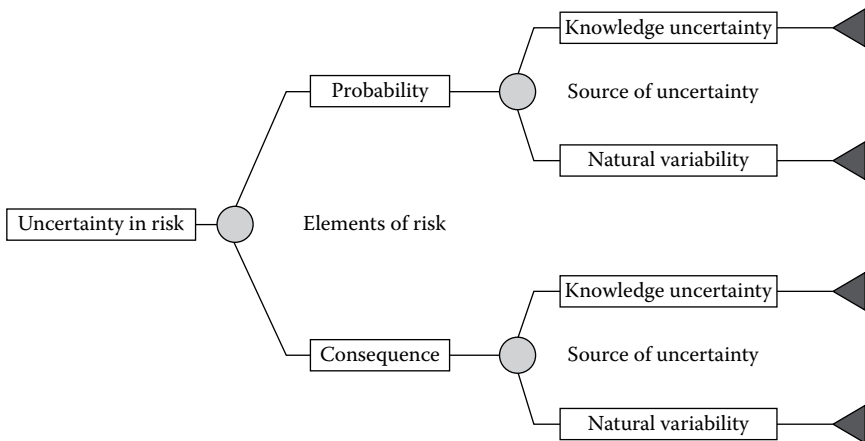


FIGURE 2.3 Source elements of uncertainty in risk analysis.

2.5 SUMMARY AND LOOK FORWARD

Uncertainty is the reason for risk analysis. Risk analysis is, in a sense, the confluence of social values and science. Uncertainty at the macro level affects values through a constantly and rapidly changing social environment. Uncertainty at the micro level occurs in the specific details of the problems decision makers face, at the level of our scientific knowledge. The two levels of uncertainty can pose markedly different challenges to risk analysts.

Separating what we know from what we do not know is a primary responsibility of the risk assessor. In the “pile” of things we do not know about a given decision problem are things that reflect our knowledge uncertainty and things that are naturally variable. It is important to know the difference between the two. Knowledge uncertainty is, in principle, reducible, while natural variability is not. This can be important to how risks are assessed, managed, and communicated.

A major purpose of risk analysis is to push risk assessors and risk managers to be intentional in how they address uncertainty in assessment and decision making. There are helpful taxonomies to aid our thinking about how to identify uncertainties and their causes. These are important to know because different kinds and causes of uncertainty have different sets of appropriate treatments. It is the risk assessor’s job to address knowledge uncertainty and natural variability in risk assessment inputs. It is the risk manager’s job to address them in risk assessment outputs.

The next three chapters will carefully unpack and explain the basic activities that comprise the three components of the risk analysis model presented in [Chapter 1](#). We begin with the risk management process, which is the cornerstone of the risk analysis process. Although there are many well-developed risk management models already in use, the approach taken here is not to put any one of these before the others so much as to find the common ground in all of them to aid your understanding and practice of the risk management process.

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3 Risk Management

3.1 INTRODUCTION

In the past, many organizations have managed risks by prescribing standards, policy, procedures, regulations, and other guidance, the rationale being that if you follow the “rules,” then the ensuing results must be okay. That is not risk management. Risk management, done well, is intentional about its process, addresses uncertainty in decision making, and focuses on outcomes. Risk management is maturing. There are now thousands of people who identify themselves as risk managers when only a few decades ago few outside of the insurance industry used this title.

There is no shortage of risk management models. As with every other aspect of risk analysis, many disciplines and organizations have spawned their own particular view of how to do risk management. Describing the risk management process in a generic fashion is, therefore, a daunting challenge. It is impossible to define risk management in a way that will satisfy many, much less all people. The Society for Risk Analysis defines it benignly as: “Activities to handle risk such as prevention, mitigation, adaptation or sharing.” It is not a lack of definitions that makes defining the term difficult so much as it is the proliferation of definitions in use by organizations and found in the literature. The U.S. Environmental Protection Agency’s *Thesaurus of Terms Used in Microbial Risk Assessment*, for example, identifies 12 different definitions for risk management (EPA, 2010).

It goes without saying that most organizations are quite fond of the nuances or parsimony of their own definitions and are not inclined to surrender it for another. No one seems to be clamoring for a universal definition, so do not look for one here. In place of a formal definition, the risk management component is described in some detail. That description will not be any more universally applicable than a definition would be, but we must begin somewhere, so we begin by identifying those risk management activities that are common to many definitions, models, and practice.

A SAMPLING OF RISK MANAGEMENT DEFINITIONS

The culture, processes, and structures that are directed toward the effective management of potential opportunities and adverse effects. (Australia/New Zealand Risk Standard)

The sum of measures instituted by people or organizations in order to reduce, control, and regulate risks. (German Advisory Council on Global Change)

Decision-making process involving considerations of political, social, economic, and technical factors with relevant risk assessment information relating to a hazard so as to develop, analyze, and compare regulatory and

nonregulatory options and to select and implement appropriate regulatory response to that hazard. Risk management involves three elements: risk evaluation; emission and exposure control; risk monitoring. (IPCS)

Coordinated activities to direct and control an organization with regard to risk. (ISO/IEC Risk Management Vocabulary)

All the processes involved in identifying, assessing, and judging risks, assigning ownership, taking actions to mitigate or anticipate them, and monitoring and reviewing progress. Good risk management helps reduce hazard and builds confidence to innovate. (UK Government Handling Risk Report)

The process of analyzing, selecting, implementing, and evaluating actions to reduce risk. (U.S. Presidential/Congressional Commission)

The process of evaluating alternative regulatory actions and selecting among them. (U.S. National Research Council “Red Book”)

I am going to call a new initiative undertaken by an organization that practices risk analysis a risk management activity. There are five basic parts to a risk management activity, all connected by continuing risk communication. The five parts are:

1. Identifying risk
2. Estimating risk
3. Evaluating risk
4. Controlling risk
5. Monitoring risk

A generic model is shown in [Figure 3.1](#). It shows the five parts in a continuous loop in order to capture the iterative nature of risk management. Risk management is making effective and practical decisions under conditions of uncertainty. As long as there is any uncertainty, a risk management decision is conditional, that is, based on what was known and not known at the time of the decision. As the uncertainty is reduced in the future or as the outcomes of the management decision become known, it may be prudent to revise the decision; hence, the ongoing nature of risk management. Every decision is based on what we know now and is subject to further revision in the future; in that sense no decision is necessarily final as long as instrumental uncertainty remains. Expanding on and explaining the elements of the risk management model of [Figure 3.1](#) is the primary work of this chapter.

You will find this to be a wide-ranging chapter, as befits the risk manager’s job. I have distilled the most consistent elements of a great many risk management models (see e.g., Presidential/Congressional Commission, 1997; FAO, 2003; FDA, 2003; ISO, 2009), as well as my own experience, to the five broad parts of a risk management activity, which are described here in some detail. To round out the discussion, a few specific risk management models are offered at the end of the chapter to illustrate how different organizations approach the risk management task, which is basically to make effective decisions about whether and how to manage risks with less than all the information desired.

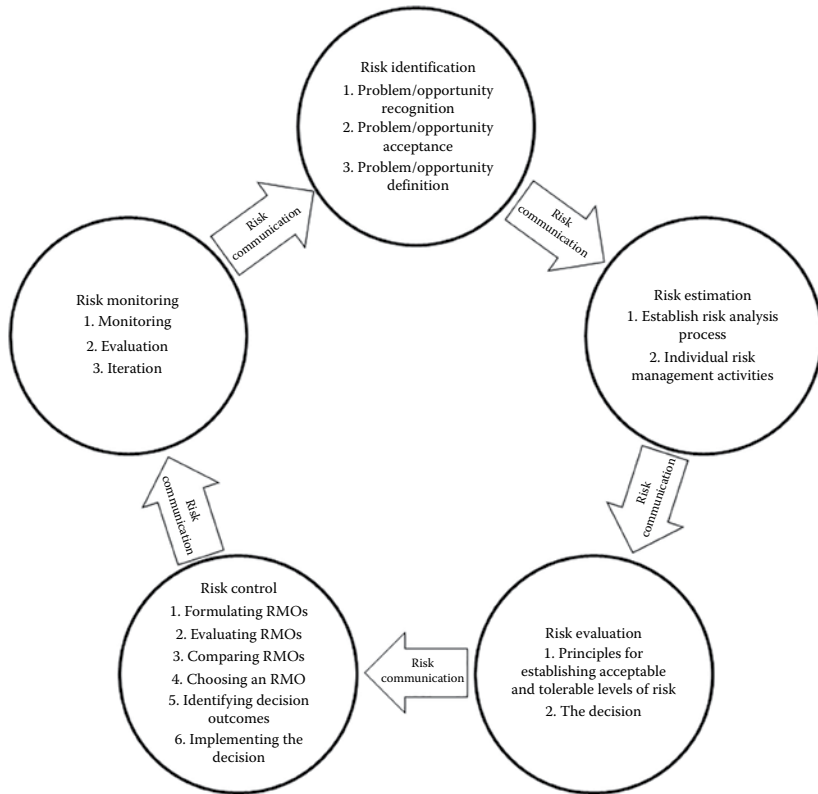


FIGURE 3.1 A generic risk management process comprising five tasks.

3.2 IDENTIFYING RISKS

Something happens to start a risk management activity. That something is usually a problem that needs attention or an opportunity* that can be pursued. In [Chapter 1](#), a risk identification process consisting of the following steps was identified:

- Identify the trigger event.
- Identify the hazard or opportunity for uncertain gain.
- Identify the specific harm or harms that could result from the hazard or opportunity for uncertain gain.
- Specify the sequence of events that is necessary for the hazard or opportunity for uncertain gain to result in the identified harm(s).
- Identify the most significant uncertainties in the preceding steps.

In this expanded discussion it will be convenient to think of risks a little differently, as problems and opportunities.

* To avoid the awkward redundancy of saying problem/opportunity throughout this section, let it be understood that problem will stand for both kinds of risky situations.

Einstein is reported to have said, “If I had one hour to save the world, I would spend 55 minutes defining the problem.” This is the stake that good risk analysis drives into the ground at its outset that helps distinguish it from other decision-making paradigms. The purpose of risk analysis is to find the right problem and to solve it. Identifying the problem (see [Figure 3.2](#)) provides a focal point for all of the risk manager’s subsequent decision-making efforts.

What often happens in organizations is that as soon as a problem arises we are so eager to solve it that we spend very little time understanding, refining, and communicating our understanding of it. As a consequence, organizations often treat the symptoms of problems rather than their causes. Worse, we often do not even know when we are unclear about a problem, and frequently the result is that we solve the “wrong” problem correctly.

EXAMPLES OF TRIGGERS FOR RISK MANAGEMENT ACTIVITIES

Crisis: Real or perceived, media, public outcry, adverse comments, changing public values or awareness, decreased consumer confidence, other

Science and technology: New knowledge or technology, emerging health problem, improved detection, surveillance, or method

Emerging or “on the horizon”: Planned search, forecasting, scan risk landscape, natural and anthropogenic disasters and events, imports

Strategic plan: Strategic planning, social needs, opportunities, can be beyond the horizon, historical precedents

These examples of the kinds of events and inputs that can trigger a risk management activity are from the US Food and Drug Administration (FDA) *Center for Food Safety and Applied Nutrition Risk Management Framework* (FDA, 2003).

Problem identification, the risk manager’s first major responsibility, is defined here as a three-part process (see [Figure 3.2](#)).

- Problem recognition
- Problem acceptance
- Problem definition

3.2.1 PROBLEM RECOGNITION

Problem recognition is the simple act of recognizing that a problem exists and gaining an initial understanding of the problem. This happens in one of two broad ways. Reactive or passive problem recognition is when a problem finds you. These are problems triggered by outside influences. Stakeholders bring you a problem or an event occurs that results in a problem you cannot ignore. Alternatively, there is

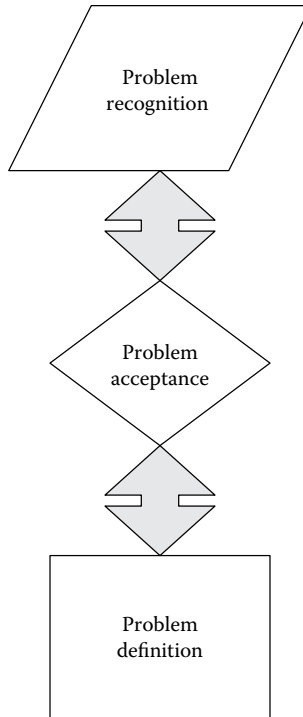


FIGURE 3.2 Problem identification steps.

proactive or intentional problem finding, in which management looks actively and often strategically for the most important problem(s) to solve.

Despite the seemingly obvious nature of this task, it is surprising how frequently organizations fail to recognize a problem. This is all the truer in a risk analysis context because risky problems often lurk unseen over the horizon or around the corner. They are frequently hidden from view, obscured by uncertainty and higher priorities, and occluded by smoke from the organizational brushfires that need constant tamping out. Anyone can recognize the problem that forces its way through your door and onto your desk at 4 p.m. on a Friday afternoon. It takes a risk manager to see the problems just over the horizon or just around the corner.

Recognizing the existence of opportunities for potential gain or betterment parallels the process of problem recognition. Fewer opportunities seem to break down the risk manager's door than do problems, however, and the search for opportunities is usually more active.

3.2.2 PROBLEM ACCEPTANCE

Once a problem makes your radar screen, the question becomes, "Will you own it and do something about it?" The second step in problem identification, therefore, is problem acceptance. This requires risk managers to articulate the problem they have

found in enough detail to determine if it is a problem they are willing and able to address. Addressing a problem means allocating resources to its solution.

Risk managers must identify the resources required to address the problem in a timely manner. Then they must evaluate the adequacy of their available resources in the context of their program authorities, organizational mission, and vision. This obviously implies consideration of competing uses for the organization's resources. We cannot solve every problem.

Problem acceptance is a priority-setting step. It is deciding to act. Accepting a problem as one to be solved or an opportunity as one to be pursued is a significant organizational commitment. Our understanding of the problem is revised and refined beyond the initial recognition in this step. Risk managers must identify and commit to the time frame and resources required to address each problem they accept.

Choosing from a number of potential opportunities and deciding which are worth pursuing is a common challenge in business decision making. Articulating and accepting the opportunities to be pursued parallels the problem acceptance step.

3.2.3 PROBLEM DEFINITION

The third step is problem definition. This is when the problem is fully articulated for the first time and linked to possible solutions. Opportunities are likewise articulated and linked to potential strategies that could realize the gains. Information needs begin to become clear and a risk management activity is initiated. This step encompasses a focused and intentional effort to provide a commonly understood description of the problem. It includes stakeholder input when appropriate.

If you cannot clearly and concisely finish the sentence, "The problem is . . .," then nothing that follows will be clear either. A written "problems and opportunities statement" is the desired output of this problem identification process. Your problems and opportunities statement provides the rationale or reason for your risk management activity. It should be considered a conditional statement that will change as you begin to gather information, reduce the initial uncertainty, and better understand the problem(s) and stakeholders' concerns. So, date that piece of paper. Risk analysis is an iterative process and you can expect to revise and refine your problems and opportunities statement several times before you are done.

SAMPLE PROBLEMS AND OPPORTUNITIES STATEMENT

P1: Increasing resistance of *Campylobacter* in chicken to fluoroquinolones due to subtherapeutic use of antibiotic drugs in food producing animals.

P2: Declining efficacy in the use of fluoroquinolones for the treatment of fluoroquinolone-resistant campylobacteriosis in humans.

O1: Reduce incidence of all campylobacteriosis in humans due to consumption of chicken.

The stakeholders in any problem context will vary. For some problems the stakeholders may comprise the general public and many special interests. In other

problem settings the stakeholders may be wholly contained within the risk managing organization. Stakeholders, however defined, should be involved in the problem identification process. The appropriate level of involvement will vary with the decision problem and its context. Some problems will be identified for you by stakeholders; at other times they will have to be made aware of the existence of a problem.

Vet your problems and opportunities statement with your stakeholders. Publish it appropriately. Make it public if your stakeholders include members of the public. Show them your best thinking and ask, “Did we get the problem(s) right? What is missing? What is here that should not be? Do you have information about these problems and opportunities that would be helpful to share?” Stakeholders can be an effective ally in reducing uncertainty.

The output of this activity is a revised problems and opportunities statement. Keep that statement up to date. Let people know how it changes and why it changes as it changes.

3.2.4 FROM PROBLEMS AND OPPORTUNITIES TO RISKS

Given a problems and opportunities statement, it is straightforward to identify the risks to be addressed in a decision. Very often the statement itself will suffice as a summary identification of risks. However, for clarity, it would be wise to expand each problem and opportunity using the risk identification steps presented at the outset of this section, described in detail in Section 1.2.

3.3 RISK ESTIMATION

Estimating risks is the assessor’s job. It cannot be done without direction and guidance from the risk manager. Risk managers have an important, but limited, role in the science-based risk assessment process. The risk manager’s positive decision-making role is found in the risk estimation activities (see [Figure 3.3](#)) that help describe the world as it actually is. That role includes establishing the organization’s risk analysis process and managing individual risk management activities.

Recommendation 1 from the U.S. National Research Council (NRC) publication *Risk Assessment in the Federal Government: Managing the Process*, also known as the “Red Book,” has been often misunderstood to mean that the assessment and management tasks must be functionally separated and should not interact. The actual recommendation follows:

Regulatory agencies should take steps to establish and maintain a clear conceptual distinction between assessment of risks and the consideration of risk management alternatives; that is, the scientific findings and policy judgments embodied in risk assessments should be explicitly distinguished from the political, economic, and technical considerations that influence the design and choice of regulatory strategies

NRC, 1983

That is a far cry from the severe separation that has been practiced at times.

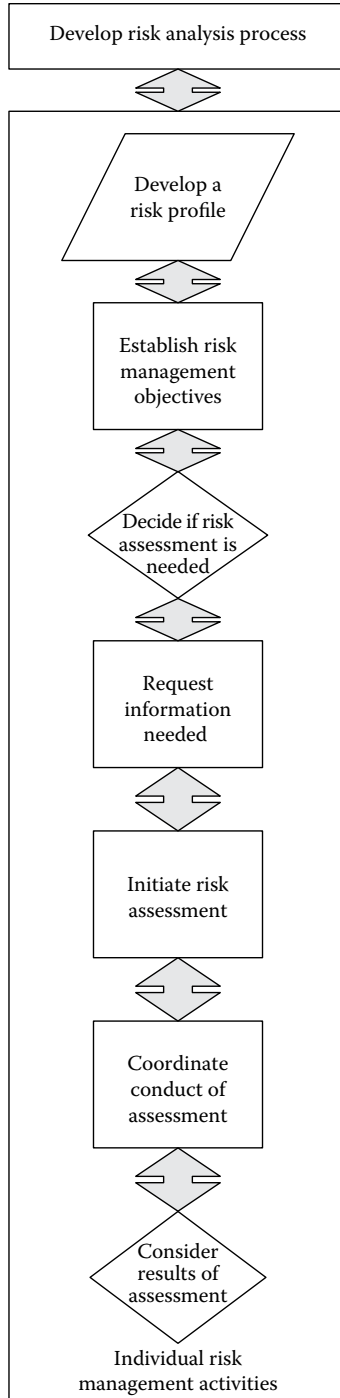


FIGURE 3.3 Risk estimation steps.

There are two groups of activities in the risk estimation part of risk management, as seen in [Figure 3.3](#). The first, developing a risk analysis process, consists of one-time or periodic activities required to establish and maintain the risk analysis process. The other, individual risk management activities, consists of duties that recur in every risk management activity. These activities are addressed in the following sections at the level of detail shown in the figure.

3.3.1 ESTABLISH A RISK ANALYSIS PROCESS

If the plethora of definitions for the basic terminology of risk analysis teaches us nothing else, it teaches us this: there is no one best way to do risk analysis. The most commonsense rule seems to be to use what works best for you. Think of risk analysis as a process that is firm in its principles but flexible in the details of how they are pursued.

The risk manager's job, with respect to establishing a risk analysis process, is basically to say, "This is how we do risk analysis here." This process establishes the risk management model the organization will use so that there is an agreed-upon framework for addressing risk problems and opportunities. It establishes the roles and responsibilities of everyone involved in the risk analysis process.

A significant piece of any risk analysis process is the risk assessment policy, which addresses the manner in which the many subjective judgments and choices that arise in the course of a risk assessment will be resolved to protect the integrity of the science and the decision-making process. Some predictable issues that will arise include how to deal with uncertainty and what assumptions to use when the available data are inconsistent. These are sometimes called "science policy" issues. It is wise to devise a means of identifying and resolving these kinds of problems before they are encountered in practice.

Establishing a risk assessment policy is the risk manager's responsibility. It needs to be a collaborative process for any organization that is engaged in making public policy or in the stewardship of public resources like public health, public safety, natural resources, or the environment. This collaboration should include risk managers, risk assessors, and risk communicators. It should provide appropriate opportunities for input and feedback from relevant stakeholders. The risk assessment policy should be documented and made publicly available to ensure consistency, clarity, and transparency. For most organizations outside the public sector, establishing a risk assessment policy is an internal affair.

SCIENCE POLICY

Science-policy choices are distinct from the policy choices associated with ultimate decision making ... The science-policy choices that regulatory agencies make in carrying out risk assessments have considerable influence on the results

NRC, 1983

When the science is unclear, what assumptions are to be made and by whom? A good risk assessment policy addresses these questions and all questions of "so-called" default assumptions.

One of the hallmarks of best-practice risk analysis is insulating the science from the policy. In the early days of risk analysis, many thought the risk management and risk assessment tasks must be totally separated from one another. This is not true. It is best when these functions are separate and handled by different people with the appropriate skill sets required by their jobs. However, it is absolutely essential that managers and assessors communicate, cooperate, and even, at times, collaborate throughout the risk analysis process.

A SCALABLE PROCESS

A good risk management process is perfectly scalable. You can use it when you have 30 minutes and no budget as easily as you can over years with millions of dollars.

Its greatest value is that it provides a systematic, science-based approach to solving problems and managing risks.

Risk managers begin and end the risk assessment process. They may collaborate with risk assessors in identifying a problem, in formulating risk management options, or on other tasks throughout the risk management activity. They will cooperate in the conduct of the risk assessment and must communicate continuously throughout the iterative risk analysis process.

The output of this task is a well-defined risk analysis process that will guide the organization. That process should include a specific risk management model and a risk assessment policy. Both of these should be carefully documented and publicized to all those with a legitimate interest in the organization's risk analysis process.

3.3.2 INDIVIDUAL RISK MANAGEMENT ACTIVITIES

Risk managers have several specific preliminary risk management responsibilities to complete before, during, and after the risk assessment. Identifying the right problem to solve is only the starting point. Additional responsibilities include:

1. Develop a risk profile
2. Establish risk management objectives
3. Decide if a risk assessment is needed
4. Request needed information
5. Initiate the risk assessment
6. Coordinate the conduct of the assessment
7. Consider the results of the assessment

Each of these activities is considered in turn in the following sections.

3.3.2.1 Develop a Risk Profile

Risk profile is a term with two distinctly different meanings. In its current context it is an initial data gathering effort. In an enterprise risk management (ERM) context,

a risk profile is something between a description of a set of risks of concern to an organization (and, thus, not markedly different from this current context) and a high-level assessment of the types of risks an organization faces. Be aware, this is a potentially confusing term. The ERM context of the term is revisited at length in [Chapter 6](#).

Once the problems have been articulated in a problems and opportunities statement, it is time to quickly find out what is and is not known about the decision problem. A risk profile presents an analysis of the types of risks an organization, asset, project, or individual faces based on available information. In the current context, a risk profile frames problems and opportunities in their risk context and provides as much information as possible to guide subsequent risk assessment, risk management, and risk communication activities. It also provides the first formal identification of the uncertainty in your decision problem.

INFORMATION YOU MIGHT FIND IN A RISK PROFILE

- Latest statement of the problem
- Description of the hazard or opportunity involved
- How assets are exposed to the hazard
- Frequency, distribution, and levels of occurrence of the hazard
- Identification of possible risks from the available scientific literature
- Nature of values at risk (human health, economic, cultural, etc.)
- Distribution of the risk and benefits from the risky activity
- High level or preliminary assessment or prioritization of the risks
- Characteristics of available risk management options
- Current risk management practices relevant to the issue
- Public perceptions of the potential risks
- Information about possible risk management (control) measures
- Preliminary identification of important scientific data gaps that may prevent or limit a risk assessment
- International implications of risk management
- Risk management objectives
- Decision to pursue a risk assessment
- Questions to be answered by risk assessment

The risk profile is the risk manager's responsibility. Managers need not do it alone or at all, for that matter, but they need to see that it is done. Profiling a risk will almost surely mean consulting and collaborating with risk assessors, and it may involve stakeholders. The preliminary risk identification is fleshed out and expanded upon in the profile. Think of this as the point at which the risk management activity team provides a situation report based on available evidence and information that more carefully develops our understanding of what can go wrong, how it can happen, the consequences of it happening, and how likely it is to happen. The profile presents the current state of knowledge related to the risks identified in a concise form at the

outset of the risk management activity. The profile will also include consideration of potential risk management options identified to date.

The profile step is important for several reasons beyond the fact that it identifies data gaps by separating what we initially know about a problem or opportunity from what we do not know. It develops the risk analysis team's knowledge and understanding of the problem and may evolve the risk identification further. It also provides the basis for some very important preliminary risk management tasks, including:

- Identifying risk management objectives
- Deciding whether or not to initiate a risk assessment
- Identifying the questions to be answered by risk assessment.

One of the most important functions of the risk profile is to reduce and better define the uncertainty relevant to the decision problem. When a risk is initially identified, it is likely that the uncertainty is going to be great. As the first formal information-gathering step in the process, the risk profile is often effective in reducing uncertainty and identifying the greatest remaining data gaps. A risk profile sometimes provides enough information to make a risk management decision.

The term *risk profile* is used extensively by the food safety risk analysis community, for one example. It may be an unfamiliar term to other communities of practice. However, the initial data-gathering step is or should be universal in any risk management activity. Finding out what is already known or readily knowable about the identified risks precedes the risk assessment. In fact, it is an essential step in deciding whether a risk assessment is even needed or in some instances whether it is doable.

The output of this step is a documented risk profile that includes the initial sorting and assessing of the things that are not known about the identified problems and opportunities. Documentation may be in a brief report, an organized sheaf of papers, an electronic folder of information sources and memoranda, or an oral narrative. A formal document is not always required.

3.3.2.2 Establish Risk Management Objectives

Objectives say what we desire to see happen and when. They define what success looks like. An objective is a clear statement of a desired outcome of the risk management activity. It is easy to confuse objectives with strategies, which describe how we intend to achieve the objectives. It is the risk manager's job to write the risk management objectives. They should be specific and conceptually measurable.

SAMPLE OBJECTIVE WORDS

Eliminate, reduce, minimize/maximize, enhance, harmonize, identify, define, describe, increase/decrease, raise/lower, strengthen/weaken, avoid, adapt, blend, reconcile, coordinate, affirm, diminish, weaken, promote, raise, complement, strengthen.

Once the risk has been profiled and the decision context is better understood, risk managers need to determine their broad risk management objectives. The problems and opportunities statement describes why a risk management activity has been initiated. The objectives state in broad and general terms what the risk managers intend to do about the problems and opportunities they face. These objectives should reflect the most important social (or organizational) values in the decision process.

A GOOD OBJECTIVE IS

Specific: It is clear and free from ambiguity

Flexible: It can be adapted to new or changing requirements

Measurable: Its achievement can be documented by some objective means

Attainable: It can be reached at the end of a course of action

Congruent: It is in harmony with other objectives

Acceptable: It is welcome or pleasing to key stakeholders

Objectives do not identify specific risk management options, they are not solutions to the problem(s) identified. They identify the intended purposes of the risk management activity. An objective is a clear statement of a desired end that risk management options are intended to accomplish.

Where do these objectives come from? Values! They reflect what is important to people. You can find values in what concerns the public, the experts, and our institutions (law, regulations, guidance, policy, organizational missions).

A GOOD OBJECTIVE IS NOT A

Management option: It does not prescribe a specific course of action

Government goal: It is not a political or governmental objective

Risk assessment task: Developing a dose-response curve is not an objective

Resource constraint: It does not address time, money, or expertise

Absolute target: It does not specify a particular level of achievement

Consider a risk management objective related to a health risk. The objective may be to reduce or eliminate the health risk. An objective does not say how that can or should be done, only that it is an objective to do so. Objectives related to economic values might include increasing jobs, income, and profits or minimizing costs. Objectives related to other public values might include things like protecting children or the environment.

Objectives reflect the most important social (or organizational) values in the decision-making process. They identify the things risk managers are trying to do. Sometimes there are important things we are trying not to do. These things we will

call constraints. Examples of constraints include not creating new risks, avoiding the loss of jobs or income, and avoiding negative impacts on endangered and threatened species. Constraints, as used here, should not be confused with resource or schedule limitations.

A formal and written objectives and constraints statement is the desired output of this task. Consider it conditional and subject to change as uncertainty is reduced and you iterate your way through the risk management activity.

This is one of the critical ways in which social values are appropriately reflected in the risk analysis process. Stakeholder input is essential for identifying good objectives and constraints. Like the problems and opportunities statement, this statement should be published and vetted as appropriate to the decision problem's context. Seek input to the formation of these objectives and ask for feedback on your statement. Not every risk management activity is going to require the same kind of review process. Private organizations making internal decisions may require no public involvement, while some government organizations may require extensive public involvement.

SAMPLE OBJECTIVES AND CONSTRAINTS STATEMENT

- O1: Reduce *Campylobacter* antimicrobial resistance to fluoroquinolones.
- O2: Reduce the number of cases of human illness due to resistant *Campylobacter* in chicken.
- O3: Support the economic viability of chicken production.
- O4: Improve animal welfare in chicken production.
- C1: Do not increase the number of nonfluoroquinolone resistant cases of *Campylobacteriosis*.

The success of a risk management activity is defined by the extent to which objectives are met and constraints are avoided. That makes preparing this statement one of the most critical steps in the risk management process. These are the things we must do and must avoid doing to succeed in solving the problems and attaining the opportunities we have identified. If we do not meet our objectives to at least some extent, our risk management activity has failed. If we violate our constraints, our risk management activity has failed.

The chain of logic is simple in best-practice risk management. If you meet your objectives and avoid your constraints, you will have solved your problems and attained your opportunities. Objectives and constraints provide a sound foundation for formulating and, later, evaluating risk management options.

So far, we are describing a rather broad and open risk management process. Not every risk management activity will require such breadth and openness. Some risk management activities are laser-focused on recurring issues of interest to only a few people. The process we are describing works as well for these activities as it does for public policy making. Risk management is a perfectly scalable process. Objectives, for an example, can be identified in 5 minutes, 5 hours, or 5 days.

3.3.2.3 Decide the Need for a Risk Assessment

Your risk profile is complete, do you need a risk assessment? Not every risk management activity requires a risk assessment. Every risk management activity requires science-based evidence, but there will be times when there is enough evidence and knowledge in a room full of experts to know how to solve a well-defined problem. Other times the risk profile will produce sufficient information to enable risk managers to know how to solve their problems and realize their opportunities.

When an issue requires immediate action or when a risk is well described by definitive data, a risk assessment will not be needed. If the risk managers already know what decision they are going to make, a sham assessment is not needed to justify a foregone decision. A relatively simple problem with little uncertainty, where the consequences of a wrong decision are minor, does not require a risk assessment. When the cars are speeding by, stay on the sidewalk. If the milk has turned sour, throw it away. Do not build in the floodplain. There are many instances where there is no need for a risk assessment. Then there will be times when the risk profile is insufficient for decision making.

WHAT'S IN A RISK ASSESSMENT?

Want to start an argument? Go to a conference or listserv of risk people and ask the above question.

Risk assessment, like everything else about risk analysis, has many different definitions. A significant point of division for many seems to be whether risk assessment includes analysis that enables risk managers to evaluate the risks in addition to the analysis required to assess the risk. This could include, for example, benefit-cost analysis of risk management options. Some insist that such information is not and should not be part of risk assessment. They consider this risk management information that is used to evaluate the acceptability of an assessed risk or risk management option.

This narrow view may work for certain kinds of risk, like public health risks. But it falls apart for other kinds of risk, like risks of financial or economic losses and gains.

For our purposes, it is not so important where the necessary decision-making information is included as that it is included. So be aware that in some interpretations risk assessment includes information from the natural sciences only, while in others it may include much more extensive information.

A risk assessment can be useful when the data are not complete and there is much uncertainty or when there are multiple values in potential conflict. Risk assessments clarify the facts and are useful for issues of great concern to risk managers or stakeholders or when continuous decision making is in order. Risk assessment is sometimes used to guide research by identifying data gaps and significant uncertainties that need to be reduced. Assessments can establish a baseline estimate of a risk or examine the potential efficacy of new risk management options. They may be helpful

in resolving international disputes. Practical issues that can affect the decision to do a risk assessment include:

- The time and resources available
- The urgency of a risk management response
- Consistency with responses to other similar issues
- The availability of scientific information

Deciding to do a risk assessment is a distinct result of the risk profiling task. A risk assessment should be requested when two conditions are met:

1. The risk profile fails to provide sufficient information for decision making.
2. The risk profile suggests there is sufficient information to complete a risk assessment.

Sometimes there is so much uncertainty and such sparse data that it is not even feasible to attempt a risk assessment. In these situations, risk managers may make a preemptive decision based on caution or some other set of values. Alternatively, the risk profile results can be used to direct research toward filling the most critical data gaps so that risk assessment can then proceed. The decision of whether or not to do a risk assessment is often based on the results of the risk profile. That decision is the desired output of this activity. The remainder of this risk estimation discussion assumes that a risk assessment will be completed.

REASONS FOR A RISK ASSESSMENT

- The information you have is not the information you want
- The information you want is not the information you need
- The information you need is not the information you can obtain
- The information you can obtain costs more than you want to pay

Source: Adapted from Bernstein (1996).

3.3.2.4 Request Information Needed

If the risk profile does not provide enough information to decide how to solve the problems or pursue the opportunities, risk managers must ask for the information they need to do so. They are going to need specific kinds of information in order to be able to meet their objectives and avoid their constraints, thereby solving the problems and attaining the opportunities. No one is better positioned to know what this information is than the person who will make those decisions, the risk manager.

Some of the information risk managers will need is likely to be scientific, evidence-based, factual information. This will be provided through risk assessment and possibly other evaluations like benefit-cost analysis and legal opinions. Some of the information they need will be more subjective in nature, for example, who is

concerned with this issue and how do they feel about it? This will be obtained through other means, including a good public involvement or risk communication program.

It is absolutely essential, however, that risk managers explicitly ask for the information they know they are going to need to make a decision. It is not sufficient to issue a general request for a risk assessment based on a specific problem. Risk managers must ask risk assessors to answer specific questions in the risk assessment. If the managers do not ask the right question(s), they may not get the right information back from the risk assessment. Risk assessments that are not guided by questions to answer may produce information managers do not want to have, or they may fail to produce the information managers need to make a good decision.

MY EXPERIENCE

I have worked on many risk management activities and risk assessments and am often called in as a consultant, usually not because things have been going well. When it is my turn to speak I hand out 3×5 index cards and ask everyone present to write down the question(s) they believe they are trying to answer through their risk assessment.

I then collect the cards and read them aloud. Amazingly, I have yet to have two cards identify the same question(s). How do we know what data to collect, what models to build, what analysis to do when we do not even agree on what question(s) we are trying to answer?

Getting the question(s) right is the next most critical step after problem identification.

The importance of the risk manager's questions can hardly be overstated. They guide the risk assessment and other evaluations required to provide the information necessary for decision making. Once these questions are answered, risk managers have the information they need to make decisions. These questions need to come from risk managers, often with input from assessors and stakeholders.

Risk analysis supports decision making by using science and evidence to identify what we know and what we do not know. It integrates this knowledge and uncertainty with social values to meet objectives and avoid constraints and thereby to solve problems. When the initial risk profile is completed, it is time to ask the most basic of all questions: "What do we know and what do we need to know?"

Risk managers ask questions. Risk assessors answer the risk questions. Other evaluations may answer other questions. If risk managers do not ask the right questions, the analysis that follows may well not meet decision makers' needs. These questions must be available at the start of a risk assessment. They must be specific and they should be specified or at least agreed by risk managers.

It is essential that they are written down. They are not real and concrete until one can articulate them in precise words on paper. The questions will almost surely be refined by negotiation among managers, assessors, and possibly stakeholders. The questions will evolve and change as our understanding of the problem and the decisions to be made will evolve. Consequently, the questions must always be

kept up to date and they must be known to everyone who is working on the risk assessment.

The desired output of this task is a written set of questions to be answered by the assessors and other analysts of the risk analysis team. Many risk assessment problems begin with missing, incomplete, inappropriate, or just plain bad questions. To make sure they get the information they need to make a decision, risk managers need to ask for it directly.

SAMPLE QUESTIONS

How many annual cases of fluoroquinolone resistant Campylobacteriosis currently occur in the United States due to eating chicken?

How many annual cases of fluoroquinolone resistant Campylobacteriosis will occur in the United States in the future due to eating chicken if there are no changes in the current usage of fluoroquinolone drugs?

How many annual cases of fluoroquinolone resistant Campylobacteriosis will occur in the United States in the future due to eating chicken if the use of fluoroquinolone drugs in all food producing animals is prohibited?

How many annual cases of fluoroquinolone resistant Campylobacteriosis will occur in the United States in the future due to eating chicken if fluoroquinolone treated chicken is sent for use in processed chicken products?

An organization with a well-defined mission and recurring issues is likely to develop standard information needs for recurring problems. When those recurring information needs become general knowledge or a standard operating procedure (SOP) this task may be simpler for everyone because they know what to do and how to do it once the information needs are institutionalized. However, every organization faces enough unique situations that this task of getting the questions right should never be overlooked.

It is impossible to anticipate all the kinds of information risk managers may require for decision making early in the process. In general, four broad categories of questions can be anticipated. Risk managers will usually want to ask questions about how to:

1. Meet objectives and constraints
2. Characterize the risks of interest
3. Mitigate the risk
4. Address other values

Risk managers may require additional information in order to know how best to meet their objectives and avoid violating their constraints. How will you achieve/avoid them? How will you measure success toward them? What kinds of information do you need to have about them in order to achieve your objectives and avoid your constraints? Some questions can be expected to focus on these kinds of concerns. They can also overlap the other question categories.

Risk characterization questions are trickier to discuss at this point because the risk assessment steps have not yet been introduced, and this is one of them. For now, think of this as the step in the risk assessment where all the various bits of information are pulled together to characterize the likelihood and consequences of the various risks you are assessing. Risk managers must direct assessors to characterize risks in ways that are going to be of most use for decision making.

Suppose a risk to public health is caused by disease and the objective is to reduce the adverse human health effects of this disease. How should assessors characterize the risks? Do managers want to know the probability of contracting this disease for a given exposure? Is the exposure of interest an annual one or a lifetime one? Might it be more useful to have the numbers of people affected by the disease? If so, are managers interested in the numbers of infections, illnesses, hospitalizations, or deaths? Are there any special subpopulations of interest to managers? Risk managers need to take great pains to ask questions at the characterization level that, when answered, will give them the information they need to make a decision about whether and how to manage that risk.

It is wise to think of risk holistically when posing risk characterization questions. There may be separate questions about existing and future risks, residual risk, transferred risk, and transformed risk. A residual risk is the risk that remains after a risk management option is implemented. When a risk management option reduces risk at one point in time or space for one kind of event or activity while increasing risk at another time or space for the same event or activity, this is called a “transferred risk.” When a risk management option alters the nature of a hazard, a population’s exposure to that hazard, or the consequences of an exposure, this is called a “transformed risk.” These concepts are not as readily applied to risks of uncertain potential gain.

Risk mitigation questions are another category of questions that will usually be appropriate to ask. What does a risk manager need to know to formulate and choose the best risk management option? What are others doing to manage this risk? What else can be done to manage this risk? How well are the different options likely to work? For example, how many illnesses will we have if there is a vaccination program? Specific questions about the efficacy of risk management options are important to ask.

Finally, there are, for lack of a better term, values questions. These focus on obvious values of importance that are not included in the objectives and constraints. Someone will almost always care about costs, benefits, environmental impacts, authority, legal considerations, and the like. Values questions may also include stakeholders’ concerns and their perceptions.

Once the questions are prepared, assessors and managers need to discuss them and what they mean. When a risk manager asks, “What is the risk of getting ill by eating an egg?” you may need to parse the question. What is meant by an egg? What kind of egg? Must it be in a shell or can it be processed? What do you mean by ill? How ill and for how long? A question that is perfectly clear to one person may be a complete mystery to another. Communication between managers and assessors is necessary to gain a clear common understanding of the questions. It may be necessary to negotiate the list of questions at times. Some questions may be incomplete, unreasonable, or impossible to answer. When that happens risk assessors must tell the risk manager. If important questions are missing they should be added. Expect questions to be clarified, modified, deleted, and added to throughout the risk management activity.

As mentioned previously, not all questions are science questions. It may take more than a risk assessment to answer all of the risk manager's questions. Some activities may require legal analysis, benefit-cost analysis, consumer surveys, market assessment, and the like, and these kinds of analyses may be considered outside the purview of risk assessment in some circumstances.

At this point we are up to three important pieces of paper that are essential to the successful completion of the risk management activity. They are:

- A problems and opportunities statement
- An objectives and constraints statement
- A list of questions the risk manager would like answered

If you vet the contents of these three pieces of paper with your stakeholders, you have the beginnings of an excellent risk communication process. These three pieces of paper and the process you went through to prepare them also provide an excellent basis for the eventual documentation of your risk management activity.

3.3.2.5 Initiate the Risk Assessment

With a decision to do a risk assessment in one hand and the questions to be answered by the assessment in the other, it is time to initiate the risk assessment. It is the risk manager's responsibility to provide the resources necessary to get the risk assessment done. In general, that means assembling an appropriate team of experts to carry out the task; providing them with sufficient time, budget, and other necessary resources; and interacting with them extensively enough to instruct them clearly on the information needed for decision making. All of this is to take place while maintaining a functional separation between risk assessment and risk management activities.

FUNCTIONAL SEPARATION

Functional separation means separating the tasks carried out as part of risk assessment from those carried out by risk management at the time they are performed. Some organizations may have separate offices to conduct the two tasks. In some situations, the same individual(s) may be responsible for management and assessment. This occurs most often in resource poor situations, but it may also occur with routine and simple issues.

It is important that safeguards be in place to ensure that management and assessment tasks are carried out separately of each other, even if they are performed by the same individuals. Management and assessment are fundamentally different. The objective assessment needs to remain objective and the subjective judgment needs to remain apart from it.

An independent interdisciplinary team of scientists, analysts, and other experts is preferred for conducting risk assessment. In routine situations, in-house experts and personnel are sufficient for a risk assessment team. In more structured or international environments, risk assessments may be carried out by an independent scientific

institution, an expert group attached to an institution, or an expert group assembled for the express purposes of the risk assessment.

Risk managers are responsible for supporting the work of the risk assessment team and other evaluations by ensuring that they have the necessary resources. In general, a good risk assessment policy will have established guidelines for much of this administrative work on a once-and-for-all basis before the actual risk assessment is initiated. The roles and responsibilities of key personnel, the manner in which different organizational units interact, milestones, methods for communicating and coordinating—all of these administrative matters are the responsibility of the risk managers.

3.3.2.6 Consider the Results of the Risk Assessment

After initiating the risk assessment, assessors go off and complete their work in a risk assessment, which is the subject of the next chapter. When the risk assessment is completed and submitted to the risk manager, the major question at this step in the risk management process is: “Did risk managers get answers to their questions that they can use for decision making?”

EXAMPLE OF RISK ASSESSMENT ROLES

The FDA’s Center for Food Safety and Applied Nutrition has established three unique positions to help with consistency, coordination, and making risk decisions. They are:

- Science Advisor for Risk Analysis
- Risk Analysis Coordinator
- Risk Assessment Project Manager

The risk assessment should clearly and completely answer the questions asked by the risk managers to the greatest extent possible. Those answers should identify and quantify sources of instrumental uncertainties in risk estimates and in the answers provided to risk managers. Whenever the uncertainty might affect the answer to a critical question and, consequently, the risk manager’s decision, or decision outcomes, this information must be effectively communicated. Hence, in addition to getting answers to their questions, risk managers must also know the strengths and weaknesses of the risk assessment and its outputs. [Chapter 19](#) is devoted to practical approaches to decision-making under uncertainty.

It is not necessary for the risk managers to understand all the details of the risk assessment, but they must be sufficiently familiar with the risk assessment techniques and models used to be able to explain them and the assessment results to external stakeholders. To understand the weaknesses and limitations of the risk assessment it is important to:

- Understand the nature, sources, and extent of instrumental knowledge uncertainty and natural variability in risk estimates.
- Understand how the answers to critical questions might be changed or how decision outcomes might vary as a result of this uncertainty.

- Be aware of all important assumptions made during the risk assessment as well as their impact on the results of the assessment and the answers to the questions and the range of decision outcomes.
- Peer review may be a useful tool for discovering implicit assumptions of the risk assessment and other instrumental uncertainties that may have escaped the assessors' awareness.
- Identify research needs to fill the key data gaps in scientific knowledge to improve the results of the risk assessment in future iterations.

If the assessment has adequately met the information needs of the risk manager, it is complete. If the assessment has failed to provide the necessary information for any reason, another iteration of the assessment may be in order.

3.4 RISK EVALUATION

The risk assessment is now complete, and it is time to evaluate the risk following the steps shown in [Figure 3.4](#). Is the risk acceptable? This is the first significant decision

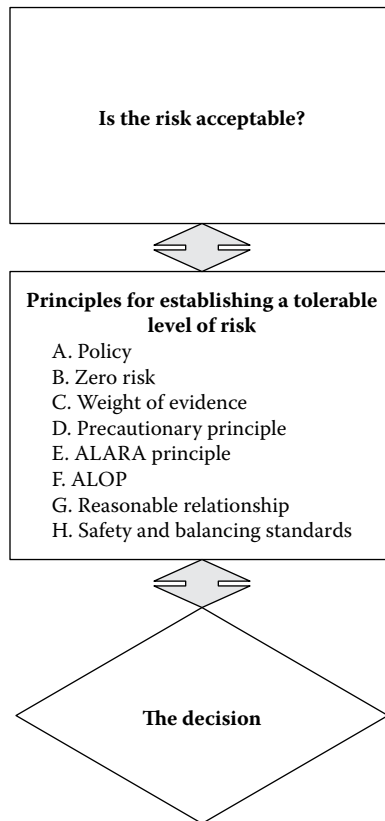


FIGURE 3.4 Risk evaluation steps.

for the risk manager to make. It requires the risk manager to be able to distinguish two important ideas: acceptable risk and tolerable risk. An acceptable risk is a risk whose probability of occurrence is so small or whose consequences are so slight or whose benefits (perceived or real) are so great that individuals or groups in society are willing to take or be subjected to the risk that the event might occur. An acceptable risk requires no risk management; it is, by definition, acceptable. A risk that is not acceptable is, therefore, unacceptable and by definition must be managed.

OPPORTUNITIES FOR GAIN

What is an acceptable uncertain potential gain? Does it make sense to talk about a tolerable level of such risk? It is impossible to anticipate every potential gain situation but for a vast majority of them the concepts of acceptable and tolerable risk hold up pretty well.

Let us consider the potential for economic gain as the endpoint. Acceptability is going to be defined by both the consequence, for example a net negative or net positive outcome, and its probability. A low probability of a large positive outcome may be acceptable while a high probability of a small positive outcome may not be, or vice versa. In situations where the combination of consequence and its probability are not acceptable, in a desirable sense, the risk can be managed to the point that it becomes tolerable. This is done by taking steps to increase the likelihood of a desirable outcome or by increasing the magnitude of the potential beneficial consequences.

Risk taking is essentially different from risk avoiding. Risk taking decisions are conscious decisions to expose one's self to a risk that could have otherwise been avoided. Consequently, managing uncertainty prior to decision making or during evolutionary decision making is a significant risk management strategy for opportunity risks.

It is conceptually possible to take steps to reduce an unacceptable level of risk to an acceptable level. More often than not, however, unacceptable risks are managed to tolerable levels. A tolerable risk is a nonnegligible risk that has not yet been reduced to an acceptable level, think of it as a subset of unacceptable risk. The risk is tolerated for one of three reasons. We may be unable to reduce the risk further; the costs of doing so are considered excessive; or the magnitude of the benefits associated with the risky activity are too great to reduce it further. A tolerable risk is not an acceptable risk, but its severity has been reduced to a point where it is tolerated.

If a risk is initially judged to be unacceptable, risk managers will seek to determine a level of risk that can be tolerated if the risk cannot be reduced to an acceptable level. Several principles (see [Figure 3.4](#)) have been used to determine a tolerable level of risk (TLR). Once a methodology for establishing the TLR is chosen, it is the risk manager's responsibility to determine the TLR as part of the risk evaluation activities. Very often, for example, the TLR is less an explicit determination than it is a default result of what it is possible to do. This determination overlaps considerably with subsequent risk control activities.

Bear in mind that risk managers are not, at this point, being asked to evaluate the effectiveness of any specific risk management options that may have been assessed in the risk assessment. That particular evaluation task is considered later under the risk control activities. It is also helpful to bear in mind that we are describing an iterative process in what amounts to a linear narrative. It will often be necessary to double back on the process and repeat a few steps. So, although the description here might suggest that the risk and all risk management options are assessed in a risk assessment that is then handed, complete, to risk managers, the real process is not always so simple.

INPUT AND FEEDBACK

Determining what risk is acceptable and establishing a tolerable level of risk (TLR) for risks that are unacceptable are decisions that cannot often be made without input from stakeholders and the public. In some decision contexts this may require a rather extensive public involvement program. In others it may be a simple risk communication task. Offering opportunities for input and providing feedback on views about what is acceptable, unacceptable, and tolerable is a critical part of an effective risk communication program.

Determining whether a risk is acceptable or not is a matter of subjective judgment. It is not a scientific determination. There is potential for the uncertainty about the best decision to make to increase at this point if the risk manager's information does not include the views of key stakeholders or if the risk communication program has not yet provided these stakeholders with opportunities for input and feedback. It is usually important to understand the risk attitudes of key stakeholders when establishing a TLR. The principles described in the following section can be used to help determine whether the assessed risk is acceptable or not. They can also be used to find a TLR when the risk is unacceptable.

3.4.1 PRINCIPLES FOR ESTABLISHING ACCEPTABLE AND TOLERABLE LEVELS OF RISK

There is no magic bullet to be found in this section. Deciding whether an assessed risk is acceptable or not and determining a tolerable level of risk for risks that cannot be rendered acceptable are fundamentally searches for subjective targets. Does the risk manager seek the highest possible level of protection, a desirable level of protection, an achievable level of protection, or something that is practical (implementable) or affordable? Does equity matter? Must there be a consistent level of protection, or is the economic efficiency of a level of protection more important? There is no one answer that will satisfy everyone. Therefore, the process by which this decision is reached may be as important as the decision rule that is used to reach it. To determine an acceptable or tolerable level of risk, managers must take into account the scientific evidence, the uncertainty, and the values evident in their objectives and constraints. Several principles used by risk managers are reviewed here briefly.

3.4.1.1 Policy

Some decisions have already been made for the risk manager by persons higher in the decision-making hierarchy. These may be the owners of a company, upper management, Congress, the president, or other elected officials. In the United States, for example, Congress and the president may pass authorizing legislation that prescribes what an agency can and must do. In that case, the risk manager's job is to figure out the best way to do it.

THE DELANEY CLAUSE

The Delaney clause is a part of the 1958 Food Additives Amendment (section 409) to the 1954 Federal Food, Drug, and Cosmetic Act (FFDCA). This clause governs regulation of pesticide residues in processed foods. It establishes that no residues from pesticides found to cause cancer in animals will be allowed as a food additive. This means that tolerance levels must be based only on the risk of carcinogenicity and that the benefits of the pesticide may not be considered. This clause was considered, at the time, to have set a zero-risk standard.

Some risk issues may be resolved by a court decision. Decision contexts initiated as a result of administrative or other legal proceedings are often circumscribed by the entity that orders the decision action. Courts at all levels of jurisdiction are increasingly being drawn into policy decisions that could affect the principles for determining an acceptable or tolerable risk.

Decisions made in the public sector, especially by agencies and organizations acting as stewards of a public asset or trust, will often be constrained by policy. Working with a government agency often means dealing with their policy restrictions and requirements. International treaties and agreements may also identify solutions or limit options. In the private sector, acceptable and tolerable levels of risk may be established in an entity's risk appetite or risk tolerance, which are topics discussed in [Chapter 6](#).

3.4.1.2 Zero Risk

Banning risky activities has been a popular approach in years gone by. Making actions that involve any risk at all taboo and declaring them forbidden has been tried in the past when it was once possible to imagine zero risk. Years ago, the limits of our knowledge and of scientific detection made it possible to find comfort in laws that appeared to legislate safety as a matter of zero risk. See the Delaney clause text box for an example.

By the middle of the 1980s, decision makers began to abandon the notion of zero risk in favor of more realistic versions of negligible risk. The one-in-a-million standard seems to have captured our imagination early. This evolved from and morphed into a notion of de minimis risk, a numerical value of risk too small to be bothered about. You can think of negligible and de minimis as “practically zero” without doing any real damage to the concepts.

Society and policy makers have, by and large, abandoned the idea that zero risk is a realistic measure of acceptable risk. Establishing a level of *de minimis* risk remains a viable concept for determining acceptable and tolerable levels of risk in certain settings.

DE MINIMIS RISK

A careful reading of official documents about the *de minimis* principle, as well as of relevant journal articles, shows that it is usually explained along one of the following three formulations. The specific-number view says a risk is *de minimis* provided its probability falls below a certain number, for example, 10^{-6} . The nondetectability view says a risk is *de minimis* provided it cannot be scientifically established whether the risk has in fact materialized or not. The natural-occurrence view for an anthropogenic risk says a risk is *de minimis* provided its anthropogenic risk does not exceed the natural occurrence of this type of risk.

Source: Peterson 2002.

3.4.1.3 Weight of Evidence

We tend to like once-and-for-all resolution of problems on the basis of compelling scientific evidence. In an uncertain world, the truth is not always easy to see. Data gaps and conflicting evidence often obfuscate risk management decisions. In a weight-of-evidence approach to evaluating risk, risk managers assess the credibility of conflicting evidence about hazards and risks in a systematic and objective manner. A formal weight-of-evidence process may rely on a diverse group of scientists to examine the evidence to reach consensus views. The evidence must be of sufficient strength, coherence, and consistency to support an inference that a hazard and a risk exist.

Evaluating the weight of evidence is an ongoing activity that attempts to balance positive and negative evidence of harmful effects based on relevant data. Thus, the evaluation of risk is conditional on the available evidence and subject to change as new evidence becomes available. When there is uncertainty about the nature of a risk, a weight-of-evidence approach may be useful in establishing whether it is acceptable or tolerable.

3.4.1.4 Precautionary Principle

Precaution may be described in this context as refraining from action if the consequences of the action are not well understood. It is prudent avoidance. The precautionary principle is broadly based on the notion that human and ecological health are irreplaceable human goods. Their protection should be treated as the paramount concern for regulatory organizations and government. All other concerns are secondary.

The precautionary principle is controversial and heavily influenced by culture and uncertainty. In a very loose and informal sense, the precautionary principle suggests that when there is significant uncertainty about a significant risk, we should err on the side of precaution, if we are to err at all. That means that activities that could give rise to catastrophic outcomes should be prohibited. It also means that if inaction could give

rise to catastrophic outcomes, we should act, not wait. The precautionary principle is generally considered to be most appropriate in the early stages of an unfolding risk problem, when the potential for serious or irreversible health consequences is great, or when the likelihood of occurrence or magnitude of consequence is highly uncertain. The desire for precaution is usually positively related to the amount of uncertainty in a decision problem. The precautionary principle can be invoked for decision making when uncertainties are large or intractable.

WINGSPREAD STATEMENT

When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically. In this context the proponent of an activity, rather than the public, should bear the burden of proof. The process of applying the precautionary principle must be open, informed, and democratic and must include potentially affected parties. It must also involve an examination of the full range of alternatives, including no action

Wingspread Conference, January, 1998

3.4.1.5 ALARA Principle

ALARA is an acronym for As Low As Reasonably Achievable. Technology and cost present two realistic constraints on what it is possible to achieve in terms of risk reduction. If a risk is not yet as low as is reasonably achievable, it is not acceptable according to this principle. One popular criterion for establishing a tolerable level of risk is to get risk as low as we are capable of making it. Then what choice do we have but to tolerate the risk that remains?

Sometimes the ALARA principle is used to take risks even lower than an acceptable level of risk. Minimizing risks even below levels that would be acceptable is sometimes justified based on the presumption that what constitutes “acceptable risk” can vary widely among individuals.

Best available technology (BAT) is a related concept. It differs in a potentially significant way, however, as BAT says to use the best available with no further qualification. ALARA introduces the idea of reasonableness, and this opens the management door to the consideration of other factors like cost and social acceptability. BAT does not consider these other factors.

3.4.1.6 Appropriate Level of Protection

An appropriate level of protection (ALOP) defines or is defined by the risk society is willing to tolerate. Despite the promising sound of this principle, it is little more than circular reasoning because it presumes one has found a way to identify the holy grail of what is “appropriate” for society. In fact, it is often little more than a statement of the degree of protection that is to be achieved by the risk management option implemented. Policy (see text box) or a rigorous public involvement program provide alternative ways to define the ALOP.

ALOP EXAMPLE

The commitment of FDA, FSIS, and CDC to reduce foodborne listeriosis was formally reaffirmed as a national public health goal in the Healthy People 2010 initiative coordinated by the United States Department of Health and Human Services (US DHHS). The federal government established a goal of working with industry, public health, and research communities to achieve an additional 50% reduction in listeriosis by 2010

FDA, 2003

The significant contribution of this concept is that it flips the focus from risk to protection, where we might think of protection as akin to different degrees of safety. The factors used to determine an ALOP typically include:

- Technical feasibility of prevention and control options
- Risks that may arise from risk management interventions
- Magnitude of benefits of a risky activity and the availability of substitute activities
- Cost of prevention and control versus effectiveness of risk reduction
- Public risk reduction preferences, that is, public values
- Distribution of risks and benefits

3.4.1.7 Reasonable Relationship

This principle suggests that costs of risk management should bear “a reasonable relationship” to the corresponding reductions in risks. It is not a benefit-cost analysis but it is an attempt to balance nonmonetary benefits (i.e., risk management outputs and outcomes) and the monetary costs of achieving them. Cost effectiveness and incremental cost analysis are often used as the basis for determining the reasonableness of this relationship.

3.4.1.8 Safety and Balancing Standards

Safety maintains deep roots within the risk analysis paradigm. A great many safety standards have been used to establish the tolerable level of risk. Safety standards encompass a bundle of standard-setting methods that rely ultimately on some degree of subjective judgment. For example, the zero-risk standard mentioned previously is one possible safety standard. Zero just happens to be one of many potential thresholds that can be established to define safety. Any nonzero level of risk can be stipulated as safe, acceptable, or tolerable. In fact, TLR has been dangled as one such tantalizing threshold standard in some of the literature. If we could develop a TLR for dam safety or for food safety or for transportation modalities, policy making would be much easier.

Many determinations of a TLR require a subjective balancing decision. Risks of uncertain potential gain or benefits may be best served by using some type of balancing standard. For example, risk-benefit trade-off analysis generally implies that greater benefits mean we are willing to accept a greater level of risk in exchange

for those benefits. The risk-benefit trade-off may explain why we are all willing to assume the risk of driving in a modern society.

Comparative risk analysis (CRA) ranks risks for the seriousness of the threat they pose. It began as an environmental decision-making tool (USAID 1990, 1993a,b, 1994; EPA 1985, 1992a,b, 1994; World Bank 1994) used to systematically measure, compare, and rank environmental problems or issues. It typically results in a list of issues or activities ranked in terms of relative risks. The most common purpose of comparative risk analysis is to establish priorities for a government agency. The concept is perfectly adaptable to any organization.

Benefit-cost analysis is another kind of balancing standard used to determine what is acceptable or tolerable by attempting to identify and express the advantages and disadvantages of a risk or risk management option in dollar terms. It is considered a useful measure of economic efficiency.

In addition to threshold and balancing standards, procedural standards are sometimes used to define what is acceptable or tolerable. Procedural standards typically identify an agreed upon process, which is often the result of negotiation or a referendum of some sort. If the agreed-upon process is followed, then the results of that process are considered acceptable or at least tolerable.

3.4.2 THE DECISION

If the assessed risk is judged by any one of these or any other method to be acceptable, there is little more for the risk manager to do. However, an unacceptable risk must be managed. The ideal would be to manage it to an acceptable level, and when that cannot be done it should be managed to a tolerable level. There are six broad strategies for managing risk. These are:

1. Risk taking
2. Risk avoidance
3. Reduce the probability of the risk event (prevent) and increase the probability of a potential gain (enhance)
4. Reduce the consequence of the risk event (mitigate) and increase the consequence of a potential gain (intensify)
5. Risk pooling and sharing
6. Retain the risk.

NO ONE SPEAKS THIS CAREFULLY

Beware. I have gone to some effort to try to carefully differentiate risk management strategies in the text. In my experience no one speaks quite this carefully. In fact, mitigation, management, control, treatment, avoidance, prevention, and probably several other terms are all used interchangeably. So, if you take pains to speak carefully and precisely, do not assume others hear you with the same precision. Take the time to clarify your meanings.

Risk managers may choose to take a risk when it presents an opportunity for gain that is acceptable or at least tolerable. When it comes to losses with no chance of gain, it is usually preferable to avoid such a risk whenever possible. If avoidance is not practical, we can try to manage either or both of the two dimensions of risk. Risk prevention reduces the likelihood of exposure to a hazard or otherwise reduces the probability of an undesirable outcome. Conversely, efforts can be made to increase the likelihood of gain from an opportunity risk. This is an enhancement strategy.

Risk mitigation allows that risky events will occur, so it seeks to reduce the impact of the risk by reducing the consequences of the event. Increasing the magnitude of a potential positive consequence, namely intensification, is another opportunity risk management strategy. A fifth option is to pool the risks into a larger group and share these risks over a greater spatial or temporal extent. A sixth strategy is to retain the risk. When no viable option for managing the risk can be found, we have no option but to put up with the risk as is. As this does nothing to lessen the risk or its impacts, some would not call it a strategy for managing risk.

If the risk manager's role in the risk assessment can be described as a positive one, then the manager's role shifts to a normative one in these risk evaluation tasks. Here the risk manager describes the world as it "ought" to be. This is a subjective deliberative decision. This normative role continues into the manager's risk control responsibilities.

3.5 RISK CONTROL

Presuming the risk has been judged to be unacceptable during risk evaluation, the risk manager's job now becomes reducing the risk to an acceptable or tolerable level. Risk control is a term of art used to avoid greater confusion with the risk management strategies described previously. It may be misleading to suggest that we can control some risks. It may be more honest to say that we struggle to manage them. However, calling this risk management activity "risk management" might cause even greater confusion. So be forewarned not to interpret control too literally in the current context, risk treatment is a synonym. The basic tasks during this risk control phase of the manager's job are shown in [Figure 3.5](#).

The extent to which the public and stakeholders are engaged in this phase may show the greatest range of variation of any risk management activity. Private risk management decisions may not involve anyone outside the organization. Collective decision-making processes can involve extensive public involvement programs for the risk control activities.

3.5.1 FORMULATING RISK MANAGEMENT OPTIONS

What does success look like? Risk management options (RMOs) are strategies that describe specific ways your risk management objectives can be achieved. These strategies are subordinate to your objectives. An RMO is relevant only to the extent that it helps you meet your objectives. Best-practice risk management recognizes that objectives can be achieved in a variety of ways and formulates alternative strategies that reflect these different ways.

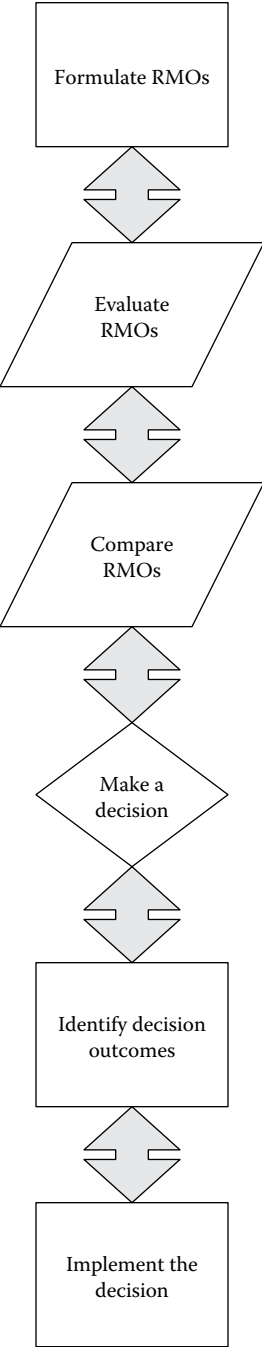


FIGURE 3.5 Risk control steps.

THE PROBLEM IS WE NEED A LEVEE

Many problems are initially identified in terms of a solution. Risk analysis focuses on getting the problem right. The problem may be flooding, it may be unrestricted land development or any other number of things. A levee is one possible solution. It is common for many problem-solving processes to begin with someone identifying the solution before the problem is clearly identified. Keep track of and consider that solution but do not let it prevent you from identifying alternative means of achieving your objectives or from properly identifying the problem.

Laws, authorities, policies, budget priorities, and politics may limit what you can actually do. None of these should limit the things you think, however. Formulate RMOs comprehensively and creatively without respect to any limitations. Thinking creatively and comprehensively about solutions to risk problems is one area in which there is room for substantial improvement for many organizations. Getting risk managers to consider a broad array of risk management options has not been the easiest thing to do. One major reason for this is that we tend to favor solutions we are familiar with or that we have the authority and ability to act upon. There is a certain obvious appeal to this sort of thinking.

If there is an effective way to manage a risk that your organization cannot implement, others may implement it voluntarily if the idea is good enough. Or perhaps there are ways to motivate those who can implement a good idea to do so. Bear in mind that good ideas for achieving worthy objectives are valid reasons for organizations to be granted new authorities.

RMOs may be formulated by the risk analysis team with input from stakeholders and decision makers. They may be imposed from above by higher authorities. They may be suggestions from the public or new scientific or technological developments. The ideas can come from Congress, agency staff, industry, government officials at all levels, academia, “the public,” television, science fiction, your left frontal lobe, or a bottle of beer. They are the children of perspiration, inspiration, and imitation. An RMO may be proposed at any point in the risk management process. Some processes may begin because someone has framed a problem (incorrectly, I hasten to add) in terms of a solution.

The process of identifying RMOs is simplified by considering a few option formulation steps. If risk managers have done a good job identifying objectives and constraints, the simplest way to begin is to identify measures that could achieve each objective. A measure is a feature that constitutes part of a strategy or RMO. Think of a feature as some physical change or an activity, where an activity is a change in the way we do something. So, for objective 1, we identify as many measures that could contribute to this objective as possible, then repeat this process for each objective and constraint.

Second, you formulate or construct RMOs from these measures. Think of the measures as building blocks and RMOs as the “structures” you build to solve problems and attain opportunities.

The third step is to reformulate RMOs. Like the rest of the risk management process, RMO formulation is iterative. Once an option is formulated, see if you can refine it. When evaluation of the options begins, it can be very effective to reformulate or tweak the options to improve their performance.

KEY POINT

When developing RMOs, quantity counts more than quality in the initial stages. You cannot be sure you have the best option unless you have considered many options. Avoid the temptation to fall in love with your first idea. Formulating alternative RMOs is an essential step in good risk management.

How do you know when a set of measures is an RMO? A good RMO should be complete, effective, efficient, and acceptable. *Completeness* means all the necessary pieces are accounted for and included in the option. *Effectiveness* means the mix of measures meets the objectives as well as possible and avoids violating constraints as much as possible. *Efficiency* means there is no less costly option that produces the same benefits and benefits cannot be increased without increasing costs. Neither can adverse effects be decreased without decreasing benefits or increasing costs. *Acceptability* means no laws or regulations are violated and there is no evident reason why the RMO could not be implemented.

3.5.2 EVALUATING RISK MANAGEMENT OPTIONS

Earlier we spoke of evaluating the risks that are assessed in the risk assessment. Don't confuse that with evaluating the risk management options that are being considered for use in managing unacceptable risks to a tolerable level. In some cases, the performance of these RMOs may have been assessed simultaneously with the risks themselves in the risk assessment. In other situations, RMOs will not even be identified until after the risk assessment is completed. The actual sequence of events can vary with the nature of the risk and the available information in any given decision context.

No matter which sequence your own risk management activity might follow, there comes a time when the formulation of RMOs is complete enough that you need to begin to evaluate these ideas. This is part of the nonscientific work of the risk management process. Values, beliefs, and biases all enter the process here, and appropriately so. This is where risk managers begin to weigh their decision options and earn their pay.

After RMOs have been comprehensively formulated, to get from a number of options to the best option you must:

- Evaluate options
- Compare options
- Make a decision (select the best option)

These can be discrete steps or they may be all mixed together. Like other risk management responsibilities, these can be iterative tasks. Up until now, the emphasis

has been on generating as many serviceable ideas for managing an unacceptable risk as are possible. Only now do we begin to go through those ideas and evaluate them to judge which are viable solutions and which are not.

Evaluation of RMOs is a deliberative analytical process. Evaluation and comparison require measurements of evaluation and comparison criteria. These will be produced by risk assessors and other analysts at the direction of risk managers. In evaluation, risk managers look at each RMO individually and consider it on its own merits. Think of this evaluation step as a pass/fail decision that qualifies some options for serious consideration for implementation as a solution and rejects others. One of the simplest ways to evaluate an RMO is to examine the effects it would have on the risk management objectives and constraints. The underlying presumption, once again, is that if we achieve our objectives and avoid violating the constraints, we will solve our problems and realize our opportunities. That is our definition of a successful risk management process.

It is, of course, common practice to focus carefully on the management of risks during the evaluation process. In a good risk management process, risk reduction can be expected to be prominently displayed among the risk management objectives.

The effects of an RMO can be identified by comparing two scenarios as shown in [Table 3.1](#). Identifying the existing levels of risk, also known as inherent risk, defines one scenario. Reestimating those risk levels with an RMO in place and functioning, that is, residual risk, is the second scenario. The differences between these scenarios can be attributed to the efficacy of the RMO, all other things being equal. [Table 3.1](#) shows a hypothetical evaluation using a scenario without any additional risk management activity (without) and a scenario with a new RMO in place (with) as the basis for the evaluation.

There are currently 50,000 illnesses and implementing RMO 1 will reduce that total to 20,000. The change is a reduction of 30,000 illnesses. The changes are what the risk managers will evaluate. If the objectives and constraints were to reduce adverse health effects, minimize costs, and avoid reductions in benefits and job losses, then a subjective judgment needs to be made about whether this particular option does this in a manner satisfactory enough to warrant serious consideration for implementation as a solution. The process is repeated for each individual RMO. All scenario comparisons would use the same “without” condition scenario as the starting point. The “with” condition scenario will vary from one RMO to another.

TABLE 3.1
Evaluating an RMO via Comparison Scenarios without Additional Risk Management and with Additional Risk Management

Effect	Future Without	Future With	Change
Annual illnesses	50,000	20,000	−30,000
Cost	\$0	\$150 million	+\$150 million
Benefits	Unchanged	Reduced	Decrease
Jobs	Unchanged	Lose 2,000	−2,000

Uncertainties affecting estimates of the evaluation criteria must be considered at this step. For simplicity, the values presented in Table 3.1 are shown as point estimates. In actual fact they may be probabilistic estimates reflecting varying degrees of natural variability and knowledge uncertainty.

Note that an option is not being compared to other options at this point. We are simply separating our RMOs into two piles. One pile “qualifies” for serious consideration for implementation and the other pile does not. The reject pile can either be reformulated to improve their performance or dropped from further consideration. The qualified RMOs will later be compared to one another.

Evaluation requires evaluation criteria. The risk management objectives and constraints are a logical source of such criteria, but risk managers are free to evaluate on any basis that serves their decision-making needs. At times the evaluation criteria may be a subset of the objectives and constraints or a set of criteria quite different from them. The risk manager’s role in evaluation includes identifying evaluation criteria and selecting qualified plans. The selection of these plans for further consideration is sometimes delegated to the assessors, as this is a screening decision. Assessors analyze the RMO’s contributions to the evaluation criteria for the managers.

3.5.2.1 Comparison Methods

Evaluating plans requires a comparison of evaluation criteria values without and with an RMO in place. To generate estimates of the effects of an RMO, some sort of comparison method is required. There are at least three different ways to compare scenarios: gap analysis, before-and-after comparison, and with-and-without comparison. The latter is generally preferred as the most objective comparison, and it is recommended for generating measurements for evaluating the impacts of an RMO. The three methods are shown in Figure 3.6 and described below. This comparison of evaluation criteria for a specific RMO is distinct and different from the comparison of alternative RMOs.

An evaluation criterion can be anything relevant to risk managers for this task. A common first step in evaluation is to describe the baseline condition of this criterion estimate. The baseline measure is often assumed to be the existing level of the criterion over time with no change. The “without” condition describes the most likely future condition of the evaluation criterion in the absence of any intentional change in risk

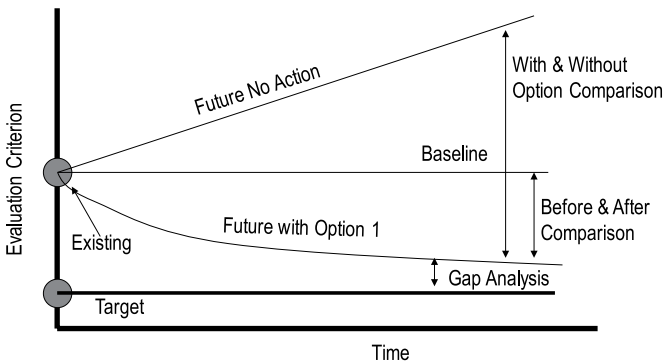


FIGURE 3.6 Three methods for comparing scenarios.

management. This scenario shows the future criterion values without additional risk management. Every RMO is to be evaluated against this same “without” condition to estimate its effect on the criterion.

The “with” condition describes the most likely future condition of the evaluation criteria with a specific RMO in place. Each intervention (e.g., RMO 1) has its own unique “with” condition. Therefore, RMO 1 will have a different “with” condition than RMO 2, and so on.

The best evaluation method compares the “with” and “without” condition levels of the evaluation criteria for each RMO. The resulting analysis provides values like those shown in [Table 3.1](#). These values serve as the basis for qualifying an RMO for further consideration or not.

Note that the before-and-after comparison, popularized by the National Environmental Policy Act (NEPA) process and also quite common in the food safety and some public health fields, could yield significantly different insights about the efficacy of an RMO. There are several definitions of gap analysis. Here, gap analysis refers to the difference between a prescribed target level of a criterion (or other effect) and what you are able to attain in reality. This graphic represents a hypothetical example to illustrate the concept; other trends in the scenarios are possible.

3.5.3 COMPARING RISK MANAGEMENT OPTIONS

A good RMO formulation process will produce numerous alternative solutions to a problem. A successful evaluation process will identify several of these as viable solutions. At this point it is necessary to compare the qualified solutions to identify the best one from among them. Comparison is an analytical step. It means establishing the similarities and dissimilarities among RMOs and contrasting the merits among them. Making a decision is based on weighing the differences among the compared RMOs such as those shown in [Table 3.2](#).

A good comparison process identifies differences among the RMOs that matter to people. It also makes the trade-offs among the options clear. A simplified example of a comparison summary is shown in [Table 3.2](#). For simplicity, it ignores the complication of expressing uncertainty about these estimates. It is important to understand that uncertainty may be an essential part of an actual comparison. Each column represents

TABLE 3.2
Comparing RMOs by Contrasting the Differences in their Effects on Decision Criteria

Effect	RMO1	RMO2	RMO3
Annual illnesses	-30,000	-40,000	-10,000
Illnesses remaining	20,000	10,000	40,000
Cost	+\$150 million	+\$500 million	+\$100 million
Benefits	Decrease	Decrease	No change
Jobs	-2,000	0	-500

a risk management option that has been qualified by the evaluation process. The rows represent decision criteria that have been identified as important to decision makers.

Table 3.2 shows how different RMOs make different contributions to the risk management objectives (assuming, for convenience, that they are reflected in the criteria chosen). RMO 2 reduces the number of illnesses more than any other option does. It also costs more. A summary table like this enables decision makers to see the differences among the options, and it makes the trade-offs more evident. Again, you are cautioned that these determinations are more difficult to make when the uncertainties in these estimates are reflected. Methods for doing this are discussed in later chapters.

Risk managers will direct the comparison process, although they will not usually do the supporting analysis. A critical management step is identifying the criteria to be used in the comparison. It is not unusual for risk assessors to suggest criteria and their metrics in unique situations. The comparison provides the analytical summary of the information that will form the foundation for a final decision. Thus, the risk manager's main role in comparison is often to request and understand the information that will be used to make a decision.

Comparisons are easiest when all effects can be reduced to a single, common metric. This, conceptually, could be lives saved, illnesses prevented, jobs created, or any metric at all. In benefit-cost analysis, that common metric is monetary. Many, if not most, comparisons involve incommensurable metrics. These situations will involve trade-off techniques. Those techniques can range from simple ad hoc decisions to sophisticated multicriteria decision analysis techniques. An example of the latter follows.

3.5.3.1 Multicriteria Decision Analysis

A decision is always easier to make when you consider only one dimension of the problem and when you are the only decision maker. Risk management decisions, however, are often complex and multifaceted. They can involve many risk managers, each with a different responsibility for the RMO, as well as stakeholders with different values, and priorities. They often involve complex trade-offs of risks, benefits, costs, social values, and other impacts because of the values in conflict as a result of the many perspectives represented by the stakeholders to a decision. One of the most predictable sources of uncertainty in any public decision-making process and in many private ones is what importance or weights should be assigned to the decision criteria. Multicriteria decision analysis (MCDA) is a bundle of techniques and methodologies that enables analysts to reduce the varied effects of different RMOs to a single utility metric that enables more direct comparison. Figure 3.7 shows the steps in a typical MCDA process (Yoe 2002). Through the evaluation step in the figure, this process tracks closely with the risk management process described here. What MCDA adds is a useful methodology for comparing options.

Multicriteria decision problems generally involve choosing one of a number of alternative solutions to a problem based on how well those alternatives rate against a set of decision criteria. The criteria themselves are weighted in terms of their relative importance to the decision makers. The overall "score" of an alternative is the weighted sum of its ratings against all criteria. The ultimate value of MCDA, both as a tool and a process, is that it helps us to identify and understand conflicts and the trade-offs they involve.

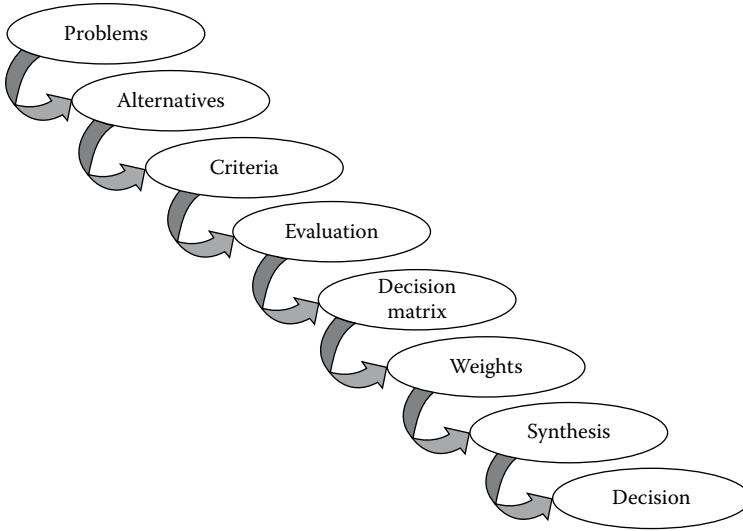


FIGURE 3.7 MCDA process.

A risk management activity defines the problem and, done well, fits the MCDA process neatly. It provides alternative means to solve the problem. Decision criteria are identified, quite possibly, from the objectives and constraints during the evaluation and comparison processes. The last four steps of a generic MCDA process are often executed by a variety of user-friendly software tools.

A simple example based on the comparison in Table 3.2 is illustrated in the following discussion using Logical Decisions.* The process begins with a simple model as shown in Figure 3.8. At the top is the decision objective. In the middle are the four criteria that will be used to make the decision, and alternative solutions are shown on the bottom.

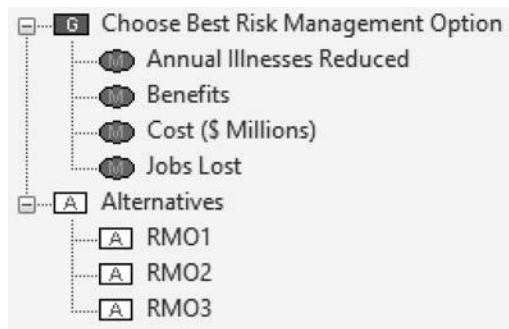


FIGURE 3.8 A simple MCDA model.

* Trademark product of Logical Decisions.

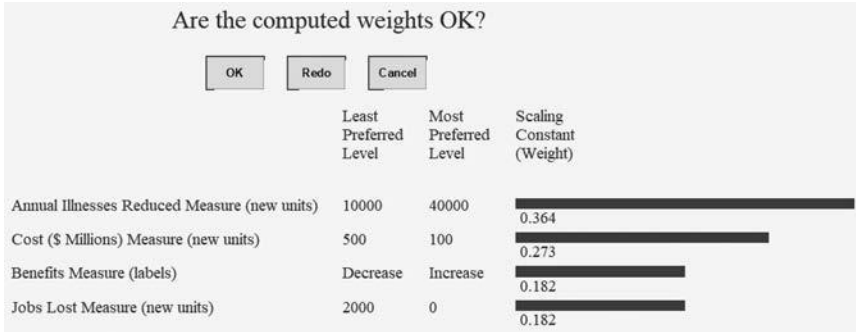


FIGURE 3.9 Assigning subjective weights to MCDA decision criteria.

TABLE 3.3
Consolidated SMART Rating for Each of Three Risk Management Options

Risk Management Option	Option Score
RMO 1	0.481
RMO 2	0.545
RMO 3	0.500

Someone must specify the relative importance of the four criteria in the decision-making process. In the hypothetical example shown in Figure 3.9, assume that the weights shown reflect the decision makers’ preferences. Illnesses reduced received 100 points, cost got 75 points, and the remaining criteria got 50 points each. When normalized over the [0,1] interval the weights are as shown.

Measurements for each alternative’s contribution to each criterion are also entered. These are simply the data from the comparison in Table 3.2. The MCDA process can accommodate estimates of the uncertainty in these values although they are not used in this example. The weights assigned by the risk manager and criteria values developed by the assessors are combined using the Simple Multi-Attribute Rating Technique (SMART) to produce scores for the three RMOs, as shown in Table 3.3.

RMO 2 is the “best” RMO based on chosen criteria, the available data, and their relative weights. Figure 3.10 illustrates the trade-offs visually. RMO 2 makes the most positive contribution to two of the criteria. It is the worst on cost. MCDA does not produce answers or decisions. It produces information that can be helpful in identifying strengths and weaknesses of alternatives in light of the social values expressed in the analysis. It can be a valuable addition to a comparison process.

3.5.4 MAKING A DECISION

Choosing the best risk management option is the risk manager’s next decision. This should be done only after taking the remaining instrumental uncertainties attending

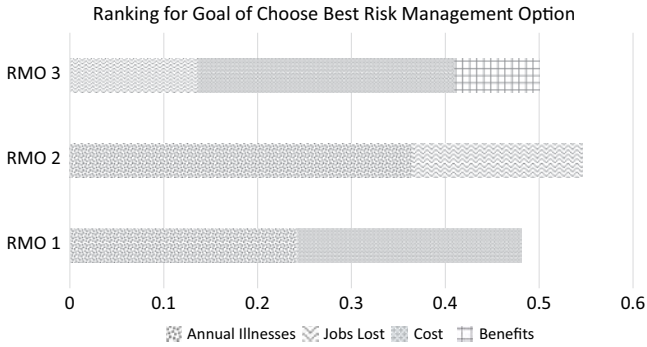


FIGURE 3.10 Contribution of options to decision criteria.

each risk management option into account. [Chapter 19](#) presents practical methods for making decisions under uncertainty.

If the uncertainty, for any reason, is significant enough to affect the nature of the answers to the risk manager's questions, to affect the choice of a course of action, or to affect the outcome of a decision, risk managers should carefully address that circumstance. That might be done through additional research, another iteration of the risk assessment, decisions phased to take advantage of the gradual resolution of key uncertainties, or an adaptive management approach to risk management.

The risk manager's role in the evaluation and comparison tasks is likely to be limited to deliberation. Risk assessors and others will do the relevant analysis. Making a decision based on the work done in these steps will usually be the risk manager's responsibility. In some decision contexts, the ultimate decision makers may be elected leaders or other personnel removed from or above the risk management process. Even in these instances, however, it is usual for risk managers to make a recommendation based on their experience and intimate knowledge of the problem.

ADAPTIVE MANAGEMENT

Adaptive management is a risk management strategy that is useful when significant uncertainties can be expressed as testable risk hypotheses. Although there are many definitions it usually consists of a series of steps that include the following:

- Identify known uncertainties at the time a decision is made.
- Include experiments that can be used to test hypotheses about the known uncertainties among the design features in the RMO.
- Measure and monitor the results of the experiments to test the identified hypotheses.
- Modify predictive models based on what is learned.
- Use the revised models to identify adjustments to the RMO actions over time to increase the likelihood that management objectives will be attained.

Adaptive management means that actions are taken to both learn about and at the same time manage the risks of interest. *Adaptive Management: The U.S. Department of the Interior Technical Guide* is an excellent resource available online (USDO, 2009).

Risk management as described in this chapter is an iterative screening process based on scientific and other criteria. Making a decision, specifically, selecting a recommended RMO, is the final screening activity for a given risk management activity. It is in the risk control activities that the risk manager's job shifts from the normative role of describing the world as it ought to be to taking action, which is the policy dimension of the risk manager's job.

It is not unusual for some organizations to rely on default decision rules. For example, some businesses will choose the option with the minimum payback period. Doing nothing is sometimes the default action for an organization, especially one affected by the National Environmental Policy Act (NEPA). It is a safeguard that attempts to ensure that any action taken is preferable to taking no action at all.

The manner in which decisions are made cannot be fairly generalized; they will vary from organization to organization, and even within an organization they may vary from situation to situation. Good decisions are strategic; they meet objectives, avoid constraints, solve problems, and attain opportunities. Selecting an RMO is, to the extent that the RMO establishes a residual risk level, equivalent to choosing a TLR. Alternatively, there may be instances where a TLR is determined first and then RMOs are formulated to attain that specific level of risk. The same decision process described may be used for this task. No matter which way it is handled, the process and the decision itself should be carefully documented.

3.5.5 IDENTIFYING DECISION OUTCOMES

One of the things that distinguishes risk management from other management approaches and decision-making methodologies is its focus on uncertainty. When decisions are made with less than perfect information, it is important to ask, "Is the decision working?" The answer to this question may not be evident in the near term when uncertainty is great, probabilities of occurrence are small, or time frames are long. On the other hand, we may learn quickly if our solution is working or not.

To deal effectively with uncertainty at this level of the process, the risk manager needs to identify one or more desired outcomes of the risk management option so we can verify that the solution is working. These outcomes should relate back to the risk management objectives. We want to be able to measure the impact of our risk decision(s) on public health, the company's bottom line, ecosystems, economic activity, or other appropriate outcomes. To do this we need outcomes that are measurable in principle. In some cases, the outcome may never, in fact, be measured, but if there is any question about the effectiveness of the RMO, it could be measured. There is no effective way to discern RMOs that work from those that do not without a performance measure.

DECISION MAKING FOR OPPORTUNITY RISKS

The concepts of acceptable and tolerable risk differ between pure and opportunity risks. When we consider these terms from the perspective of an opportunity risk, an acceptable risk is one with a negligible probability of a negative outcome or with positive consequences so large that it offsets the chance of a negative outcome. Alternatively, the negative consequences may be so slight that individuals or groups in society are willing to take or be subjected to the risk. Investing in a project that has zero chance of negative net environmental benefits might be an acceptable risk.

A tolerable opportunity risk is one that is not acceptable. Risk taking is essentially different from risk avoiding. Risk taking decisions are conscious decisions to expose oneself to a risk that could have otherwise been avoided. Consequently, managing uncertainty prior to decision making or during evolutionary decision making is a significant risk management strategy for opportunity risks.

WHO OWNS THE RISK?

Although we have spoken of risk managers as if they are all members of the same organization, that is rarely the case for decision making in the public sector. The success of an RMO may depend on many different people managing their piece of the risk.

A flood risk management (FRM) decision, for example, may require approval by and funding from Congress and the president. The U.S. Army Corps of Engineers must diligently construct all FRM structures approved by Congress. The county government may be expected to manage land use in flood hazard zones as part of the plan. State government may be responsible for operating and maintaining the FRM structures and individual residents of the flood plain may be expected to obtain flood insurance and obey evacuation orders.

A food safety risk analysis decision may involve producers, processors, wholesalers, retailers, and even consumers in the management of a risk.

Once a plan has been selected, the number of risk managers may increase markedly. They, of course, will not all have the full range of responsibilities described in this chapter.

3.5.6 IMPLEMENTING THE DECISION

Implementing an RMO means acting on the decision that was made. It requires risk managers to identify and mobilize resources necessary to actualize the RMO. Implementing a decision will very often expand the definition of who is a risk manager.

Implementation may require the cooperation of many people outside the relatively small circle of people who have worked on a risk management issue. The details of the RMO must often be implemented by a great many people. A plan to reduce

traffic accidents may involve highway engineers, automobile manufacturers, drivers, and others. Reducing the number of illnesses from *Salmonella enteritidis* in shell eggs will involve farmers, food processors, transportation companies, retailers, and consumers. Many parties can own a piece of the responsibility for implementing risk management options. The specific manner of implementation will, of course, vary markedly with the nature of the risk problem and its solution.

What can we do to ensure that the various risk managers will cooperate and implement the chosen risk management strategy? This commitment is best achieved throughout the risk management process. Best practice calls for an explicit public involvement plan as part of the risk communication process for gaining commitment to the RMO. Stakeholders and the public can be expected to have an interest in the risk management decision. At a minimum, they need to know what the decision is, how it will affect them, and what their implementation responsibilities are. Most stakeholders will want to know how the decision was made and especially how trade-offs of interest to them were resolved. Risk managers must see that this communication takes place in a timely and effective manner.

3.6 RISK MONITORING

Good RMOs can fail through faulty implementation or unravel because of false assumptions. The most brilliant strategy can be undermined if communication breaks down. Risk analysis is an evidence-based process. What is the evidence our RMO is working? If we were charged in a court room with successfully managing the risk, would there be enough evidence to convict us?

How do we know our solution works? Hubbard (2009) suggests that if we cannot answer this question, the most important thing a risk manager can do is find a way to answer it and then adopt an RMO that does work if the one currently in place does not. [Figure 3.11](#) shows the steps comprising the last risk management task: monitoring, evaluating, and iterating.

3.6.1 MONITORING

It is important to provide feedback to the organization and its stakeholders on how well they are achieving their objectives. Risk managers are responsible for monitoring the outcomes of their decisions to see if they are working. There are actually three distinct things that may be monitored in any given situation. These are decision information, decision implementation, and decision outcomes.

Some risk management decisions may not yield immediately observable outcomes. Actions taken now to change conditions in the distant future are not observable, for example, measures taken to ameliorate effects of future sea level change. Some risk problems are so uncertain that the risks themselves may be considered speculative. It is difficult to observe the reduction of risks of rare events. In these kinds of situations, it may be important to monitor information to see if data gaps are being filled. Were the underlying assumptions of the risk assessment valid? Is the risk assessment consistent with the external data? If not, are the inconsistencies known and justified? As uncertainty is reduced, a new iteration of all or part of the risk management process

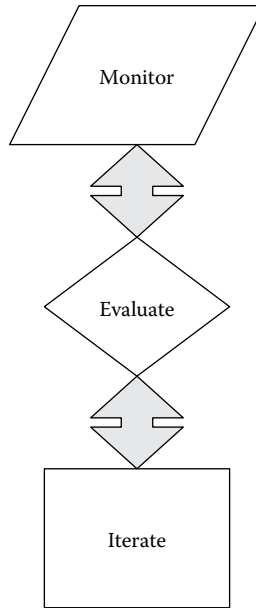


FIGURE 3.11 Risk monitoring steps.

may be warranted. A new risk assessment, for example, may lead to better solutions in those instances where it is not yet possible to observe the effects of the RMO.

Monitoring actual implementation of the RMO is likely to be important in the near term once an organization decides to implement a specific measure. Are people doing what they are supposed to be doing? Audits can answer these questions for processes under the direct control of an organization, but when implementation requires large groups of stakeholders or the public to take or avoid certain activities, other methods of monitoring will be required. If everyone is doing what they need to do to get the RMO to work, then it is time to start monitoring outcomes.

A good risk management process will identify the outcomes to monitor in order to judge the success of an RMO. Monitoring means to watch, keep track of, or check for a special purpose. In this instance, that purpose is to determine if the desired risk reductions and other outcomes of an RMO are being achieved. In other words, “Are we meeting our risk management objectives?”

Decision makers do not always ask, “What measurable effect has our risk management option had?” The monitoring part of the risk management activity requires the risk manager to do that and to consider:

- What will we measure?
- How often will we measure?
- For how long will measurements be taken?
- Who will measure?
- What will they do with the measurements?
- Who will decide if the results are good, bad, or indifferent?

- How much will measurement cost?
- Who will pay?

It may not be necessary to begin to make these measurements immediately, but the desired outcomes (see Section 3.3.2.2) need to be identified before the RMO is implemented. Risk managers need to articulate for themselves and others what success looks like and how it will or could be measured. All of this should be tied directly to the risk management objectives so all can see how well they are being achieved and to allow for corrective action if necessary.

3.6.2 EVALUATION AND ITERATION

Once the monitoring information is gathered, it must be evaluated. This process should compare results to the original objectives to decide whether the RMO is successful. This means looking at the monitored outcomes data and judging them as satisfactory or not. One way to do this is to compare them with risk management expectations based on the risk assessment and other data. Are the desired risk reductions being achieved? Have you attained the potential benefits from your opportunities? An alternative evaluation can mean contrasting your results with what you believe is possible from other actions. Are these the best possible results? This evaluation is part of the risk manager's postimplementation responsibility.

If the evaluation step produces unsatisfactory results, the risk management decision should be modified. That modification most often will take the form of a new iteration of some or all of the risk management process. It could mean beginning again from the problem identification task, or revising and updating the risk assessment, or formulating new RMOs, or modifying the decision or its implementation strategy. The public and stakeholders should be kept informed of any and all postimplementation findings and changes in the risk management option.

Hubbard (2009) discusses four potential objective evaluations of risk management. The first is statistical inference based on a large sample. This can be a difficult way to establish the effectiveness of an option. For example, if the RMO is intended to reduce the risk of rare events, it could take a very long time indeed to compile a sample sufficient for drawing conclusions. The ability to perform risk management experiments is even more rare. Comparing results of experiments to establish the best measures is virtually unheard of in most risk management arenas. Opportunities to evaluate through statistical inference are limited by data.

Second, one can seek direct evidence of cause-and-effect relationships between our RMOs and lower risk. This approach is reasonably common in certain applications. For example, we have repeated evidence of public works projects producing the desired effects as well as of safety devices functioning as designed. Each time airport security catches a hazard at check-in we have evidence. When a seat belt restrains a passenger, there is a clear cause-and-effect relationship.

A third method is component testing of risk management options. This method looks at the gears of risk management rather than at the entire machine. Sometimes it is possible to examine how components of the RMO have fared under controlled experiments or prior experience even if we cannot evaluate the RMO as a whole. Thus,

if a pasteurization step in a food process achieves the desired log reduction in pathogens, we can have some confidence in the RMO that includes such a step.

A check of completeness is Hubbard's fourth suggestion. This technique does not measure the validity of a particular risk management method. Instead, it tries to address the question of whether the RMO is addressing a reasonably complete list of risks or risk components. You cannot manage a risk that no one has identified. Hubbard counsels risk managers to consider any list of considered risks to be incomplete.

To better ensure completeness, four perspectives should be considered: internal completeness, external completeness, historical completeness, and combinatorial completeness. Internal completeness requires the entire organization to be involved in risk identification. External completeness involves all stakeholders in identifying risks. Historical completeness considers more than recent history. It goes back as far as possible to consider potential situations of risk. Finally, the risk manager should consider combinations of events to help explore the unknown unknowns of risk.

3.7 RISK COMMUNICATION

Risk communication is a risk management responsibility that runs throughout the risk management model presented here. The risk manager need not conduct the risk communication but the risk manager is responsible for seeing that it gets done.

Risk managers must develop strategies for the internal and external communication required for successful risk management. Internal risk communication refers to essential risk communication that takes place within the risk analysis team, this is chiefly the communication between risk assessors and risk managers, although communication with risk communicators is, necessarily, a part of that process. The external communication process refers to communications between the risk analysis team and all those external to the team. Thus, external communications can involve members of the organization undertaking a specific risk management activity.

A transparent and open risk management process requires communication with all relevant stakeholders, and it is integral to good risk management decisions. This communication should include input and feedback opportunities for stakeholders as appropriate throughout the risk management activity.

It is important to make the communication process known to those with an interest in communicating. Communication must be timely. Risk managers, with the assistance of risk communicators and public involvement experts, must decide when and how to communicate. An open communication process shares what is being done to find answers to the important questions of risk managers and stakeholders. Providing public access to your data and models enhances both transparency and openness in a public-sector risk management process. Private-sector risk management will be much more circumspect. The nature of the risk communication task is addressed in [Chapter 5](#).

3.8 RISK MANAGEMENT MODELS

Very few people have actually been educated or formally trained to be risk managers. There are an infinite variety of ways to approach all or some subset of the tasks

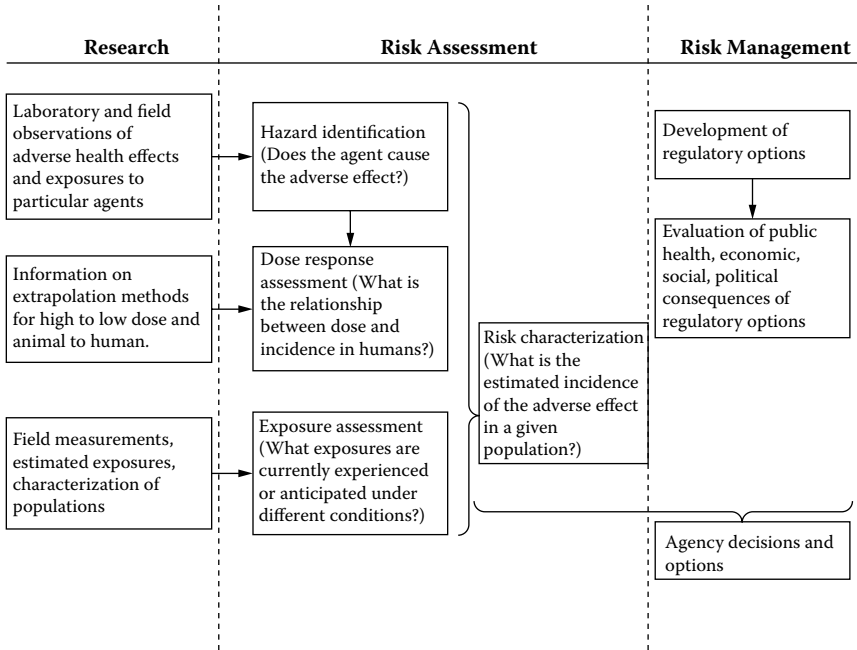


FIGURE 3.12 Elements of risk assessment and risk management. (National Research Council. 1983. Committee on the Institutional Means for Assessment of Risks to Public Health. *Risk assessment in the federal government: Managing the process*. Washington, DC: National Academies Press.)

described in this chapter. It is helpful to have mental models that inform people about how an organization handles the risk management task. In the world of risk management, there are a few relatively generic models and many more organization- or application-specific models.

One of the earliest models of risk management, shown in Figure 3.12, comes from the “Red Book” (NRC 1983). In the early days of risk analysis, risk assessment was the centerpiece of the risk analysis process. Figure 3.12 shows that risk assessment is supported by research. Risk management in a government regulatory context is rather crudely depicted as a matter of formulating and choosing the regulatory option to use to respond to the assessed risks.

It is not much of a stretch to suggest that in the early days of risk analysis the general recognition of the existence of a risk initiated the conduct of a risk assessment. Risk management was more of a reaction to the risk assessment than the proactive, directive, and foundational step it is becoming today.

One of the first more evolved generic risk management models offered in the United States was developed by the Presidential/Congressional Commission on Risk Assessment and Risk Management (1997). It is shown in Figure 3.13. It begins with defining the problem and decision context and proceeds through a series of seven mostly distinct steps in an iterative fashion.

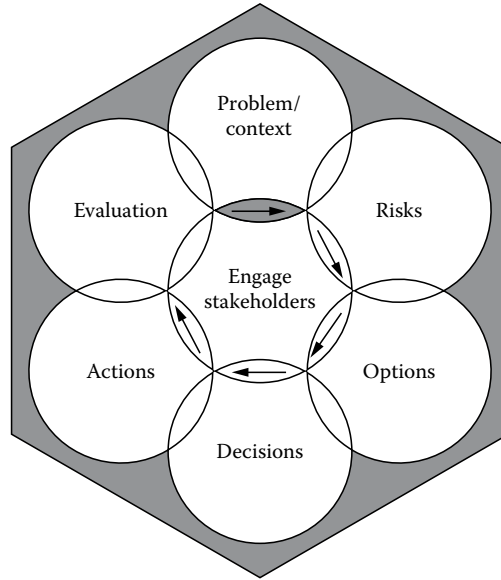


FIGURE 3.13 Risk management framework of the Presidential/Congressional Commission on Risk Assessment and Risk Management.

Once the problem is defined, risks are identified and assessed, RMOs are formulated, and the best option is chosen in the decisions step. Implementation occurs in a series of actions, and the success of the RMO is subsequently evaluated. This can lead to another iteration of the risk management process. At the center of the process is stakeholder involvement.

One of the more widely applied risk management models was developed by the International Organization for Standardization (ISO), ISO 31000, “*Risk Management—Principles and Guidelines*” (ISO, 2009). The basic model is shown in Figure 3.14. It is not specific to any industry or sector, and it can be applied to any type of risk, whatever its nature, whether it has positive or negative consequences. The model shown is quite consistent with the content of this chapter. The ISO risk management model has been updated and is revisited in Chapter 6. Be forewarned that ISO defines many terms rather differently but at its heart is consistent with the process described in this chapter.

The ISO model has five steps and two ongoing processes as well as documentation, as seen in Figure 3.14. It begins by establishing the decision context. This is followed by three steps that comprise the risk assessment process. Risks are identified and then qualitatively or quantitatively described in an analytical step (not to be confused with the overall risk analysis process) that produces information that enables risk evaluation. Risk treatment involves selecting one or more options for modifying risks and then implementing those options. Communication and consultation among managers and assessors as well as with external stakeholders takes place throughout the process. Monitoring and review embodies the iterative

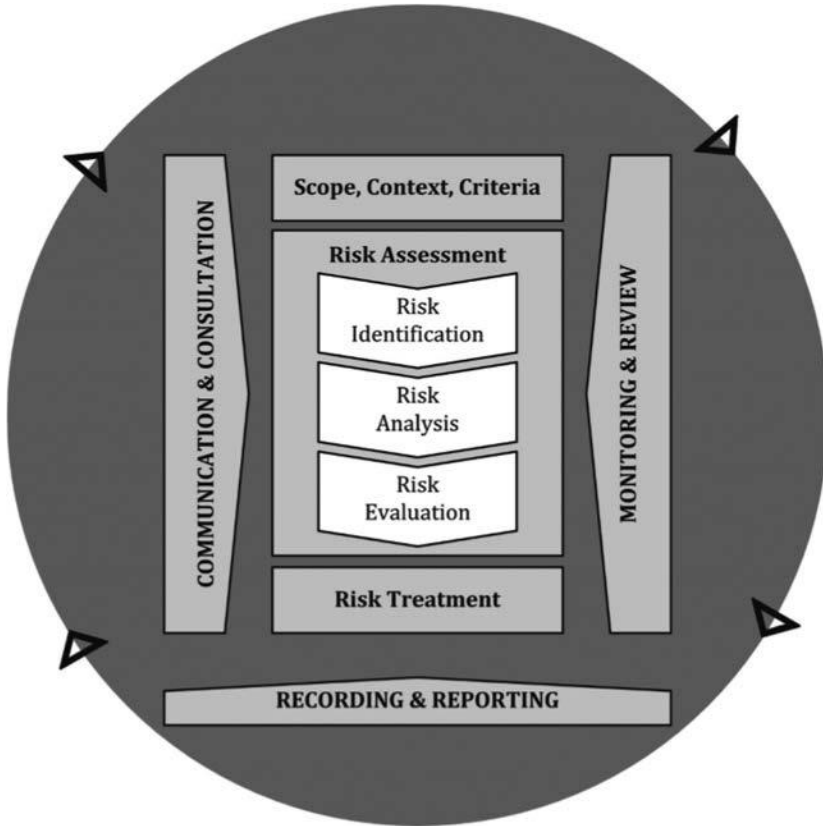


FIGURE 3.14 International Organization for Standardization risk management framework.

nature of this risk management process as well as the kinds of tasks discussed in the body of this chapter.

In addition to these generic models, there are infinite varieties of application/organization-specific risk management models. One such model is presented in [Figure 3.15](#) as an example. This model is a microbiological risk management model (FAO 2003) to be applied to food safety problems. The details of this model are less important than the greater point that there is no one right way to do risk management. There are generic models that can be adapted for specific use; the model presented in this chapter and the ISO 31000 model are good examples. In addition, there are any number of organization-/industry-/application-specific models. The best of all of these embody most if not all of the tasks described previously in this chapter.

What is most important for any organization that seeks to do risk analysis is to develop its own risk management model or adapt and adopt one of the existing models. Risk management is a process. People must know and use the process; that means the organization must have one!

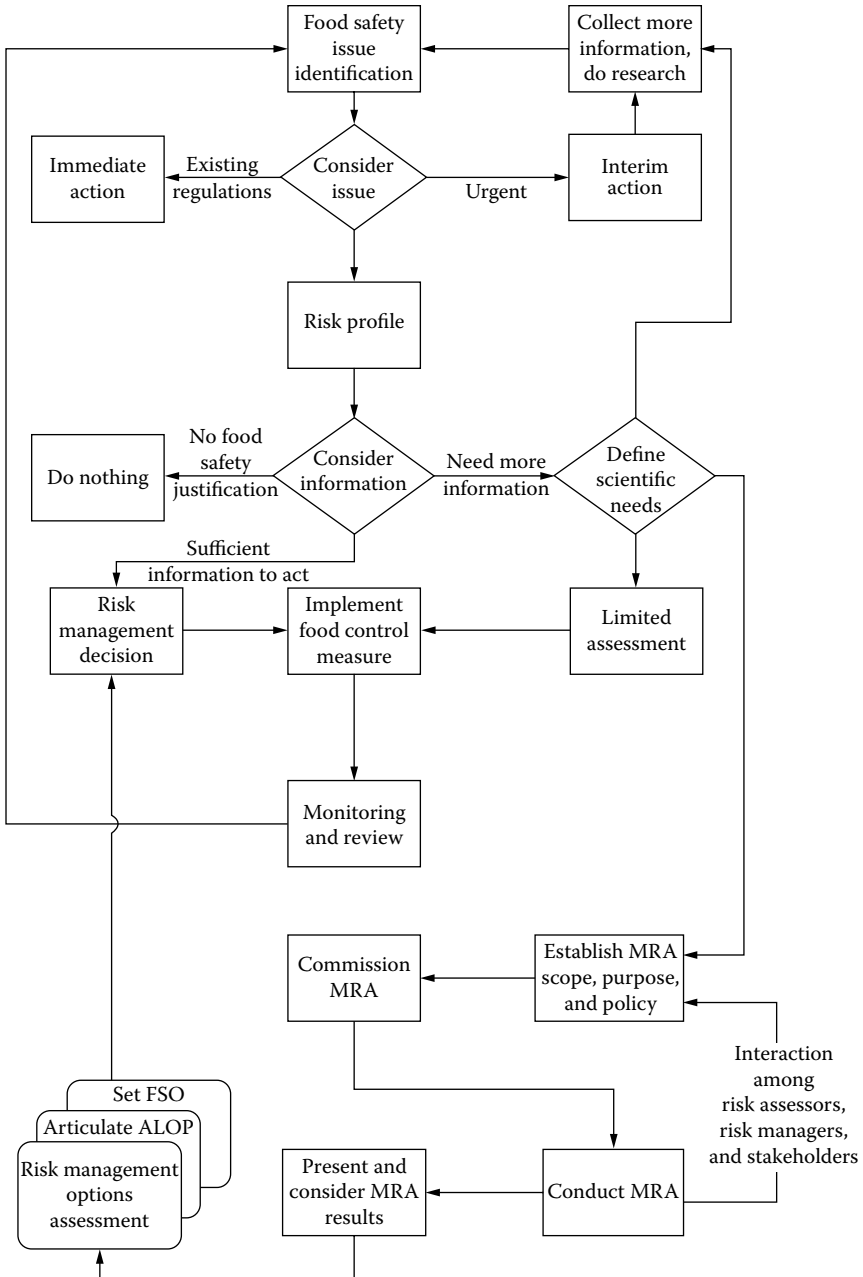


FIGURE 3.15 Microbiological risk management model. (Food and Agricultural Organization. 2003. United Nations. *Guidelines for microbiological risk management*. Orlando, FL: Codex Committee on Food Hygiene.)

3.9 SUMMARY AND LOOK FORWARD

To do successful risk analysis you must have a risk management process. Then you must spend time working your process. Risk management begins and ends the risk analysis process. The risk manager's job may be described by the responsibilities they have in identifying risk, estimating risk, evaluating risk, controlling risk, and monitoring risk. You have to spend time on each of these activities to do good risk management.

Ultimately, the risk manager's job is to make effective and practical decisions under conditions of uncertainty. Establishing a process that ensures that the best available evidence is gathered, analyzed, and considered is the risk manager's responsibility. Carefully considering the instrumental uncertainties encountered in a risk management activity and seeing that their potential effects are carefully communicated to all interested parties is a primary responsibility of the risk manager.

The next chapter continues to unpack and explain the components of the risk analysis process. The practice of risk assessment is endlessly varied because of the broad and growing number of applications of the risk analysis paradigm. Risk assessment is where the initial focus of the evolving risk analysis paradigm was concentrated. In fact, there are many practitioners who would argue vociferously that risk assessment is still the heart of risk analysis. Consistent with the aim of this text, the common elements of many of these risk assessment models are identified and presented.

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4 Risk Assessment

4.1 INTRODUCTION

Risk assessment pursues truth. Some risk assessments require science to discern that truth. In private-sector organizations, many risk assessments simply require sound evidence to know the truth. The absolute truth is usually opaque, because of uncertainty. Good risk assessment tells the truth about what we know and what we do not know. It is the science-based component of risk analysis that provides the evidence for decision makers. It answers the risk manager's questions about the risks. It provides the objective information needed for decision making, including a characterization of the instrumental uncertainty that could influence the decision or its outcome. An assessment is done to gain an understanding of the risk(s) and to measure and describe them to the fullest extent possible. A good risk assessment meets the information needs of risk managers for decision making. It provides an objective, unbiased treatment of the available evidence in well-organized and easy to understand documentation that clearly links the evidence to its conclusions. It also describes and addresses uncertainty in intentional ways.

Risk assessment is based on orderly reasoning. It is a set of logical, systematic, evidence-based analytical activities designed to provide risk managers with the best possible identification and description of the risk(s) associated with the decision problem. Evidence can be considered to include anything that helps assessors and managers discern the truth about matters of concern to them. Risk assessment is a methodical process with specific steps that provide for a thorough and consistent approach to the assessment of risks. It meets the manager's specific decision-making needs for timing, quality, and comprehensiveness of evidence. It also provides a thorough appreciation for the uncertainties that attend those risks. Because it includes the best available scientific knowledge, it is science-based.

SCALABLE RISK ASSESSMENT

In practice, you can find that there are risk assessments that warrant the complete treatment described in this chapter and there are risk assessments that require little more than the application of a risk assessment tool. Risk assessment can take months or years and a team of people with a very large budget or it may take one person with a risk matrix an hour or so, as well as everything between these two extremes.

This chapter describes a process that is suitable for any risk assessment effort, although it is presented as if for a substantial analytical effort. The process is, of course, perfectly scalable and its steps are as suitable for that multi-year effort as it is for the one-hour effort.

This chapter begins by considering what makes a good risk assessment. This is followed by a few definitions. Risk assessment models and techniques vary widely from one application to the next. The common elements of these have been distilled into a generic set of risk assessment activities, the description of which comprises the bulk of the chapter. Several specific risk assessment models are presented to illustrate the manner in which some communities of practice have formalized the assessment process. The chapter concludes with a brief description of the differences between qualitative and quantitative risk assessment.

4.2 WHAT MAKES A GOOD RISK ASSESSMENT?

During the 1990s, I offered a week-long course in risk assessment through the U.S. Department of Agriculture Graduate School. On Friday afternoon I always had a panel of practitioners come in and speak about what makes a good risk assessment. I sat in the back of the room and took notes. Those notes are summarized below in 14 aspects of a good risk assessment process (see text box).

A good risk assessment gets the questions right, then answers them carefully. Good risk assessment begins with the questions risk managers would like to have answered in order to manage the risk. These are to be answered by the risk assessment. In best practice, risk assessors will understand the entire decision context and help ensure that risk managers get the questions right. Good risk assessment answers the questions clearly and concisely.

Risk assessment is usually a team sport. Evidence-based analysis requires subject matter experts. It is unusual, but certainly not unheard of, for a single person to be able to complete a risk assessment. As risk analysis grows in acceptance, the number of routine risk assessment applications likewise increases. The more complex and unique risk assessments are never completed by a single person. Good teams are at least multidisciplinary. Better teams are interdisciplinary. The best teams are transdisciplinary.

WHAT MAKES A GOOD RISK ASSESSMENT?

Here are the 14 aspects of a good risk assessment described in this section:

Questions	Sensitivity
Team	Relevant Risks
Magnitude of Effort	Qualities
Point of View	Results
Science/Assumption	Evaluation
Data	Education
Uncertainty	Documentation

Multidisciplinary teams ensure that the needed expertise is available. Experts on these teams tend to function as experts in isolation of one another's disciplines. The knowledge tends to be integrated by one or a few individuals. This stands in contrast

to the interdisciplinary team, where all the experts integrate their knowledge with that of others. Engineers understand something about economics, and economists understand a little engineering. Biologists know a little about what the statistician is doing, and the statistician knows some biology. The team itself is integrating the knowledge of its member experts. An interdisciplinary team works more efficiently and effectively than a multidisciplinary team. A transdisciplinary team dissolves the boundaries among disciplines and moves beyond integration to assimilation of perspectives. In the process they are often able to construct knowledge and understanding that transcends the individual disciplines. Transdisciplinary teams are preferred, but they are still rare.

The best teams spend time together working on substantive issues of common interest. Good assessment teams are collaborative and effective. Roles and responsibilities are well defined and conscientiously executed. The team answers the risk manager's questions.

The magnitude of a good assessment effort is commensurate with the resources available and in proportion to the seriousness of the problem. The effort should reflect the level of risk. Risk analysis in general and risk assessment in particular are perfectly scalable processes. A good risk assessment process can be completed in an hour if that is all the time you have or in a couple of years if that is what is warranted—the attendant uncertainty will vary markedly between these situations. The assessment process does not have to take months or years and millions of dollars, but there may be a lot of uncertainty in a quick one.

The process itself is often as valuable as the result. The process provides a basis for trust as well as for information. The process aids the understanding of the problem and its solutions. The process has to be sufficient to allow for answers to the questions posed by risk managers.

A good risk assessment has no point of view. It yields the same answers to the same questions regardless of who finances or sponsors the assessment. Although a question from the risk managers may, appropriately, reflect a point of view, the answer never should. It is not the assessor's job to protect the children, to make a product look profitable, to punish or reward anyone. It is to provide objective evidence-based answers to the questions they have been asked.

On a related note, assessors should not pursue their own curiosity in a risk assessment. Nor should they ever pursue a desired answer to any question. An assessment should never be designed to provide analysis to support a predetermined answer. If risk managers know what they want to do, a risk assessment is not necessary. Not every decision requires a risk assessment. Those that do, begin with the questions that are objectively answered.

Good risk assessment separates what we know from what we do not know, and it focuses special attention on what we do not know. Risk assessment is not pure science. The existence of uncertainty often prevents it from being so, but good risk assessment gets the right science into the assessment and then it gets that science right. Science provides the basis for answering the risk manager's questions. Honesty about uncertainty provides the confidence bounds on those answers.

Good science, good data, good models, and the best available evidence are integral to good risk assessment. Assessors need to tie their analysis to the

evidence and to take care to ensure the validity of the data they use. It is both useful and important to know that not all data are quantitative. Likewise, data are not information. Skilled assessors are needed to extract the information value from data in ways that are useful and meaningful to risk managers. The answers to the risk manager's questions stand or fall on the quality of the information used to answer the questions.

It is the way that risk analysis handles the things we do not know that makes it such a useful and distinctive decision-making paradigm. In a good risk assessment, all assumptions are clearly identified for the benefit of other members of the assessment team, risk managers, and anyone else who will read or rely upon the results of the risk assessment. Risk assessors should not rely on their own default assumptions. If any default assumptions are to be used, they should be identified in the organization's risk assessment policy, prepared by risk managers.

There is uncertainty in every decision context. Risk assessors must recognize the uncertainty that exists. Moreover, they need to identify the instrumental uncertainties that influence the answers to questions, describe their significance for decision making and decision outcomes, and then address these uncertainties appropriately throughout the risk assessment. There has always been uncertainty in decision making. In the past, including the recent past, it has been commonplace to overlook or ignore the existence of uncertainty, often to the regret of those affected by decisions made this way. Admitting the things that one does not know when making a decision has often been perceived as a weakness. We like confident and bold decision makers. But we also like decisions that produce good outcomes, and the two are not always compatible. Uncertainty analysis is a strength of good risk assessment, not a weakness. Good risk assessment addresses knowledge uncertainty and natural variability in the risk assessment inputs. Good risk management addresses the variation, that is, the remaining uncertainty, in risk assessment outputs.

ASSUMPTIONS

No risk assessment can be completed unless the evidence is supplemented with assumptions. Explicit assumptions are those that assessors consciously make. In principle they can be readily documented.

Implicit assumptions are those that escape the conscious awareness of the assessors. They may be based on the culture of the organization, the beliefs of the assessors, the basic assumptions, principles and theories of the different disciplines employed, and so on. They are rarely documented. An independent review of a risk assessment by a multidisciplinary review panel can often be effective in picking up implicit assumptions, because the implicit assumptions of one discipline or person often conflict with those of another discipline or person and, thus, stand out.

All significant assumptions, whether explicit or implicit, need to be conveyed to the risk managers and other users of the assessment.

Sensitivity analysis should be a part of every risk assessment, qualitative or quantitative. Testing the sensitivity of assessment results, including the answers to the risk manager's questions, to changes in the assumptions assessors made to deal with the uncertainties they encountered is a minimum requirement for every assessment. Explaining how this uncertainty could affect decision making or the outcomes of decisions is the endgame for sensitivity analysis. The scenarios used to describe the risks we assess must reflect reality. That means they should be based on good science and field experience. Risk assessors need to understand how answers to the risk manager's questions might change if realizations of risk assessment inputs were to change due to their uncertainty.

The risk assessment should address all the relevant risks. Risk is everywhere. Zero risk is not an option for any of us. Risk assessment is different from safety analysis, although safety analysis is an integral part of some risk assessments. To distinguish risk assessment from safety analysis, we need to consider risk broadly and focus on the risks of interest. These may include:

- Existing risk
- Future risk
- Historical risk
- Risk reduction
- New risk
- Residual risk
- Transferred risk
- Transformed risk

It will not always be necessary to consider each of these kinds of risk but it is rarely adequate to consider only one of these kinds of risk. Good risk assessment considers both the explicit and implicit risks relevant to the questions posed by risk managers.

Good risk assessments share some qualities in common. First, they are unbiased and objective. They tell the truth about what is known and not known about the risks. They are as transparent and as simple as possible but no simpler. Practicality, logic, comprehensiveness, conciseness, clarity, and consistency are additional qualities desired in a risk assessment. Of course, a risk assessment must be relevant. To be relevant it must answer the questions risk managers have asked.

Risk assessments may produce more estimates and insights than scientific facts. The assessment results provide information to risk managers; they do not always produce the truth and they never produce decisions. Risk managers make decisions. The best assessments evaluate their own assumptions and judgments and convey that information to risk managers and other interested parties often in the form of confidence or uncertainty ratings. A good process makes the assessment open to evaluation. It is often wise to submit a controversial or important risk assessment to an independent evaluation or peer review.

Good risk assessments can have educational value. They often identify the limits of our knowledge and in so doing guide future research. They can help direct resources to narrowing information gaps. They help us learn about the problems, our objectives, and the right questions to ask. Completed risk assessments may be conducive to learning about similar or related risks.

There may be more than one audience for the risk assessment. Each audience is likely to have different information needs and they may each require separate documentation. This makes documentation an important part of the risk assessment process. Effective documentation tells a good story well. It is explained in simple terms and is readable by the intended audience. A good document is clear and spells important details out in terms the audience can understand. Scientific details are often most appropriately presented in technical appendices. Most important, a good risk assessment lays out the answers to the risk manager's questions clearly, well, and simply.

4.3 RISK ASSESSMENT DEFINED

At its simplest, risk assessment is estimating the risks associated with different hazards, opportunities for gain, or risk management options. Many definitions of risk assessment simply identify the steps that comprise the assessment process for that application. No one definition is going to meet the needs of the many and disparate uses of risk assessment. Nonetheless, it can be informative to consider a few formal definitions.

RISK ASSESSMENT LANGUAGE IS ALSO MESSY

The World Organization for Animal Health (OIE) defines risk assessment as follows:

The evaluation of the likelihood and the biological and economic consequences of entry, establishment, or spread of a pathogenic agent within the territory of an importing country.

It has four steps:

1. Release assessment
2. Exposure assessment
3. Consequence assessment
4. Risk estimation

The International Plant Protection Convention of the United Nations defines risk assessment as:

“Determination of whether a pest is a quarantine pest and evaluation of its introduction potential.”

ISO Guide 73:2009, definition 3.4.1 defines risk assessment as the overall process of risk identification, risk analysis and risk evaluation.

There are no generally agreed upon definitions for risk assessment. Fortunately, the ability to develop useful and serviceable definitions for specific organizations and applications has rendered the need for a single generic definition moot. Feel free to adopt, adapt, or invent your own definition if it helps you describe the risk(s) of interest to you.

The seminal definition may be found in *Risk Assessment in the Federal Government: Managing the Process* (NRC, 1983, p. 19). This book, known widely as the “Red Book,” for its cover, represents the first formal attempt to provide a description of the risk assessment process. The risks of primary interest at the time were chemical risks found in the human environment. Risk assessment was initially defined as follows: “Risk assessment can be divided into four major steps: hazard identification, dose-response assessment, exposure assessment, and risk characterization.”

The steps are described by the National Research Council (NRC) as follows:

- *Hazard identification*: the determination of whether a particular chemical is or is not causally linked to particular health effects
- *Dose-response assessment*: the determination of the relation between the magnitude of exposure and the probability of occurrence of the health effects in question
- *Exposure assessment*: the determination of the extent of human exposure before or after application of regulatory controls
- *Risk characterization*: the description of the nature and often the magnitude of human risk, including attendant uncertainty

RISK ASSESSMENT

When asked to name the riskiest things they do, most people will quickly identify driving. A simple risk assessment process can be demonstrated by asking the four questions used to define risk assessment in [Chapter 1](#).

What can go wrong? One could have an accident.

How can it happen? The driver could be impaired, road or weather conditions could be hazardous, the car could be poorly maintained.

What are the consequences? Property damage, injury, fatalities, or perhaps only delay and annoyance could result from an accident.

How likely is it? Perhaps knowing yourself you might say, not very likely.

That is a risk assessment process. Is it good enough to run an insurance company or to design highways? Of course not! However, it is perfectly adequate to demonstrate the idea of a scalable and systematic process. Given more time, resources, and importance, all of the answers could be expanded and quantified.

STEM

Cox (2002) says a risk can be defined by answering the following four questions:

- What is the **source** of the risk?
- What or who is the **target** that is at risk?

- What is the adverse **effect** of concern that the source may cause in exposed targets?
- By what causal **mechanism** does the source increase the probability of the effect in exposed targets?

These definitions have been and continue to be the focal point for many definitions of risk assessment. The *Codex Alimentarius*, for example, defined risk assessment for food safety purposes in 2004 as follows: “Risk Assessment: A scientifically based process consisting of the following steps: (i) hazard identification, (ii) hazard characterization, (iii) exposure assessment, and (iv) risk characterization” (FAO/WHO, 2004, p. 45). The roots of the original definition are clearly evident in this one, which has simply broadened the notion of using a dose-response assessment to characterize the consequences of exposure to a hazard.

The NRC definition as broadened by the *Codex* has a lot of appeal for risk assessors. It begins by identifying the hazard, which is the thing or activity that can cause harm. The hazard characterization step describes the nature of that harm and the conditions required to cause it. The exposure assessment describes the manner in which people or other assets of value can become exposed to the hazard under conditions that will cause harm. The last step, risk characterization, pulls together the information in the three preceding steps to describe the probability that the risk will occur as well as the severity of its consequences.

The Presidential/Congressional Commission on Risk Assessment and Risk Management (1997a,b) defined risk assessment more generally. It said that risk assessment is the systematic, scientific characterization of potential adverse effects of human or ecological exposures to hazardous agents or activities. It is performed by considering the types of hazards, the extent of exposure to the hazards, and information about the relationship between exposures and responses, including variation in susceptibility. Adverse effects or responses could result from exposures to chemicals, microorganisms, radiation, or natural events. This definition did not catch on with federal agencies in the United States because it did not meet the widely varying needs of the agencies using risk assessment.

ISO 31000:2009 *Risk Management--Principles and Guidelines* (ISO, 2009) defines risk assessment as the overall process of risk identification, risk analysis, and risk evaluation. Beware the messy language of risk! Risk identification is the process of finding, recognizing, and describing risks. Risk analysis is a process to comprehend the nature of risk and to determine the level of risk. It is equivalent to risk assessment as described in this chapter. Risk evaluation is the process of comparing the results of risk analysis with risk criteria to determine whether the risk and/or its magnitude is acceptable or tolerable. The Society for Risk Analysis defines risk assessment as a systematic process to comprehend the nature of risk, express and evaluate risk, with the available knowledge.

For the general purposes of this book, risk assessment is defined as a systematic evidence-based process for describing (qualitatively or quantitatively) the nature, likelihood, and magnitude of risk associated with some substance, situation, action,

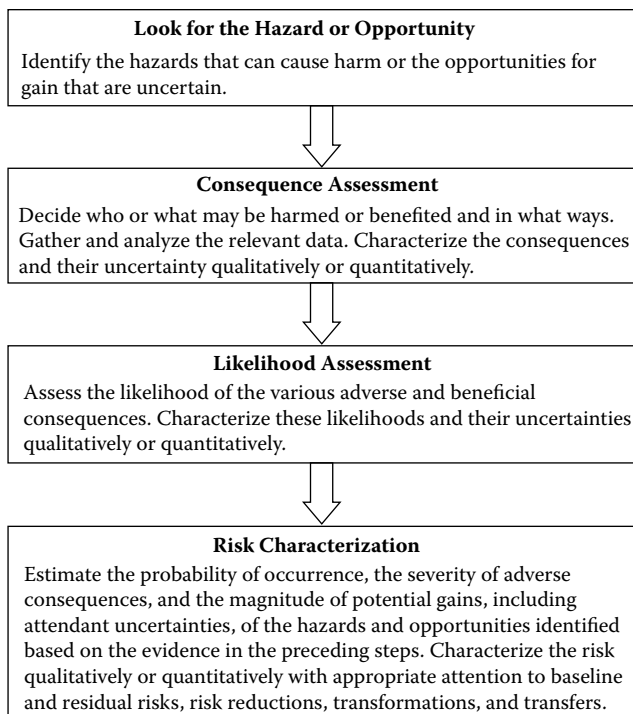


FIGURE 4.1 Four generic risk assessment components.

or event that includes consideration of relevant uncertainties. The generic assessment steps adopted for this book are shown in [Figure 4.1](#).

Risk assessment is a continuously evolving process with a stable core that takes many forms, as evidenced by the previous definitions and the models that follow in this chapter. The core of risk assessment may best be described by the four informal questions introduced in [Chapter 1](#):

- What can go wrong?
- How can it happen?
- What are the consequences?
- How likely is it to happen?

4.4 RISK ASSESSMENT ACTIVITIES

The great variety of risk assessment models, methods, and applications makes it difficult to speak about risk assessment in a way with which all will agree. I describe the risk assessment component of risk analysis by breaking it down into eight generic risk assessment tasks that appear to varying extents in one form or another in all best-practice risk assessment. They are shown in [Figure 4.2](#) and are addressed in the sections that follow.

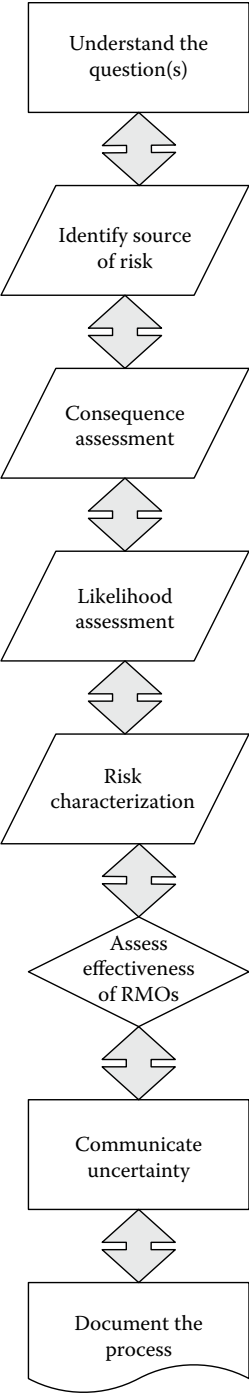


FIGURE 4.2 Eight risk assessment tasks.

The tasks, although presented in a linear fashion, are often accomplished in an iterative fashion. Some tasks may be initiated simultaneously, for example, the consequence and likelihood assessments may be done concurrently. It is less important that the tasks be accomplished in a rigid fashion than that all of the tasks get done at least once.

4.4.1 UNDERSTAND THE QUESTIONS

In case you had not picked up on the importance of questions from earlier in the chapter, risk assessors need to understand what information they are being asked to provide back to risk managers. Assessors are often involved in helping risk managers to identify the questions that need to be answered for risk managers to achieve their risk management objectives and solve their problems. Questions are just one common way of eliciting information that is needed for decision making. Questions need not literally be questions. Information needs can be expressed in any number of ways. Whether assessors are involved or not, obtaining a preliminary set of the questions to be answered by the risk assessment is the essential starting point for any risk assessment.

Assessors should review the questions with the managers to make sure they have a common understanding of the meaning of the questions and the information required to answer them. If the assessors know it is going to be impossible to answer some of the questions, they need to tell the risk managers this. A revised set of questions needs to be negotiated and approved by the managers. If important questions are missing, assessors should argue for their inclusion.

SOME REAL QUESTIONS

- What is known about the dose-response relationship between consumption of *Vibrio parahaemolyticus* and illnesses?
- What is the frequency and extent of pathogenic strains of *Vibrio parahaemolyticus* in shellfish waters and in oysters?
- What environmental parameters (e.g., water temperature, salinity) can be used to predict the presence of *Vibrio parahaemolyticus* in oysters?
- How do levels of *Vibrio parahaemolyticus* in oysters at harvest compare to levels at consumption?
- What is the role of post-harvest handling on the level of *Vibrio parahaemolyticus* in oysters?
- What reductions in risk can be anticipated with different potential intervention strategies?

Source: Quantitative Risk Assessment on the Public Health Impact of Pathogenic *Vibrio parahaemolyticus* in Raw Oysters (FDA, 2005).

Some organizations face recurring situations or they handle a specific kind of risky situation as a matter of routine. In these instances, the specific questions to be answered may be well known and long established. For example, the Animal Plant Health Inspection Service (APHIS) of the U.S. Department of Agriculture routinely

processes requests from countries that would like to export their plants and plant products to the United States. APHIS has developed a standardized risk assessment process that relies on a well-defined set of questions that is used for all such routine requests.

The U.S. Army Corps of Engineers routinely addresses flood problems across the country. No two of them are alike, but flood risk management investigations are similar enough that many of the information needs have become standardized. Estimating what the expected annual flood damages are with and without risk management measures in place are universal questions that have been standardized in guidance documents and practice.

The food-additive safety assessment process has a well-established procedure for assessing health risks of chemicals added to food. It begins by undertaking toxicity studies of the substance. These studies are used to determine the “No Observed Adverse Effect Level” (NOAEL). A safety or uncertainty factor is used to extrapolate the NOAEL results from animals to humans. Dividing the NOAEL by the safety factor yields an Acceptable Daily Intake (ADI). This is the maximum amount the average human can consume daily for a lifetime with no adverse health effect. Simultaneous efforts to calculate the Estimated Daily Intake (EDI) of the substance are undertaken, and the two are compared via the ratio, EDI/ADI. Values greater than 1 require risk management. These data input requirements are well established.

SELECTED SOURCES OF SCIENTIFIC INFORMATION FOR RISK ASSESSMENTS

- Published scientific studies
- Professional literature
- Specific research studies designed to fill data gaps
- Administrative data and internal documents
- Gray literature—unpublished studies and surveys carried out by academia, government, industry, and nongovernmental agencies
- National and other monitoring data
- National human health surveillance and laboratory diagnostic data
- Disease outbreak investigations
- National, published, and proprietary surveys, inventories, and the like
- Expert panels to elicit expert opinion where specific data sets are not available
- Risk assessments carried out by others
- International databases
- International risk assessments

Thus, the risk manager’s data needs may already be well established for some risk assessments. These will usually be available in official policy, guidance, or common practice. In other unique instances, risk managers will have to carefully articulate each of their data needs. The majority of risk assessments may well fall between these two extremes. Regardless of the individual circumstances of an assessment, the risk

manager's questions should be written down and understood by all. These questions guide the risk assessment.

4.4.2 IDENTIFY THE SOURCE OF THE RISK

Data collection and analysis begin in earnest when risk assessors seek to identify, understand, and describe the source of the harm that could occur or the gain that may be realized. The source of the risk—the hazards that can cause harm or the opportunities for gain that are uncertain—may already have been identified, as the decision context was established by the managers, with or without the assistance of the assessors, especially if a risk profile was prepared first. It is usual for assessors to participate in the preparation of a risk profile.

In many risk assessment models, this step is called “hazard identification.” For Environmental Protection Agency (EPA) Superfund risks, this is the process of determining whether exposure to a chemical agent can cause an increase in the incidence of a particular adverse health effect (e.g., cancer, birth defects) and whether the adverse health effect is likely to occur in humans. For food safety concerns, it may mean identifying a pathogen-commodity pair that is of concern. For engineering projects, it may mean describing an earthquake or coastal storm risk, or it could be determining the demand on a structural component relative to its capacity. For APHIS, it may include identifying a pest of potential quarantine concern. For a pharmaceutical firm, it may be impurities or irregularities in the production of a drug. It could also mean identifying the potential gains from an investment in tourism or the gain associated with opening a new store or launching a new product line. In enterprise risk management it could be anything that threatens a firm's ability to meet its strategic objectives.

TWO CONSEQUENCE CAVEATS

Managers and assessors need to remain vigilant against imprecise language. It is easy to ask: what is the risk associated with eating oysters contaminated with pathogenic *Vibrio parahaemolyticus*? But what are the consequences of concern to risk managers? Is it annual deaths, hospitalizations, illnesses, or exposures? Should they be segregated by age, gender, ethnicity, or other factors? Do we want estimates of the probability of death and illness? If so, should they be per exposure or annually? Or are other measures like loss of life expectancy, working days lost, and quality adjusted life years appropriate?

Managers and assessors also need to think broadly about consequences. A narrow focus on consequences can cause managers to overlook important impacts of both the risk and the RMOs. For example, if the assessment is motivated by public health consequences it is easy to overlook important impacts on trade, industry, and consumers.

The cure for these mistakes is found in a good risk management process and those “three pieces of paper” it produces.

Identifying the source of the risk is more than simply naming a hazard or opportunity. It includes understanding the background, context, and aspects of the hazard or opportunity relevant to the problem being addressed and communicating that to others. The extent of this process will vary from situation to situation. For example, identifying a food-borne pathogen may be very straightforward for well-known microbiological hazards yet far from fully developed for emerging or new microbiological hazards. Economic opportunities may need to be supported with market studies and cost details. Technological risks need to be explained in a narrative fashion that facilitates understanding by all interested parties. In other words, assessors must gather the evidence necessary to establish the existence of a hazard or opportunity.

The risk assessor should think comprehensively about risks. This means identifying all of the decision-relevant risks. It is all too easy to focus too narrowly and too quickly on a single risk when there may in fact be more than one. It also means considering all the relevant dimensions of a risk, including not only the existing risk, but residual, new, transformed, and transferred risks. Identifying the source of a risk is primarily a qualitative analysis. Importantly, hazard/opportunity identification is the point in the risk assessment where risk assessors begin to carefully identify and separate what we know about a risk from what we do not know.

4.4.3 CONSEQUENCE ASSESSMENT

In this task, risk assessors characterize the nature of the harm caused by a hazard or the gain that is possible with an opportunity. Assessors identify who or what may be harmed or benefited and in what ways by the sources of risk identified in the previous task. This activity might be described as the cause-effect link in the risk assessment. What undesirable effects do the hazards have? What desirable effects might the opportunities offer? Risks affect human, animal, and plant life, public health, public safety, ecosystems, property, natural and cultural resources, human systems (political, legal, education, transportation, communication, and the like), business operations and bottom lines, infrastructure, economies, international trade and treaties, financial resources, and so on. Carefully identifying the consequences and linking them to the hazards and opportunities is an essential early step in any risk assessment. It also helps solidify the definition of the risk. This activity may be likened to the hazard characterization step of the Codex model.

The consequences of most importance should already be reflected in the “three pieces of paper” developed by risk managers before the risk assessment was initiated. In an iterative process, such as risk assessment, it is to be expected that, as uncertainty is reduced, some aspects of the assessment will become better understood. This may necessitate revising the initial assessment of relevant consequences.

Effectively managing a risk requires a broad understanding of the relevant losses, harm, consequences, and potential gains to all interested and affected parties (NRC, 1996). Consequences may be characterized qualitatively or quantitatively. No matter which type of characterization is used, it is essential to catalogue the significant uncertainties encountered in describing and linking the consequence to the source hazards and opportunities.

If the risk has not previously been carefully identified, it will be useful to identify the specific consequences of interest in the assessment before initiating the likelihood assessment. As noted earlier, it is important to answer the “likelihood of what?” question before investing much effort in assessing the likelihood. In ongoing programs with recurring types of risks the consequences may be well defined by policy and practice that enable the assessors to conduct a simultaneous likelihood assessment.

4.4.3.1 Dose-Response Relationships

The earliest risk assessments used dose-response relationships to characterize the consequences of human health risks. Dose-response relationships, often represented as curves, remain the primary health-consequence model used to characterize the adverse human health effects of chemicals, toxins, and microbes in the environment. There is extensive literature on these dose-response relationships that includes its own journal, *Dose-Response*. A discussion of consequence assessment is not complete without a brief mention of this often-used relationship.

Consider the conceptual representation of a dose-response curve shown in Figure 4.3, adapted from Covello and Merkhofer (1993), where they described the effect of a risk agent on a large population. First, notice that the dose of the risk agent increases from left to right on the horizontal axis. The response, on the vertical axis, is not specified. In practice, this axis may be the probability of illness or of some other adverse health effect, the number of excess tumors above those observed in a control group, for example, or virtually any adverse health effect. The metrics on the vertical axis are most often developed for a representative individual of the general population, the general population itself, or any subpopulation of interest.

Five different conceptual distinctions are made in the figure to aid the general understanding of the relationship. Let us illustrate these concepts using two different responses. The first is an unspecified set of variable adverse health effects

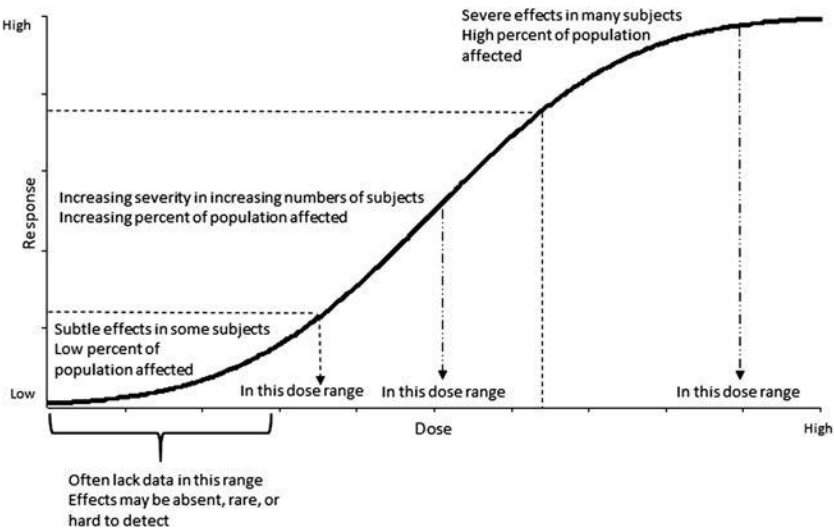


FIGURE 4.3 A stylized dose-response relationship.

encompassing such effects as excessive salivation, elevated blood pressure, infection, organ failure, and death. The second response is lifetime probability of cancer. First, at sufficiently low doses there may be significant uncertainty about the response. “No threshold” models assume there is no absolutely safe level of exposure. However, for many risk agents there may be no effects at very low doses regardless of the duration of the exposure. At this level of exposure when the response is, say, the probability of cancer for a representative member of the population, the shape of the curve in this range of doses may be highly uncertain.

At somewhat higher levels of exposure, subtle adverse health responses may be detected in some subjects. This might include low impact effects like excess salivation or using the probability of cancer, we would see a low but increasing probability.

As the dose increases more, we might see the beginning of some severe effects in some members of the population with a growing number of less severe effects. The cancer risk model simply has an increasing likelihood of cancer. In that fourth dose region, we would expect to see increasing numbers of severe health effects among members of the population. Both incidence and severity increase with these relatively high doses of the risk agent. If the dose increases high enough and lasts long enough, all members of the population are at risk of some adverse response. Similarly, the probability of cancer rises to higher levels. The final response range corresponding to the highest dose levels results in death or a probability of cancer approaching one.

This conceptual model is not to be taken literally. Response will not always be a continuum from no effects to death; the probability of cancer response presents one alternative. The doses themselves will vary as well. Chemical exposures, for example, may be measured in mg/kg/body weight daily for a lifetime. Microbial doses may be measured in the number of cells or colony-forming units per some amount of food.

4.4.4 LIKELIHOOD ASSESSMENT

Risk assessors analyze the manner in which the undesirable consequences of hazards or the desirable consequences of opportunities occur so they can characterize the likelihoods of the sequence of events that produce these outcomes. Risks cannot be directly observed or measured because they are potential outcomes that may or may not occur. Uncertain occurrence is a necessary, but not sufficient, condition for risk; an undesirable outcome is the other necessary condition. Probability is the most common language of uncertainty. Thus, qualitatively or quantitatively assessing the probability/likelihood of the various adverse and beneficial consequences associated with the identified risks is necessary for risk assessment. This step is most analogous to the exposure assessment task of the NRC “Red Book” or *Codex* models.

Assessing the likelihoods of the consequences associated with identified risks can often be aided by developing a risk hypothesis. A risk hypothesis is a model or scenario that credibly explains how the source of the risk can lead to the consequences of concern by identifying the appropriate sequence of uncertain events that must occur for this to happen. The likelihood assessment characterizes the chance of that sequence of events occurring. Think of this step as estimating the probability that a risk target (person or thing) will be exposed to the hazard that can cause harm. Alternatively, it is estimating the probability that an opportunity does (or does not) yield a favorable outcome.

In the relatively loose, that is, nontechnical, language of risk, probability and likelihood are used as synonyms. Some draw a nontechnical distinction that uses probability for quantitative estimates and likelihood for qualitative estimates. More rigorously, likelihood is not a probability but we yield to the use of these words as synonyms in this text.

Three simple risk hypotheses are illustrated in [Figures 4.4](#) through [4.6](#). The first example in [Figure 4.4](#) is a risk model for estimating expected annual flood damages. For the upper right quadrant it is assumed that property damage (consequence), measured in dollars, increases with water depth. The upper left quadrant shows the volume of water flow (hazard) required to reach the corresponding depths of water. On the lower left, the likelihoods of the various flows being equaled or exceeded in a year are shown. These three relationships* together yield the fourth relationship (damage-frequency) in the lower right quadrant, which when integrated provides a measure of property damages called expected annual damages. The likelihood characterization is derived from the middle two quadrants.

A second risk hypothesis is seen in [Figure 4.5](#). This shows the presumed relationship between a human activity (logging), the stressors it creates, and the adverse effects that can result in a forest environment (EPA 1998). A likelihood assessment would require estimating the likelihood of each of these model elements.

The risk hypothesis embodied in the FDA risk assessment on *Vibrio parahaemolyticus* in raw oysters (FDA 2005) is shown in [Figure 4.6](#). The likelihood characterization is more complexly woven through elements of this hypothesis.

It is essential to identify the significant uncertainties and to analyze their potential impact on the likelihoods of the risks. This may be done qualitatively or quantitatively, in concert with the level of detail in the overall risk assessment.

4.4.4.1 Exposure Assessment

The likelihood characterization includes the special subset of “exposure assessments” that virtually all health-related risk assessments require. An exposure assessment estimates the intensity, frequency, and duration of exposure to a risk agent. Exposure assessments identify the relevant pathways by which a human or other population is exposed to a hazard. The exposure assessment is often the most difficult part of a risk assessment, because the pathways can be both numerous and complex. They are also plagued by knowledge uncertainty and natural variability.

Exposures can be monitored directly, when direct measurement of the individual’s exposure by instruments is possible. Otherwise we are restricted to measuring factors that affect exposure rather than the exposure itself. These are indirect methods of monitoring. Spatial and temporal variations are often important considerations in exposure assessments. Models used to capture the relevant aspects of an exposure pathway can be quite complex.

* Adapting the terminology of the NRC definition of risk assessment, the depth-damage curve is a dose-response relationship. The depth-flow and flow-frequency curves comprise an exposure assessment. The damage-frequency curve is a risk characterization.

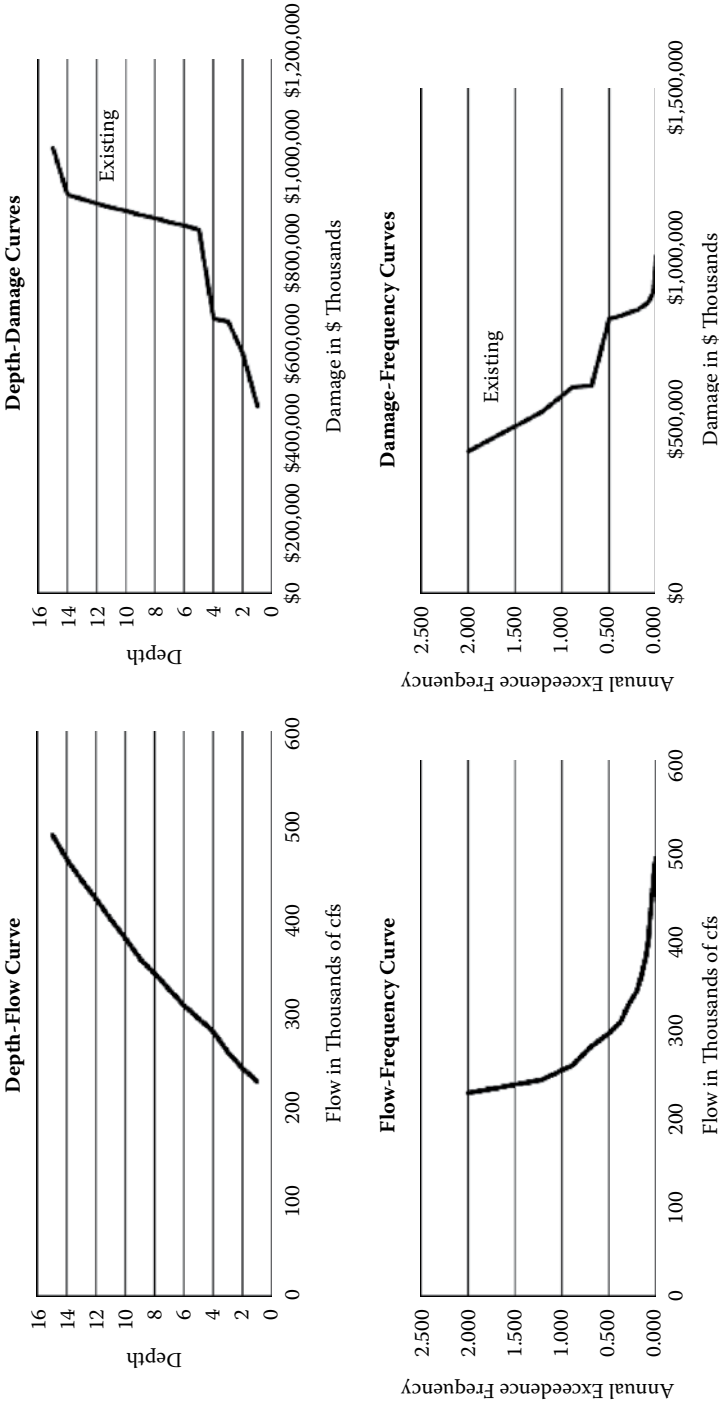


FIGURE 4.4 Hydroeconomic model for flood risk.

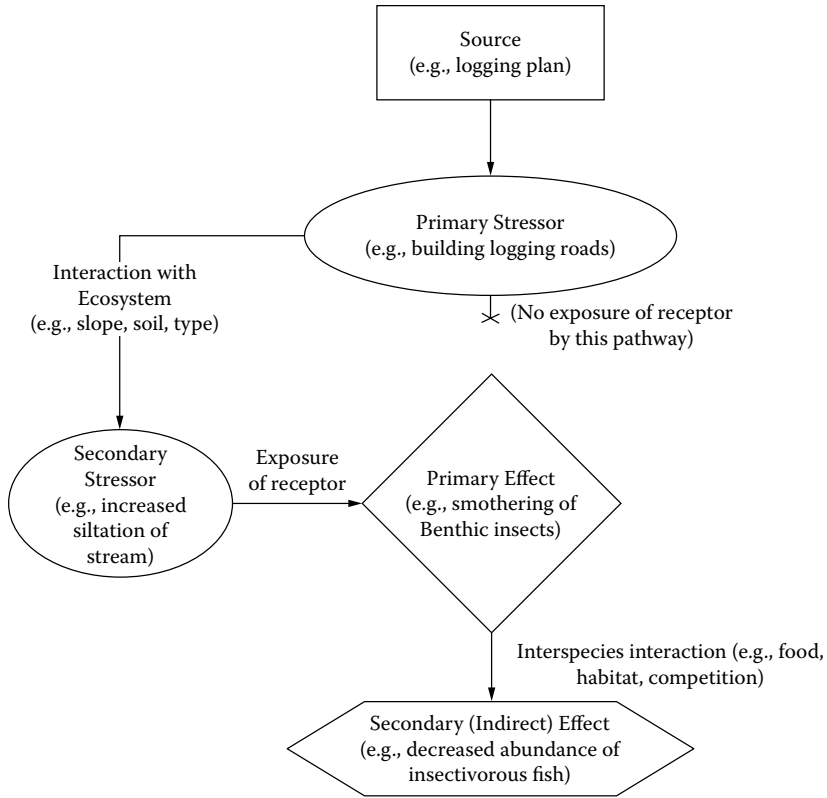


FIGURE 4.5 Conceptual model for logging forest products. (From Environmental Protection Agency. 1998. *Federal Register* 63 (93): 26846–26924.)

A general exposure equation adapted from the EPA (Covello and Mumpower, 1985) is:

$$\text{Intake} = \frac{\text{Concentration} \times \text{Contact rate} \times \text{Exposure frequency} \times \text{Exposure period}}{\text{Body weight}} \tag{4.1}$$

Here, intake is defined as mg/kg of body weight per some duration of exposure. The concentration of the risk agent (e.g., a chemical) in a medium during the exposure period is multiplied by the amount of contaminated medium contacted per unit of time or per event to get the amount of risk agent per exposure. The exposure frequency (days per year, for example) is multiplied by the exposure period (number of years) to get the duration of the exposure. The product of these two values (amount of risk agent and duration of exposure) is divided by body weight to get a dose to which one is exposed. This dose may then feed into a dose-response relationship, as discussed previously.

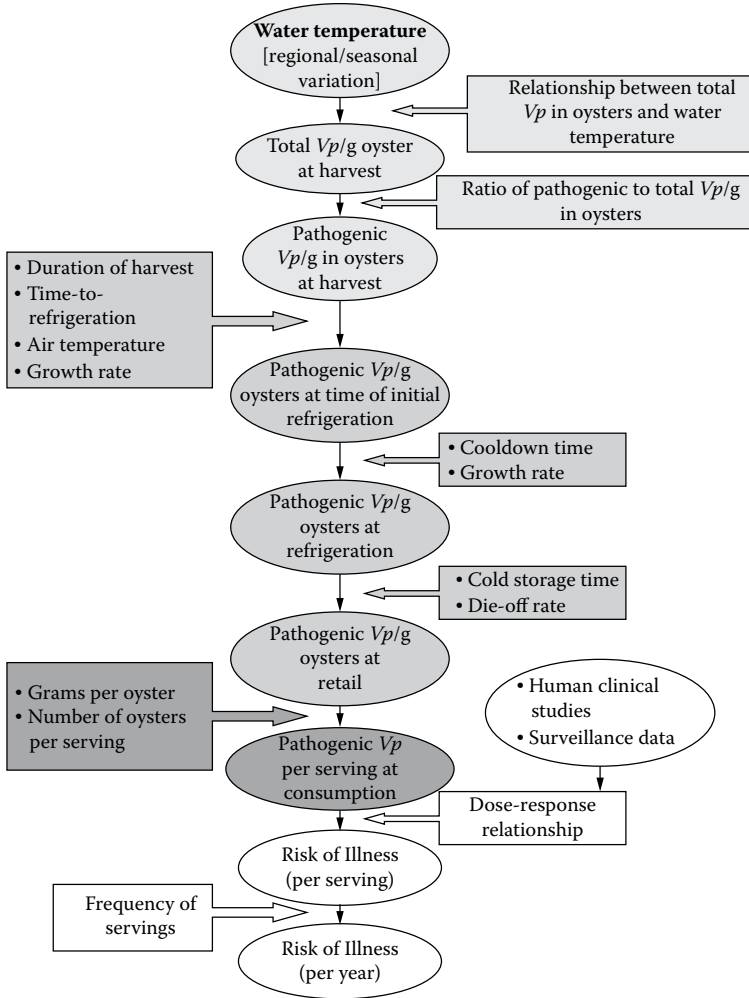


FIGURE 4.6 Schematic representation of the *Vibrio parahaemolyticus* risk assessment model. (From Food and Drug Administration. 2005. *Quantitative Risk Assessment on the Public Health Impact of Pathogenic Vibrio Parahaemolyticus in Raw Oysters*. College Park, MD: Center for Food Safety and Applied Nutrition. <http://www.fda.gov/Food/ScienceResearch/ResearchAreas/RiskAssessmentSafetyAssessment/ucm050421.htm>.)

In the event of a microbial exposure, a general exposure equation might be:

$$\text{Intake} = \text{Concentration of pathogen per medium weight} \times \text{Total weight of medium} \tag{4.2}$$

The resulting number of cells or colony-forming units provides an estimate of the dose, which might have an associated probability of an adverse health effect if a dose-response relationship is available.

4.4.5 RISK CHARACTERIZATION

Risk characterization is where many of the risk manager's questions usually get answered. Risk characterization typically includes descriptions of the probability of occurrence and the severity of adverse consequences associated with hazards, as well as the magnitude of potential gains from opportunities identified based on the evidence and analysis in all the preceding steps. Risks can be characterized qualitatively or quantitatively.

Characterizations include one or more estimates of risk and their accompanying risk descriptions. A risk estimate is an estimate of the likelihood and severity of the adverse effects or opportunities, which addresses key attending uncertainties. Quantitative estimates are numerical in nature and are usually preferred over narrative qualitative estimates. Risk estimates should include all the relevant aspects of the risk, which may encompass existing, future, historical, reduced, residual, new, transformed, and transferred risks. A risk description is a narrative explanation and depiction of a risk that bounds and defines a risk for decision-making purposes. The story that accompanies the risk estimate is what places it in a proper context for risk managers and others to understand.

There are different approaches to risk characterization. The choice of an approach depends on the needs, objectives, and questions of the risk managers. Any good risk characterization will convert the scientific evidence base into a statement of risk that answers the manager's questions. It is convenient to think of the different risk characterization approaches as running along a continuum from qualitative to quantitative. Between the two lie semi-quantitative risk characterizations, which are sometimes useful.

It is during the risk characterization that the overall importance of the various uncertainties encountered throughout the risk assessment begins to come into focus. Risk characterization should include sensitivity analysis or formal uncertainty analysis commensurate with the nature of the risk assessment.

4.4.6 ASSESS EFFECTIVENESS OF RISK MANAGEMENT OPTIONS

In most cases, risk assessors will be asked to estimate risk reductions attributable to the risk mitigation options (RMOs) under consideration. In some situations, assessors or others may be asked for additional evaluations of the RMOs along with the evaluation of RMO efficacy. These evaluations might include economic costs and benefits, environmental impacts, social impacts, legal ramifications, and the like.

EXAMPLE: RISK DESCRIPTION AND RISK ESTIMATE

The 'risk per annum' is the predicted number of illnesses (gastroenteritis alone or gastroenteritis followed by septicemia) in the United States each year. As shown in the Summary Table, for each region, the highest number of predicted cases of illnesses is associated with oysters harvested in the summer and spring and the lowest in the winter and fall. Of the total annual predicted *Vibrio parahaemolyticus* illnesses, approximately 92% are attributed to oysters harvested from the Gulf Coast (Louisiana and non-Louisiana states) region in the spring, summer, and fall and from the Pacific Northwest (intertidal) region

in the summer. The lower numbers of illnesses predicted for the Northeast Atlantic and Mid-Atlantic oyster harvests are attributable both to the colder water temperatures and the smaller harvest from these regions. The harvesting practice also has an impact on the illness rate. Intertidal harvesting in the Pacific Northwest poses a much greater risk than dredging in this region (192 vs. 4 illnesses per year). This is likely attributable to elevation of oyster temperatures during intertidal exposure leading to *Vibrio parahaemolyticus* growth.”

SUMMARY TABLE

Predicted Mean Annual Number of Illnesses Associated with the Consumption of *Vibrio Parahaemolyticus* in Raw Oysters

Region	Mean Annual Illnesses ^a				
	Summer	Fall	Winter	Spring	Total
Gulf Coast (Louisiana)	1,406	132	7	505	2,050
Gulf Coast (Non-Louisiana) ^b	299	51	3	193	546
Mid-Atlantic	7	4	<1	4	15
Northeast Atlantic	14	2	<1	3	19
Pacific Northwest (Dredged)	4	<1	<1	<1	4
Pacific Northwest (Intertidal) ^c	173	1	<1	18	192
TOTAL	1,903	190	10	723	2,826

Source: Quantitative Risk Assessment on the Public Health Impact of Pathogenic *Vibrio parahaemolyticus* in Raw Oysters (FDA, 2005).

- ^a Mean annual illnesses refers to the predicted number of illnesses (gastroenteritis alone or gastroenteritis followed by septicemia) in the United States each year.
- ^b Includes oysters harvested from Florida, Mississippi, Texas, and Alabama. The time from harvest to refrigeration in these states is typically shorter than for Louisiana.
- ^c Oysters harvested using intertidal methods are typically exposed to higher temperature for longer times before refrigeration compared with dredged methods.

EXAMPLE: EFFECTIVENESS OF RMOs

SUMMARY TABLE

Predicted Mean Number of Illnesses per Annum from Reduction of Levels of Pathogenic *Vibrio Parahaemolyticus* in Oysters

Region	Predicted Mean Number of Illnesses per Annum			
	Baseline	Immediate Refrigeration ^a	2-log Reduction ^b	4.5-log Reduction ^c
Gulf Coast (Louisiana)	2,050	202	22	<1
Gulf Coast (Non-Louisiana)	546	80	6	<1

Mid-Atlantic	15	2	<1	<1
Northeast Atlantic	19	3	<1	<1
Pacific Northwest (Dredged)	4	<1	<1	<1
Pacific Northwest (Intertidal)	192	106	2	<1
TOTAL	2,826	391	30	<1

Source: Quantitative Risk Assessment on the Public Health Impact of Pathogenic *Vibrio parahaemolyticus* in Raw Oysters (FDA, 2005).

- ^a Represents refrigeration immediately after harvest; the effectiveness of which varies both regionally and seasonally and is typically approximately 1-log reduction.
- ^b Represents any process which reduces levels of *Vibrio parahaemolyticus* in oysters 2-log, for example, freezing.
- ^c Represents any process which reduces levels of *Vibrio parahaemolyticus* in oysters 4.5-log, for example, mild heat treatment, irradiation, or ultra-high hydrostatic pressure.

Typically, the existing level of risk is assessed, and if it is judged to be unacceptable, it will be reduced to a tolerable level if it cannot be eliminated. Often the unspoken “default” level of tolerable risk is as low as reasonably achievable. In other instances, risks are reduced to the point where the costs of further reductions clearly outweigh the benefits of additional risk reductions.

In some decision settings the trade-offs among risk reduction, cost, and other criteria are more complex, and an array of RMOs may be under consideration. In these situations it is usually desirable to use a “with” and “without” risk management option comparison, as described in the previous chapter, along with a more formal trade-off analysis.

Considering residual, new, transferred, and transformed risk at the time that risk reductions are estimated is likely to be efficient. In some instances, RMOs will be reasonably well formulated at the time that the risk assessment is initiated. In other situations, due to the iterative nature of risk analysis science, RMOs may not even be identified until well after the risk assessment has begun. In other cases it may not even be appropriate to begin to formulate RMOs until after the risk has been initially assessed and judged to be unacceptable. For these reasons, this RMO assessment step, often considered an integral part of risk characterization in some descriptions of risk assessment, is separated out here. Uncertainties concerning the performance or efficacy of an RMO in reducing unacceptable risks to acceptable or tolerable levels should be investigated and documented so that risk managers and other interested parties may be made aware of them.

4.4.7 COMMUNICATE UNCERTAINTY

It is not enough for risk assessors to identify and investigate the significance of the instrumental uncertainties identified throughout the risk assessment. They must communicate its significance for decision making to risk managers. Methodologies for effectively conveying information about what is known with certainty and

which remaining uncertainties could affect the risk characterization or the answers to the risk manager's questions need to be developed and carried out. When it comes to decision making, it is better to have a general and incomplete map, subject to revision and correction, than to have no map at all (Toffler 1990). But those using the risk assessment map to make decisions must know its limitations.

Characterizing the significance of the instrumental uncertainties in a risk assessment is critical to informed decision making. The NRC (1994) said, "Uncertainty forces decision makers to judge how probable it is that risks will be overestimated or underestimated." This is important for risk managers to understand, as they determine the need for and appropriate choice of an RMO.

Characterizing uncertainty can also support the informed consent of those affected by risk management decisions. When people are asked to live behind a levee or near a nuclear power plant, to get a vaccination for a seasonal flu, or to board an airplane, they have a right to know the limitations of the risk management measures taken on their behalf as well as the limitations of the information on which those measures were based. Characterizing uncertainty is essential to the transparency of a risk assessment. Transparency enhances the credibility of the process, improves the defensibility of actions taken or not taken, and empowers affected individuals to make better choices for themselves in response to the risks that remain.

Uncertainty analysis also identifies important data gaps, which can be filled to improve the accuracy of the risk assessment and, hence, support improved decision making. Risk assessors should communicate their degree of confidence in the risk assessment they have done so that risk managers can take this into consideration for decision making. To do this, risk assessors should explicitly address natural variability and knowledge uncertainty and their potential impacts on the risk estimate in every risk characterization, qualitative or quantitative. All assumptions should be acknowledged and made explicit. The impacts of these assumptions on the risk characterization and subsequently the manager's use of the risk assessment in decision making are to be thoroughly discussed. Assessors should describe the strengths and limitations of the assessment along with their impacts on the overall assessment findings. Assessors should also say whether they believe the risk assessment adequately addresses the risk manager's questions.

The International Programme on Chemical Safety (IPCS, 2008) has proposed four tiers or levels of uncertainty analysis, which provide a useful way to think about this activity. These are:

- Tier 0: Default assumptions
- Tier 1: Qualitative but systematic identification and characterization of uncertainty
- Tier 2: Quantitative evaluation of uncertainty making use of bounding values, interval analysis, and sensitivity analysis
- Tier 3: Probabilistic assessment with single or multiple outcome distributions reflecting uncertainty and variability

Each of these tiers entails different responsibilities for the risk assessors. In best practice, default assumptions will rarely be used. Uncertainty can be discussed in

the absence of quantitative data. It is always possible to tell decision makers what is known with certainty, what we suspect based on incomplete data, and what we assume based on inadequate or missing data. The key is to adopt a systematic approach to communicate the uncertainty qualitatively. This will help to ensure that the job is done adequately.

Quantitative risk assessments lend themselves to numerical characterizations of the uncertainty attending risks. Deterministic risk characterizations can be supplemented by offering high/low, optimistic/pessimistic, or more formal statistical confidence interval estimates of decision criteria and risks estimated in the assessment. Using interval estimates for uncertain inputs and tracking their impact on critical outputs is a feasible way to identify and communicate what is most important. In probabilistic risk assessment, the challenges of communication are greater, because although there is usually more useful information, it is quantitatively complex and problematic for many risk managers and stakeholders who lack training in interpreting and understanding probabilistic data. Examples of both qualitative and quantitative risk assessment techniques are found in later chapters.

The basic problem in risk assessment is that our data are incomplete and we are uncertain about many things. None of this absolves us of the need to make decisions, however. Risk assessment is a process through which complex, incomplete, uncertain, and often contradictory evidence and scientific information are made useful for decision making (NRC, 1983). As a decision-support framework, risk assessment fills the gap between the available evidence and the RMOs being considered to respond to the risks identified. Risk managers must understand those gaps, how they were bridged, and their significance for decision making. It is the assessor's job to explain all of this to them.

4.4.8 DOCUMENT THE PROCESS

Risk assessment is initiated to support decision making that solves problems and realizes opportunities. Substantial resources are dedicated to risk assessment, and it is essential that we carefully and effectively document its findings. It is equally important to document the basis for the risk management actions taken or not taken. Think of documentation as a set of different communications that authenticate and support the results of the risk management activity. The hope is that risk management decisions will be directly linked to the evidence found in the risk assessment documentation.

Assessors are well advised to document the assessment process as it progresses rather than to wait until it has been finished to write up a report. Risk assessment generally progresses in an iterative fashion. Our understanding of problems evolves as the assessment progresses. Analysis is refined as data gaps are filled and models are built. Numerous people will be involved at many points along the way. It is often easier to have assessors document their findings as they go, revising them as new data and analysis warrant. [Chapter 21](#) discusses strategies for how to tell the story of a risk assessment or other risk management activity.

TELLING YOUR STORY

Story telling is underestimated as an effective communication skill. Stop listing facts and dumping data into reports and tell a simple story well. We all remember engaging stories from our childhood and they had three key elements in common:

- An engaging beginning...once upon a time
- An interesting middle...consider a talking mirror
- A satisfying ending...they all lived happily ever after

Tell the story by structuring the facts so they have a narrative quality. Let your documentation be a journey with a narrative theme. Good stories are simple and let the facts speak for themselves.

Documentation need not be restricted to a written report. Nontraditional risk assessment documentation methods might include:

- Interactive web sites
- Interactive digital media
- Video reports
- Workshops
- Chat rooms
- Wikis
- Discussion groups
- Electronic files
- Training in the use of the risk assessment model
- Live online briefings
- Page limits on written documents

Identify your audience and choose a suitable documentation format.

4.5 RISK ASSESSMENT MODELS

The generic risk assessment tasks you've been reading about have been standardized for a variety of applications and communities of practice (CoP). The food-safety community, for example, has been aggressive in trying to harmonize risk assessment methods in part to facilitate international trade. They, like other CoPs, have promulgated models for use by their constituents. A few of these models are presented in this section to illustrate the diverse range of ways in which these rather generic risk assessment activities are being formalized for specific applications. The details of the model are less important than the overarching point that risk assessors exercise a great deal of latitude in the specific ways they do risk assessments.

The *Codex Alimentarius* represents the international food-safety community. They employ a familiar risk assessment model, shown in [Figure 4.7](#). Within or alongside

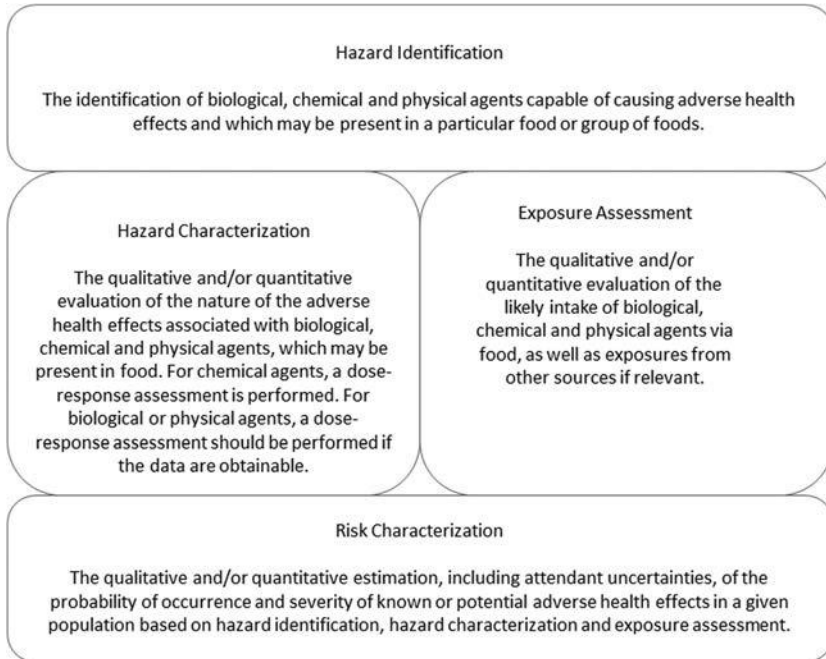


FIGURE 4.7 Generic Codex description of the risk assessment components. (Food and Agricultural Organization. 2006. *United Nations. FAO Food and Nutrition Paper 87. Food safety risk analysis: A guide for national food safety authorities*. Rome, Italy: FAO.)

of this framework, CoPs have developed distinctive models and methodologies for different hazards like food-additive chemicals, pesticides, microbiological hazards, food nutrients, antimicrobial resistance, and genetically modified organisms.

Chemical food additives are evaluated using a safety assessment, which on the surface looks quite different from the generic model of this chapter. Its six steps comprise the following: test toxicity, identify NOAEL, choose a safety factor, calculate the ADI, calculate the EDI, and characterize the risk with the ratio EDI/ADI.

A conceptual application of the model is presented in [Figure 4.8](#). Toxicity studies, most often based on animal data, are used to identify a level of exposure to a chemical, usually measured in a lifetime dose that causes no adverse effects. This is equivalent to a hazard characterization. In the example in [Figure 4.8](#), this level is 5 mg per kg of body weight daily for a lifetime.

To extrapolate from animal studies and their typically high doses to humans and their typically low doses, an uncertainty factor (in the example, 100) is used to identify an ADI. Thus, a NOAEL of 5 mg/kg/day/lifetime divided by 100 yields an ADI of 0.05 mg/kg/day/lifetime.

A survey of consumption behavior yields the daily consumption of the additive for a high-end consumer, say the 90th percentile consumer of this additive, and this is used as the EDI. This constitutes the exposure assessment. The risk characterization

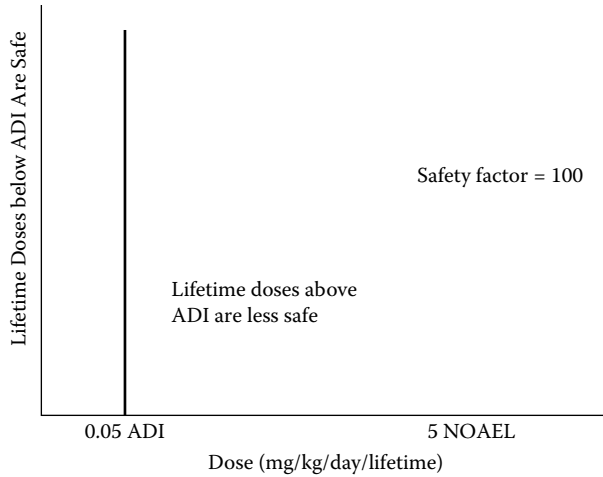


FIGURE 4.8 Representation of the food-additive safety assessment model.

is completed by simply comparing the EDI to the ADI. There is no effort to explicitly identify the likelihood of an adverse outcome in this assessment model.

Pesticide chemical risks are somewhat similar, although the language changes a little:

- Identify pesticide residue of interest
- Undertake toxicity studies of substance if needed
- Determine the NOAEL
- Select a safety factor or uncertainty factor to extrapolate results from animals to humans
- Calculate the ADI
- Identify a suitable index of residue levels to predict residue intake—usually the maximum residue limit (MRL)
- Estimate the dietary intake of the residue (exposure assessment)
- Compare exposure to ADI (when exposure exceeds ADI, some sort of risk mitigation is required)

Note that although the language differs in each, they all exhibit elements of the previously described generic process. The hazard is identified; the consequences and likelihoods (or exposures) are assessed; and it is all pulled together in some sort of characterization of the risk.

Antimicrobial-resistant risk assessment is used to evaluate the safety of new animal drugs with respect to concerns for human health. Exposing bacteria in animals to antimicrobial drugs could increase the number of resistant bacteria to the point where it reduces the efficacy of antimicrobial drugs prescribed for human health. This model, shown in [Figure 4.9](#) and taken from FDA Guidance Document 152 (FDA, 2003), suggests a qualitative approach for identifying new drugs as potentially high, medium, or low risks for human health.

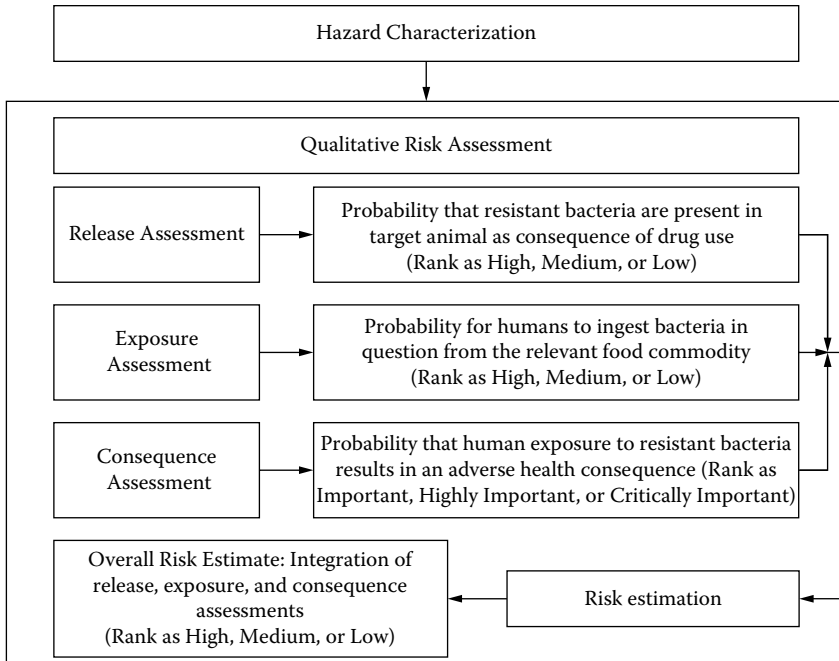


FIGURE 4.9 Components of a qualitative antimicrobial-resistance risk assessment. (Food and Drug Administration. 2003. *Guidance for Industry Evaluating the Safety of Antimicrobial New Animal Drugs with Regard to their Microbiological Effects on Bacteria of Human Health Concern. No. 152*. Rockville, MD: Center for Veterinary Medicine. <http://www.fda.gov/downloads/AnimalVeterinary/GuidanceComplianceEnforcement/GuidanceforIndustry/UCM052519.pdf>.)

Food safety is not the only COP to have developed standardized mental models to guide thinking about risk assessment. The U.S. EPA (1998) developed the model shown in Figure 4.10 for ecological risk assessment. Note that it differs from the four-step definition of the “Red Book” but has clear roots in that model as well. The “Red Book” model was developed principally for assessing human health risks due to chemicals in the environment. The ecological model expands the notion of hazards to include a broad class of stressors and it includes adverse effects on ecosystems. It has three main steps: problem formulation, analysis, and risk characterization.

Hazards are identified as stressors in problem formulation. The analysis step is divided into characterizations of exposure and ecological effects, the latter of which is evocative of the hazard characterization step. The risk characterization step serves the familiar purpose. The point here is that although the models vary in their language and details, they remain firmly committed to the principles articulated in the tasks identified earlier in this chapter.

If you search Internet images using the phrase “risk assessment model,” you’ll see thousands of different models in millions of hits. Many risk assessment problems are so unique that they cannot be usefully fit to any of the existing mental models for risk assessment. It is always wise to familiarize yourself with any standardized

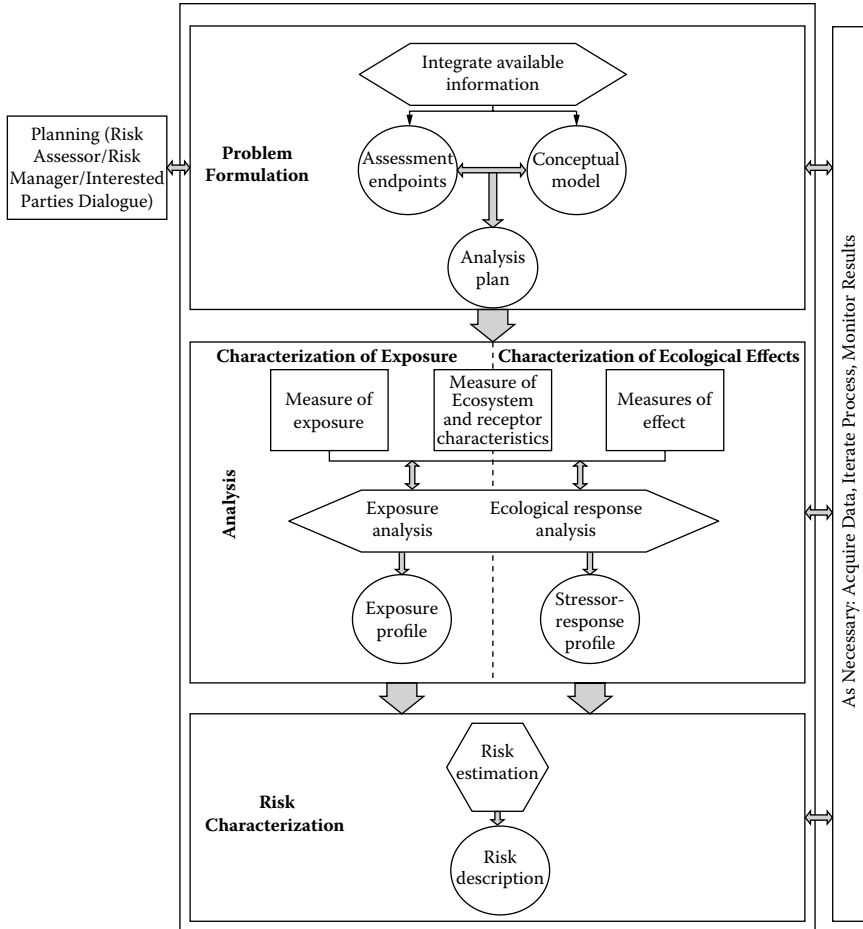


FIGURE 4.10 Ecological risk assessment framework, with an expanded view of each phase. (From Environmental Protection Agency. 1998. *Federal Register* 63 (93): 26846–26924.)

assessment models used by your CoP. More importantly, you should always feel free to adapt these models or to develop your own mental model when it suits your decision-making needs to do so. If you flounder at times, keep coming back to the four informal questions: What can go wrong? How can it happen? What are the consequences? How likely is it? Find a way to ask and answer these questions and you will be doing risk assessment, formal model or not.

Very often an organization has a model with a well-established structure. Consider the model in Table 4.1, which is used to estimate the costs of a dredging project that includes marsh creation for disposal of the dredged material. It is not difficult to imagine that risk managers may be concerned with the risk of a cost overrun. There is no need here to develop a conceptual model. In this instance, the structure of the model is well established and we need only reach into the risk assessor’s toolbox for the appropriate techniques for assessing this risk using our four informal questions.

TABLE 4.1
Channel Modification Dredging Cost Estimate

Account Code	Description	Quantity	Unit	Unit Price	Amount
01	Lands and damages	0	LS	—	—
02	Relocations				
	Lower 20 pipeline, 653 + 00	427	LF	\$843.66	\$359,979
	Remove 8" pipeline, 678 + 00	986	LF	\$47.85	\$47,197
02	<i>Total—relocations</i>				\$407,176
06	Fish and wildlife facilities (mitigation)				
	Oyster reef creation	0	ACR	—	—
06	<i>Total—fish and wildlife facilities (mitigation)</i>				—
12	Navigation, ports, and harbors				
	Mobe and demobe	1	LS	\$500,000	\$500,000
	Pipeline dredging, Reach 1	576,107.00	CY	\$2.43	\$1,398,788
	Pipeline dredging, Reach 2	1,161,626.68	CY	\$2.76	\$3,209,691
	Pipeline dredging, Reach 3A	1,532,227.12	CY	\$3.72	\$5,693,450
	Pipeline dredging, Reach 3B	708,252.02	CY	\$2.89	\$2,049,398
	Scour pad, Reach 1	16,484	SY	\$16.62	\$273,906
	Geotubes, 30', Reach 1	1,345	LF	\$221.03	\$297,192
	Geotubes, 45', Reach 1	4,601	LF	\$291.00	\$1,338,995
	Scour pad, Reach 3	39,059	SY	\$16.62	\$649,029
	Geotubes, 45', Reach 3	13,848	LF	\$291.00	\$4,029,879
12	<i>Total—navigation, ports, and harbors</i>				\$19,440,328
	<i>Subtotal</i>				
30	Engineering and design	8%			\$1,587,800
31	Construction management	6%			\$1,190,850
	<i>Total project cost</i>				\$22,626,154

Abbreviations: LF = linear feet; LS = lump sum; CY = cubic yards; SY = square yards, ACR = acres.

For now it is sufficient to understand that there is a large class of problems that require no specific risk assessment model. Often it is sufficient to pay appropriate attention to the uncertainty that has always been present in our work. In many instances, risk assessment can mean doing what you have always done, with the exception of paying close attention to the things you do not know. Using the generic risk assessment activities described here should provide you with a serviceable model when a formal one is not available.

4.6 RISK ASSESSMENT METHODS

Any self-contained systematic procedure conducted as part of a risk assessment is a risk assessment method (Covello and Merkhofer, 1993). These methods are conveniently divided into qualitative and quantitative methods. There has been

a misperception on the parts of some and a bias on the parts of others who have suggested that qualitative risk assessment is not a valid form of risk assessment. I think it fair to say that quantitative risk assessment is preferred whenever there are data adequate to support it. It is equally fair to say that qualitative risk assessment is a valid and valuable form of risk assessment. Quantitative assessments use numerical expressions to characterize the risks, qualitative assessments do not. Examples of each are provided in later chapters.

4.6.1 QUALITATIVE RISK ASSESSMENT

The fundamental need is to manage risk intentionally and to do that better than has been done in the past. Quantitative risk assessment is not always possible or necessary, so qualitative risk assessment is often a viable and valuable option. It is especially useful:

- For routine noncontroversial tasks
- When consistency and transparency in handling risk are desired
- When theory, data, time, or expertise are limited
- When dealing with broadly defined problems where quantitative risk assessment is impractical

A qualitative risk assessment process compiles, combines, and presents evidence to support a nonnumerical estimate and description of a risk. Numerical data and analysis may be part of the input to a qualitative risk assessment, but they are not part of the risk characterization output. Qualitative assessment produces a descriptive or categorical treatment of risk information. It is a formal, organized, reproducible, and flexible method based on science and sound evidence that produces consistent descriptions of risk that are easy to explain to others. Its value stems from its ability to support risk management decision making. If you can answer the risk manager's questions adequately and describe the risk in a narrative or categorically, then a qualitative assessment is sufficient. Uncertainty in qualitative assessments is generally addressed through descriptive narratives. Several specific qualitative risk assessment methodologies can be found in [Chapter 10](#).

4.6.2 QUANTITATIVE RISK ASSESSMENT

Quantitative risk assessment relies on numerical expressions of risk in the risk characterization. Numerical measures of risk are generally more informative than qualitative estimates. When the data and resources are sufficient, a quantitative assessment is preferred, except where the risk manager's questions can be adequately answered in a narrative or categorical fashion.

Quantitative assessments can be deterministic or probabilistic. Deterministic assessments produce point estimates of risks. Probabilistic assessments rely on probability distributions and probability statements to estimate risks. The choice depends on the risk manager's questions, available data, the nature of the uncertainties, the skills of the

assessors, the effectiveness of outputs in informing and supporting decision makers, and the number and robustness of the assumptions made in the assessment.

Generally, quantitative risk characterizations address risk management questions at a finer level of detail and resolution than a qualitative risk assessment. This greater detail usually introduces a more sophisticated treatment of the uncertainty in the risk characterization than is found with qualitative assessment.

4.7 SUMMARY AND LOOK FORWARD

Risk assessment is where the evidence is gathered. It is the primary place where we separate what we know from what we do not know and then deal intentionally with those things we do not know. It is where we get the right science focused into the analysis and take pains to get that science right.

In general terms, risk assessment is the work you must do to answer four informal questions. What can go wrong? How can it happen? What are the consequences? How likely is it? The four primary steps that comprise a risk assessment and answer these questions are: identify the hazards and opportunities, assess the consequences, assess the likelihood, and characterize the risk. There are any number of application-specific refinements of these notions in widespread use. Recurring kinds of problems lend themselves well to the development of standardized approaches to assessing these risks.

In the best practice of risk assessment, risk managers will identify specific questions they want the risk assessment to answer. Risk assessors answer these questions and characterize the uncertainty in their assessment in ways that support risk-informed decision making. The answers to these questions can be provided in a qualitative or a quantitative manner, depending on the needs of the risk management activity.

Estimating and describing risks in the risk assessment is the critical analytical step in risk analysis. But if we are not able to communicate this often complex information to risk managers, stakeholders, and the public, all will have been for naught. The next chapter addresses the risk communication component of risk analysis. Until relatively recently, risk communication has been treated like the stepchild of risk analysis, too often an afterthought or an add-on. More recently it has begun to receive more of the attention it rightfully deserves.

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5 Risk Communication

5.1 INTRODUCTION

Risk communication is one of the three components of risk analysis. It is now prominently featured in most risk analysis models. Let me summarize the history of risk analysis in three nonscientific figures, seen in [Figure 5.1](#).

An ideal balance of the three risk analysis tasks is shown in the figure on the bottom left. Here the three tasks are coequal, with modest overlap but functional integrity. Not so long ago, risk analysis might have been described by the figure on the top left. Risk assessment was the tail wagging the dog. Risk management was an afterthought, and risk communication was scarcely on the horizon. In fact, there were many models of risk analysis that did not even mention it! Risk communication was for years the bastard child of risk analysis, seldom talked about and often ignored or treated poorly. Other than a few devoted adherents, it struggled for any recognition at all.

In the recent past, risk management has grown in importance and stature, and the descriptive model might be that shown on the top right of [Figure 5.1](#). While risk management came of age and now guides risk assessment, risk communication too often remained the weak link in actual practice. That always comes at a cost. Because of those costs, risk communication is finally coming into its own, and it is now increasingly recognized in models and, more importantly, by organizations as being at least as important as the assessment and management tasks. Like the other components, its definition is difficult to pin down in words that will satisfy everyone. The term means different things to different people, and a wide variety of definitions can be found in the literature and organizational guidance of different institutions.

Despite the variations in definitions, there is a growing consensus on a set of core principles for risk communication that include the following:

- It is an interactive exchange of information and opinion.
- It takes place throughout the risk analysis process.
- It concerns risk, risk-related factors, and risk perceptions.
- It involves risk assessors and risk managers as well as affected groups and individuals and interested parties.
- It includes an explanation of the risk, an explanation of the risk assessment, and the basis for the risk management decision.

There are many reasons to communicate about risks, including the goals of achieving a consensus understanding of the magnitude of the risk and developing credible and acceptable risk management responses. Risk communication improves understanding of the risk and risk management options (RMOs). It enhances trust

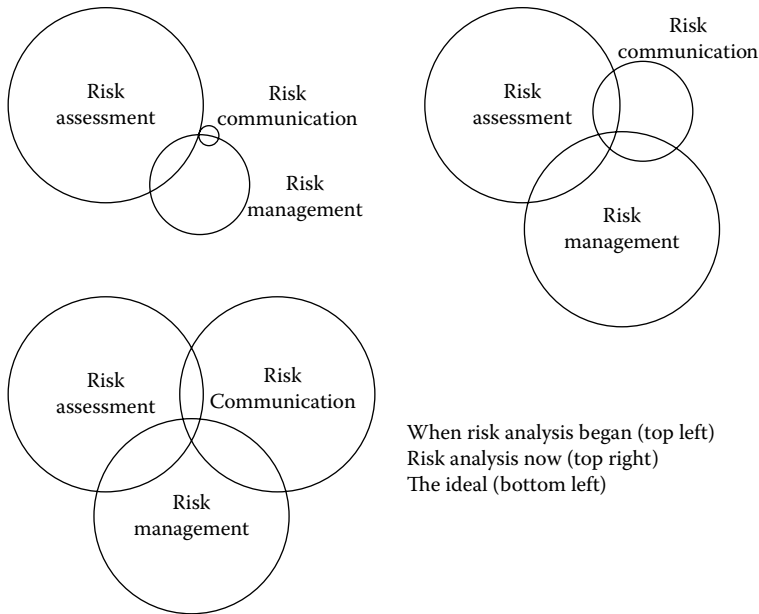


FIGURE 5.1 The role of risk communication in risk analysis.

and confidence in the decision-making process and promotes the participation and involvement of interested parties. Done well, it can strengthen working relationships among stakeholders.

Risk communication is needed to explain actions to avoid or take risks, and it is needed to explain the rationale for the chosen RMO. The effectiveness and workings of a specific option need to be communicated to people so they understand their own risk management responsibilities and know what actions they must take to reduce the risk. The benefits of an RMO as well as the costs of managing the risk and who will bear them, are additional information to be conveyed to interested parties. Risk communication needs to pay special attention to describing the risks that remain after the RMO is implemented. The uncertainty that could affect the magnitude of the risk or the efficacy of the RMO must be carefully communicated to stakeholders and the public. This should include the weaknesses, limitations of, or inaccuracies in the available evidence. It should also include the important assumptions on which risk estimates are based so that stakeholders can understand the sensitivity of both risk estimates and the efficacy of an RMO to changes in those assumptions and how those changes can affect risk management decisions. It should include a description of the range of outcomes that can result from a risk management decision.

Risk communication does not require everyone to reach a consensus or an agreement. Neither is it intended to get everybody on the “same page.” It is, however, about providing people with meaningful opportunities for input before decisions are made and for feedback as evidence is accumulated. It is about listening to and

understanding people’s concerns so they can be considered in decision making and so the public will respect the process even if they disagree with some of its decisions and outcomes.

Risk communication theory and practice are well documented in a very rich risk communications literature. For example, see the works by Chess et al. (1989, 1994), Covello and Mumpower (1985), Covello and Allen (1988), Covello and Cochrane (1989), Covello and Merkhofer (1993), Covello and Sandman (2001), Covell (2002), Covell et al. (1988, 1989, 2001), Fischhoff (1986, 1995), Fischhoff et al. (1978), Hance et al. (1990), Johnson et al. (1987), Krinsky et al. (1988), Sandman (1987, 1989, 1999, 2004, 2010a, 2010b, 2010c), Sandman et al. (2003, 2005), Slovic (1987), Slovic et al. (1980, 1990), and others presented in the references at the end of this chapter. How one frames the risk communication component for the purposes of risk analysis is of some importance because the scope and role of risk communication is rapidly advancing. To some, the risk communication component is relatively narrow and focuses on risk and crisis communication. I think this is far too narrow a definition, even while recognizing its adequacy for many situations. A more proactive expanded view of risk communication is provided in [Figure 5.2](#).

Risk communication can first be split into internal and external tasks. Internal risk communication takes place within the risk analysis team. It begins with the coordination between the assessors and managers that has been described in the previous two chapters. This aspect of risk communication is arguably little different from the kind of good organizational communication that is part of any effective organization’s management philosophy. I make a distinction here because risk

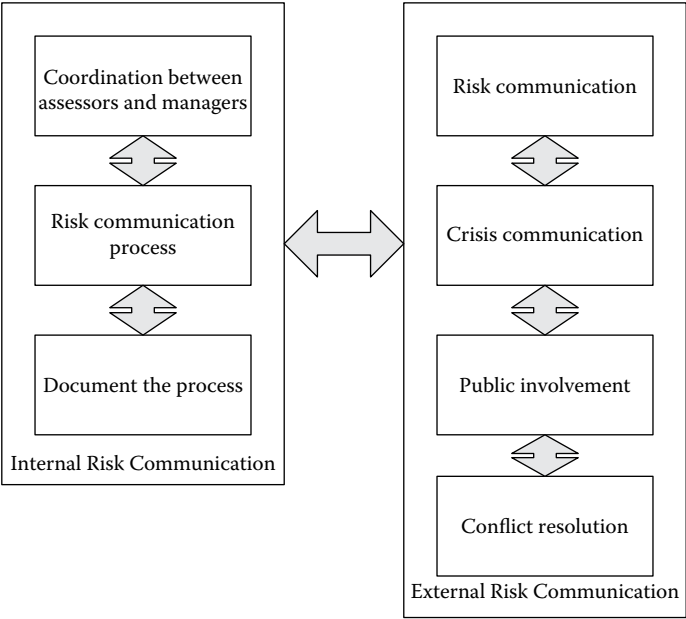


FIGURE 5.2 Components of the internal and external risk communication tasks.

management involves communicating about uncertainty, and talking about what we do not know is not something many organizations do well. The coordination is ongoing throughout a risk management activity.

Developing and conducting an effective risk communication process is not something that happens by accident. Good risk communication cannot be an afterthought or an add-on. Neither is it a hypodermic needle injection into the activity at prescribed or periodic points in time. It needs to be a dynamic ongoing process. To be so, it must be designed.

BEST PRACTICES FOR RISK COMMUNICATION

1. Infuse risk communication into policy decisions.
2. Treat risk communication as a process.
3. Account for the uncertainty inherent in risk.
4. Design risk messages to be culturally sensitive.
5. Acknowledge diverse levels of risk tolerance.
6. Involve the public in dialogue about risk.
7. Present risk messages with honesty.
8. Meet risk perception needs by remaining open and accessible to the public.
9. Collaborate and coordinate about risk with credible information sources.

Source: Effective Risk Communication: A Message-Centered Approach (Sellnow et al., 2009).

Documenting the process is usually described (including in this book) as a management or assessment process, and it is. There is little that is more fundamental to the internal risk communication process, however, than documenting the results of the activity and the decisions made from them. These internal risk communication tasks are often given little attention in the literature, which tends to favor the external risk communication processes shown on the right side of [Figure 5.2](#).

Most texts on risk communication focus on risk and crisis communication, as will this chapter. Nonetheless, my work with risk analysis organizations around the world suggests that there is a growing recognition of the need to expand the public's role in the risk analysis process. It makes sense to me to expand the definition of risk communication activities to include public involvement and, in some cases, conflict resolution activities; however, I am not sure there is anything close to a consensus on that idea just yet.

The chapter begins with definitions. It then briefly considers the three internal risk communication tasks of [Figure 5.2](#). It moves into the area of external risk communications and begins a discussion of risk and crisis communications by considering the important distinction between the hazard and outrage dimensions of risk, which interact to define very distinct risk communication strategies.

perceptions, the next topic, are important for understanding the disconnect between producers and consumers of risk information.

Just as strategies for risk communication vary, so do the audiences for these strategies. The next discussion covers the importance of knowing the psychographic characteristics of the audiences for your communications. A basic communication model is presented to lay the framework for emphasizing the role of stress in risk communication, followed by an introduction to the three M's of risk communication. Some of the critical differences between crisis and risk communication are considered before the chapter turns to the challenge of explaining risk to nonexperts. This leads into a discussion about explaining uncertainty, a task as critical to risk assessors and risk managers as it is to risk communicators. The chapter ends with a short consideration of public involvement and conflict resolution.

To prepare you for what follows I offer two key words. The keyword for the internal risk communication task is uncertainty. The keyword for the external risk communication task is emotion. Get a handle on how to communicate uncertainty to people who are feeling strong emotions and the efficacy of your risk communication efforts will improve dramatically.

5.2 DEFINITIONS

No one formal definition of risk communication will meet the needs of all practitioners of risk communication. The *Codex Alimentarius* offers a definition that is quite expansive. It says risk communication is “the interactive exchange of information and opinions throughout the risk analysis process concerning risk, risk-related factors and risk perceptions, among risk assessors, risk managers, consumers, industry, the academic community and other interested parties, including the explanation of risk assessment findings and the basis of risk management decisions” (FAO, 2004).

COMMUNICATING WITH THE PUBLIC: 10 QUESTIONS TO ASK

1. Why are we communicating?
2. Who is our audience?
3. What do our audiences want to know?
4. What do we want to get across?
5. How will we communicate?
6. How will we listen?
7. How will we respond?
8. Who will carry out the plans? When?
9. What problems or barriers have we planned for?
10. Have we succeeded?

Source: Chess & Hance (1994).

A shorter and simpler definition from the U.S. Department of Agriculture is also useful. Risk communication is “an open, two-way exchange of information and opinion about risk leading to better understanding and better risk management decisions” (University of Minnesota, 2006). An informal definition is implicitly offered by the 10 questions shown in the text box. Risk communication is the work you have to do to answer those 10 questions.

5.3 INTERNAL RISK COMMUNICATION

5.3.1 COORDINATION BETWEEN ASSESSORS AND MANAGERS

The internal risk communication task is essential to ensure effective interaction between managers and assessors. Three rules of thumb are suggested for this task for the managers and assessors:

- Collaborate early
- Coordinate often
- Cooperate always

Early risk analysis experience and, subsequently, models showed the need to separate the roles of managers and assessors. In their zeal to ensure the integrity of the science-based foundation of risk analysis, some early practitioners were somewhat manic about this separation and stretched it almost to the point of no contact. That is most emphatically not best practice. Although the integrity of the science needs to be relentlessly protected, managers and assessors need to interact constantly throughout the risk analysis process despite the fact that they have very clear and different individual responsibilities.

Referring to the risk management activities described in [Chapter 3](#), the extent of the interaction between risk assessors and risk managers is suggested below using a scale of no, minimal, moderate, and maximum interaction based on the author’s experience:

1. Problem identification
 - a. Problem recognition: *moderate interaction*
 - b. Problem acceptance: *no interaction*
 - c. Problem definition: *maximum interaction*
2. Risk estimation
 - a. Establish risk analysis process: *minimal interaction*
 - b. Develop a risk profile: *maximum interaction*
 - c. Establish risk management objectives: *moderate interaction*
 - d. Decide on the need for risk assessment: *no interaction*
 - e. Request information: *moderate interaction*
 - f. Initiate risk assessment: *moderate interaction*
 - g. Coordinate the conduct of the assessment: *moderate interaction*
 - h. Consider the results of the assessment: *maximum interaction*

3. Risk evaluation
 - a. Is the risk acceptable: *no interaction*
 - b. Establish tolerable level of risk: *moderate interaction*
 - c. Risk management strategies: *maximum interaction*
4. Risk control
 - a. Formulating risk management options (RMOs): *maximum interaction*
 - b. Evaluating RMOs: *moderate interaction*
 - c. Comparing RMOs: *moderate interaction*
 - d. Making a decision: *no interaction*
 - e. Identifying decision outcomes: *moderate interaction*
 - f. Implementing the decision: *no interaction*
5. Monitoring
 - a. Monitor: *moderate interaction*
 - b. Evaluate: *moderate interaction*
 - c. Modify: *moderate interaction*

Turning to the risk assessment activities of [Chapter 4](#) and using the same subjective scale, the author's judgments are:

1. Understand the question(s): *maximum interaction*
2. Identify the source of the risk: *moderate interaction*
3. Consequence assessment: *no interaction*
4. Likelihood assessment: *no interaction*
5. Risk characterization: *no interaction*
6. Assess effectiveness of RMOs: *moderate interaction*
7. Communicate uncertainty: *maximum interaction*
8. Document the process: *moderate interaction*

Some of the most critical points of interaction occur at the beginning and end of the risk management activity. Identifying problems, objectives, and the initial list of questions together are essential early interactions, as is preparing a risk profile. These tasks will also provide stakeholders with opportunities for input and feedback in best-practice risk communication.

Revising the risk assessment questions together, when necessary, is an especially important interaction. This clarifies the information needs of the risk managers and is an essential step in managing the expectations of both managers and assessors. Interaction is clearly needed to set reasonable assessment schedules, budgets, and milestones together. The two parties are to do their own jobs, but they should brief each other often. After the risk assessment is completed, understanding the results of the assessment and significant uncertainties together are critical interactions. Interaction continues, but the manager's role increases relative to the assessor's after the assessment is completed. The risk manager's role is preeminent when asking, "Is the current level of risk acceptable" or "What level of risk is tolerable?"

Managers and assessors should formulate risk management options together. They also need to coordinate the evaluation of options together to ensure that

managers have the information they need to decide which measures are best. This may happen before, during, or after the risk assessment. Assessors are responsible for the analytical work in the evaluation of RMOs, while risk managers do the deliberating in these tasks.

To a great extent, this internal communication task is just good organizational management. It is not unique to risk analysis. What is somewhat unique in risk analysis is the role of communicating effectively about those things that are uncertain and potentially important for decision making.

5.3.2 RISK COMMUNICATION PROCESS

Designing the external risk communication process, outlined in the remainder of this chapter, is a critical part of the risk analysis team's internal communications task. Creighton's (2005) book on public participation provides an excellent blueprint for those looking to provide a larger and more active role for the public. A narrower and more traditional risk communication program can be designed following the templates in risk communication handbooks like those of Lundgren and McMakin (2009) and Heath and O'Hair (2009).

5.3.3 DOCUMENTING THE PROCESS

Telling the story of the risk management process and the risk assessment is also an important part of the internal risk communication task. The decision process must be carefully documented to provide a defensible rationale for actions taken or not taken as a result of the risk analysis process. Risk managers, ideally with the assistance of risk communication experts, should carefully plan the documentation of the process. This topic, introduced in [Chapter 3](#), is taken up at length in [Chapter 21](#), which is devoted to telling the risk story.

5.4 EXTERNAL RISK COMMUNICATION

The external communication tasks generally describe how the risk analysis team (managers, assessors, and communicators) interacts with their various publics and external stakeholders. These interactions can overlap with the internal tasks, as may be the case for identifying problems and objectives as well as preparing the risk profile and the initial list of questions, when external input is likely to be important. The extent to which this may happen will depend on how involved the public is in the risk management activity. Four broad tasks have been identified as part of the external risk communication process. These are:

- Risk communication
- Crisis communication
- Public involvement
- Conflict resolution

An external communication program will not always require all four elements. For the purposes of the current discussion we will focus narrowly on a more traditional

risk communication process and will return to considerations of public involvement and conflict resolution at the end of the chapter.

GOALS OF RISK COMMUNICATION

1. Promote awareness and understanding of the specific issues under consideration during the risk analysis process, by all participants.
2. Promote consistency and transparency in arriving at and implementing risk management decisions.
3. Provide a sound basis for understanding the risk management decisions proposed or implemented.
4. Improve the overall effectiveness and efficiency of the risk analysis process.
5. Contribute to the development and delivery of effective information and education programs, when they are selected as risk management options.
6. Foster public trust and confidence in the safety of the food supply.
7. Strengthen the working relationships and mutual respect among all participants.
8. Promote the appropriate involvement of all interested parties in the risk communication process.
9. Exchange information on the knowledge, attitudes, values, practices, and perceptions of interested parties concerning risks associated with food and related topics.

Source: The Application of Risk Communication to Food Standards and Safety Matters, a Joint FAO/WHO Expert Consultation (UN, 1998).

The external risk communication process can have many different goals. Three reasonably common, if not universal, generic goals (Food Insight 2010)* are:

1. Tailor communication so it takes into account the emotional response to an event.
2. Empower the audience to make informed decisions.
3. Prevent negative behavior and encourage constructive responses to crisis or danger.

Unlike the basic unidirectional, “We tell them what we did” communication model, risk communication is two-way (listening and speaking) and multidirectional. It uses multiple sources of communication, and it actively involves the audience as an information source. Risk analysts can learn from individuals, communities, and organizations.

* I would like to acknowledge the Food Insight materials, sponsored by the International Food Information Council Foundation, as a major source of information for much of the discussion in Section 5.4 of this chapter.

The desired outcomes of effective risk communication will vary from problem to problem, but there are some generic outcomes that recur with regularity. First, it can decrease deaths, illness, injury, and other adverse consequences of risks by informing people and changing behaviors. Alternatively, it can increase the positive outcomes of opportunities. It fosters informed decision making concerning risk and empowers people through useful and timely information to make their own informed decisions. It prevents the misallocation and wasting of resources and keeps decision makers well informed. Good risk communication builds support for risk management options and can aid the successful implementation of an RMO. It also can counter or correct rumors.

Risk communication is not spinning a situation to control the public's reaction, nor is it public relations or damage control. It is more than how to write a press release or how to give a media interview. It is not always intended to make people "feel better" or to reduce their fear. It is multidirectional communication among communicators, publics, and stakeholders that considers human perceptions of risk as well as the science-based assessment of risk. It includes activities before, during, and after an event. It is during these activities that risk communication can broaden to include public involvement. Risk communication is an integral part of an emergency response plan. Aware of the many dimensions of risk communication, let us drill down a little deeper to understand it better.

5.4.1 RISK AND CRISIS COMMUNICATION

This section covers the first two elements of the external risk communication task. The discussion begins with some important background information that addresses the dimensions and perceptions of risk before it turns to the importance of knowing and engaging one's audiences. The value of psychographic information is considered as a lead-in to the consideration of risk, stress, and the communication model. The three M's of risk communication are then discussed. Risk and crisis communication are juxtaposed for distinction, and then the discussion turns to the challenges of explaining risk and uncertainty to nonexperts.

5.4.1.1 Risk Dimensions

Virtually everything we do involves risk, and zero risk is unachievable in both our personal and professional lives. Risk communication is complicated by the fact that people interpret risk in very different ways, especially experts and the public. Risk involves both facts and feelings, and these competing dimensions of risk—the objective vs. the subjective—give rise to some unique communication challenges.

Peter Sandman (1999) describes these two elements of risk as hazard and outrage (see text box). These two elements shape the perceptions of risk. In general, hazard (the something that can go wrong, its factual consequences, and the likelihood of it happening) is what the assessors and scientists are primarily concerned with. Experts think about these hazards, and they know things that others do not. Predictive microbiologists know the conditions under which a pathogen may grow or die off. Engineers understand the hydrographs of rivers. Financial advisers understand the

subtle details of their derivatives. Toxicologists know how much of a chemical is toxic. Most of the rest of us do not know these things.

HAZARD AND OUTRAGE

Let's divide the "risk" that people are worried about into two components. The technical side of the risk focuses on the magnitude and probability of undesirable outcomes: an increase in the cancer rate, a catastrophic accident, dead fish in the river, or a decline in property values. Call all this "hazard."

The non-technical side of the risk focuses on everything negative about the situation itself, as opposed to those outcomes. Is it voluntary or coerced, familiar or exotic, dreaded or not dreaded? Are you trustworthy or untrustworthy, responsive or unresponsive? Call all this "outrage"

Source: (Sandman, 1999).

The public is concerned less with the science, numbers, and facts of the risk and more with the personal and social context of the risk. The public feels things about the risks, and they believe things to be true or not, often without respect to the facts of a situation. The public is less concerned with the details of the probabilities than they are with a subjective evaluation of the relative importance of what might be lost. They do not care about pathogen growth; they care that their daughter got sick. They could care less about the hydrograph; they do care that their first floor was damaged by the flood. The details of the derivatives are of less interest than the college fund that was lost.

These two distinct dimensions of a risk can lead to a disconnect between the scientist/risk professional and the public. Scientists tend to focus on what they know and think, while the public focuses on what they feel and believe. Both dimensions of a risk are important, but for different reasons. They are very different aspects of a risk. Sometimes the public worries when perhaps the scientists would say they shouldn't, for example, about irradiated foods. Other times they may not worry about things scientists think they should be worried about, for example, the oncoming hurricane.

Risk communication that is based wholly on explaining the facts of the risk may well miss the greater concerns of the public, which tend to be the social context and personal meaning of the risk. There is a whole lot more to risk communication than explaining the results of your risk assessment. This disconnect between producers (scientists) and consumers (the public) of risk information gives rise to four kinds of risk communication strategies (adapted from Sandman and Lanard, 2003), as shown in [Figure 5.3](#).

When people are outraged but the actual hazard is low, the appropriate communication strategy is outrage management. Its goal is to reduce outrage so people don't take unnecessary precautions. The opposite situation—when the danger is high but the public is not very concerned—is precaution advocacy. Its goal is to increase concern for a real hazard in order to motivate people to take preventive action.

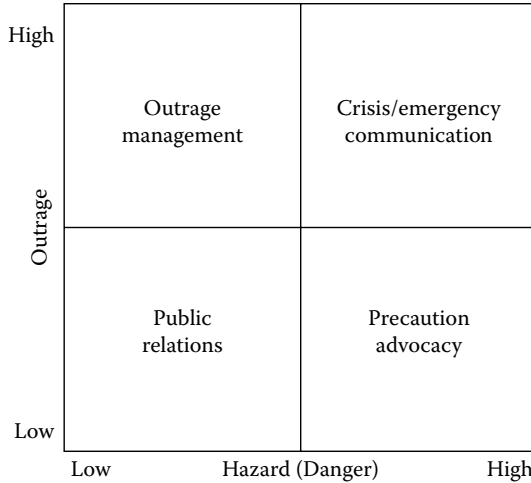


FIGURE 5.3 Four different types of risk communication strategy. (From Sandman and Lanard 2003. *Fear of fear: The role of fear in preparedness...and why it terrifies officials.* Peter M. Sandman Risk Communication web site. <http://www.psandman.com/col/fear.htm>.)

When both the outrage and danger are high, crisis communication is in order. It acknowledges the hazard, validates the concerns of the public, and gives people effective ways to act to manage their risk. Situations of low hazard and low outrage are well served by ordinary public relations communications. These communications are brief messages that reinforce whatever appeals are most likely to predispose the audience toward your goals.

These different situations and their associated strategies give rise to an obvious need to understand the perceptions of the public. Risk professionals who do not realize that the public perceives risks differently than they do are in danger of choosing an ineffective risk communication strategy.

5.4.1.2 Risk Perceptions

What scares people the most? What kinds of conditions increase stress and anxiety? The public takes a rather complex array of factors into account when they form their perception of a risk. The correlation between hazard or actual danger and the public’s outrage is not always as high as we might like. Psychometric research has done a great deal to help explain this disconnect.

In the 1980s, Slovic published seminal research in the perception of risk that helped explain people’s extreme aversion to some risks and their indifference to others. Fifteen risk characteristics were identified, but many of them proved to be highly correlated to one another, so they were consolidated via factor analysis into two factors called “dread risk” and “unknown risk” (Slovic, 1987; Slovic et al., 1980). As the names suggest, characteristics describing the extent to which the consequences of a risk are dreadful comprise one factor, while characteristics capturing the unknown nature of a risk comprise the other.

TABLE 5.1
Factors that Increase or Decrease Dread and Unknown Aspects of Risk Consequences

Increases Dread	Decreases Dread
Uncontrollable	Controllable
Dread	No dread
Global catastrophic	Not global catastrophic
Fatal consequences	Nonfatal consequences
Not equitable	Equitable
Catastrophic	Individual
High risk to future generations	Low risk to future generations
Not easily reduced	Easily reduced
Risk increasing	Risk decreasing
Involuntary	Voluntary
Increases Unknown	Decreases Unknown
Not observable	Observable
Unknown to those exposed	Known to those exposed
Delayed effect	Immediate effect
New risk	Old risk
Risk unknown to science	Risk known to science

Source: Slovic, P. 1987. *Science* 236 (4799): 280–285.

Slovic’s (1987) research showed that the dread and unknown factors increased or decreased for risks with the characteristics in [Table 5.1](#). Furthermore, research at the time suggested that risks with a high unknown factor were perceived as riskier. [Figure 5.4](#) shows a mapping of the cognitive perceptions of Slovic’s subjects. Although it is not a universal mapping, it does provide some insight into the nature of risk perception when combined with the information in [Table 5.1](#).

Since that groundbreaking research, a number of other outrage factors have been found to affect both the perception and acceptability of risks. Some of them are effects on children, the manifestation of effects, trust in institutions, media attention, accident history, benefits associated with the risk, reversibility of effects, origin (natural risks are more acceptable than human-made risks), memorability, moral relevance, and the responsiveness of the risk management process. The riskier a situation “feels” based on these kinds of characteristics, the less acceptable or the more unacceptable it is in people’s perceptions.

5.4.1.3 Know and Engage Your Audience

“Audience” is a tricky word; it suggests a one-way communication in its common usage. Here it is used to identify a particular group of the public that will be the target of a risk communication activity. I will use “public” to mean the collection of all audiences.

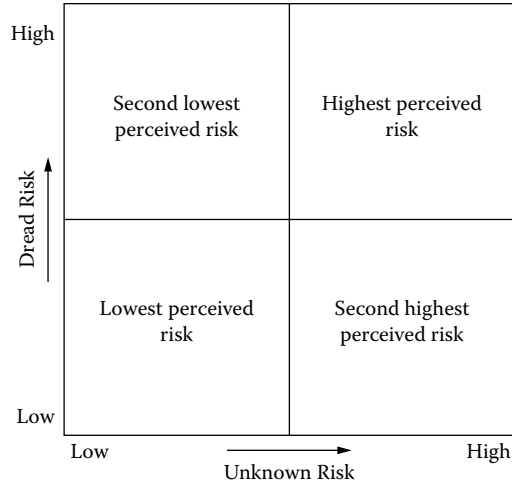


FIGURE 5.4 The effect of dread and the unknown on risk perceptions.

There are many different kinds of audiences, and some will be more difficult to persuade or communicate with than others. Take care to avoid the mistake of thinking you have one monolithic audience. Government, industry, academia and research institutions, media, consumers and consumer organizations, and the general public might comprise your audiences. Within the general public are many audience subpopulations that vary based on such things as family situations, locations, education, professions, physical differences, cultural differences, generational differences, language differences, social status, past experience with the risk, prior knowledge of the topic, attitudes toward the responsible organization, belief systems, and so on. Covello and Cohrssen (1989) offered seven rules for engaging the audience that have stood the test of time. They are summarized here to help guide your risk communication efforts.

5.4.1.3.1 Rule 1: Accept and Involve the Public as a Legitimate Partner

People expect the opportunity to participate in decisions that affect their lives in a democracy. Risk communicators must demonstrate respect for the public; they are going to hold you accountable. Do not attempt to diffuse the public's concern or to preempt any action they may be inclined to take. Instead, aim to develop an involved, interested, reasonable, thoughtful, solution-oriented, and collaborative public-involvement program. Involve people early and in meaningful ways. For example, there may be an important role for the public when preparing the problems-and-opportunities statement, the objectives-and-constraints statement, and the list of questions risk assessment is to answer. If so, that involvement must be planned from the beginning of the risk management activity. This planning is work that would be done as part of the second task in the internal risk communication process (see [Figure 5.2](#)).

5.4.1.3.2 *Rule 2: Plan Carefully and Evaluate Your Efforts*

You need different communication strategies for different audiences and situations; these strategies must be carefully planned. Begin your communication planning with clear and explicit objectives. Be sure to evaluate your information ahead of time; know its weaknesses as well as its strengths.

Use an effective spokesperson with good presentation and interaction skills. Prepare two or three talking points, word them simply, and learn them cold. Pretest your message whenever it is possible to do so. Pretest with typical people, not activists or community leaders. Always pretest your message before going on television. Then carefully evaluate your efforts and learn from your mistakes.

5.4.1.3.3 *Rule 3: Listen to Your Audience*

Listen to the audience if you expect them to listen to you. Identify their concerns. They are often more concerned with fairness, trust, credibility, competence, control, caring, and voluntariness than they are with the details of your risk assessment.

Do not assume what people know, think, or want done about the risks. Find out what they are thinking. Never walk into a meeting with no preparation. Use interviews and focus groups to learn. Arrive early to meetings and mingle to find out what people are thinking. Let all interested people be heard. People come to the table with prior life experience, beliefs, personal knowledge, and values. They can be a valuable source of information, especially about social values. Recognize the public's emotions and let them know you have heard them and understand their concerns.

5.4.1.3.4 *Rule 4: Be Honest, Frank, and Open*

Trust and credibility are your most important assets. If you lose them, they are difficult to regain. State your credentials, but do not expect them to validate you. If you do not know the answer to a question, do not fake it. Admit you do not know and get back to them with an answer.

Give people risk information as soon as possible. Do not speculate about or distort the level of risk. Admit mistakes when you make them. Be sure to discuss uncertainties and the strengths and weaknesses of your data. If you must err, err on the side of sharing too much information rather than too little.

5.4.1.3.5 *Rule 5: Coordinate and Collaborate with Other Credible Sources*

Avoid conflicts with other credible sources of information. Allies can make the risk communication task easier. Develop relationships with other sources of risk information, preferably in advance of a crisis. Coordinate your messages so the public hears a consistent interpretation of the situation. Determine who is best able to answer questions about risk and let them speak.

Never be blindsided by new information. Monitor the public media on your issue as well as your technical sources. Avoid public disagreements but acknowledge uncertainty when it leads to different interpretations. If others do not coordinate their message with yours, do not argue; be respectful to the other party, but state your position clearly as well as your reasons for it.

5.4.1.3.6 *Rule 6: Meet the Needs of the Media*

The media are a major channel for disseminating risk information. They are essential to your ability to tell your story and to get information out to your audiences. The media are usually not out to get you; they are out to get a story, so don't be the story. Be accessible to the media and understand their needs for simplicity, conflict, and a "hook" for stories. Supply a hook the media can use. Prepare media materials in advance and tailor them to the specific type of media you use. They should be sufficient for a reporter to tell the whole story in print, video, or audio.

It is wise to establish long-term relationships with media representatives well in advance of a crisis. If a reporter uses you as a reliable source when they need one, they're more likely to come to you when you need to get word out.

5.4.1.3.7 *Rule 7: Speak Clearly and with Compassion*

Risk assessment is science-based, but communication is not. Avoid technical language, jargon, and acronyms. Use simple, nontechnical language and be sensitive to local norms and expectations about speech and dress. Use concrete, relevant, and simple examples. Vivid metaphors and effective risk comparisons can help to put risks in perspective. People respond better to stories than to theories or a recitation of facts. Tell stories but be consistent with your message.

SOURCES OF STAKEHOLDER ANGER

Fear
Threat to self
Threat to family
Frustration
Feeling powerless
Feeling disrespected
Feeling ignored

Source: Risk Communication, Applications, and Case Studies (Neeley, n.d..)

Be sure to respond to emotions that people express, for example, fear, anger, helplessness, outrage. When responding to emotional outbursts and histrionics, never cut someone off. Speak with them gently. Convey empathy for the person's response while at the same time expressing skepticism over inaccurate things that may have been said. This is not the time to challenge core community attitudes and beliefs!

Never restate a problem in objective terms without the emotional content. Regain control of the discussion by restating the concerns expressed. Watch your body language; it is the greater part of communication.

5.4.1.4 Psychographic Information

Psychographics is the use of demographics to study and measure attitudes, values, lifestyles, interests, beliefs, and opinions, usually for marketing purposes.

Psychographics can also help you deal with your different audiences and to construct messages. For example, some psychographic measures with significance for risk communication are self-esteem, involvement, anxiety, fear, and trust.

Self-esteem embodies our feelings of self-worth and the effectiveness of our own actions. Risks that deal with our health or well-being will be perceived through the lens of our self-esteem. Self-esteem, through its self-efficacy dimension, can affect our perceptions of risk management options like weight loss, exercise, and changes in personal behavior. Groups or individuals with low self-esteem present unique risk communication challenges.

The theory of vested interest (Crano and Burgoon, 2001) identifies four levels of involvement that reflect the degree of concern an audience has regarding a risk. These are:

- Value-relevant involvement
- Outcome-relevant involvement
- Impression-relevant involvement
- Ego-relevant involvement

When people are involved in an issue because it is relevant to their value system, they can be hard to persuade if the situation challenges their values, especially highly engrained ones. To succeed in communication with these groups, your message must reflect their values.

Those involved in an issue because of the personal consequences (i.e., outcome) of the issue can be persuaded if they believe what you propose is in their best interest. The key to the risk communication message is to show them how the topic affects their personal interest and is in their best interest.

Impression-relevant involvement stems from behaviors that serve to create or maintain a specific image of the individual. This self-image tends to inhibit change in general. Effective risk communication must ensure the audience that the actions you want them to take are not silly and that people will not think less of them because they took them.

When a person's involvement is motivated by ego, that person can be difficult to persuade. Messages that threaten the ego evoke defensive reactions, and defensiveness causes people to disparage the source of the message. Consequently, it is important to avoid insulting people.

When the risk is perceived as high and efficacy is perceived as low, anxiety results. The good news is that anxious people are motivated to seek information. The bad news is that anxiety interferes with our ability to process information.

Fear and trust are adaptive survival processes. Fear rises rapidly and is slow to cease. It is easily reestablished. Trust, on the other hand, is slowly acquired and easily destroyed. Once destroyed, it is very difficult to reestablish.

Sandman and Lanard (2003, 2005) suggest that reactions change with the perception of risk, as shown in [Figure 5.5](#), and that humans usually adapt well to risk. As the perception of the risk increases, our reactions progress from acceptance through fear, denial, and finally panic. Panic, however, is a rare response.

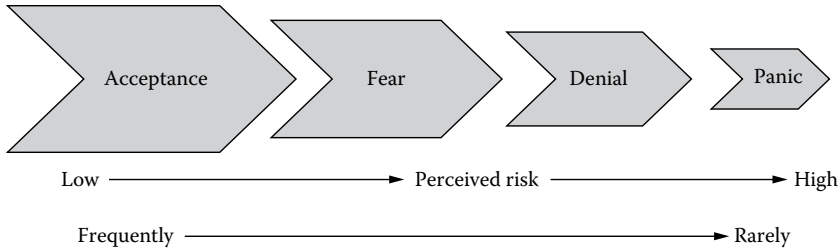


FIGURE 5.5 Progression of our reactions to a perceived risk. (From Sandman, P.M. and J. Lanard 2003. *Fear of fear: The role of fear in preparedness...and why it terrifies officials*. Peter M. Sandman Risk Communication web site. <http://www.psandman.com/col/fear.htm>; Sandman, P.M. and J. Lanard 2005. *Adjustment reactions: The teachable moment in crisis communication*. Peter M. Sandman Risk Communication web site. <http://www.psandman.com/col/teachable.htm>)

Fear is an adjustment reaction that is natural in a crisis. Sandman and Lanard (2005) say that fear:

- Is automatic
- Comes early
- Is temporary
- Is a small overreaction
- May need guidance
- Serves as a rehearsal
- Reduces later overreaction

Smart risk communicators know this and encourage, legitimize, ally with, and guide these adjustment reactions.

Overreacting to a risk is a natural first reaction when it is new and potentially serious. Typically, we will pause, become hypervigilant, personalize the risk, and take extra precautions that are at worst unnecessary and at best premature.

When this fear grows it leads to denial, which is less common than fear but more dangerous because it keeps people from taking precautions. Risk communication can reduce denial by legitimizing the fear, taking action by doing something, and empowering people to decide how to respond by providing them with a range of actions they can take.

Panic is a sudden strong feeling of fear that prevents us from reasonable thought or action. Panicky feelings are not unusual, but actual panic is quite rare. We often worry that providing people with unfavorable information or that presenting them with a dire scenario will result in “panic.” This can lead communicators to withhold information or to overassure people. The orderly evacuation of the World Trade Center Twin Towers on September 11, 2001, and the January 15, 2009 emergency water landing of a jetliner in the Hudson River, provide vivid examples of how rare panic really is. Most people can cope with and manage their fear. Risk communicators can help mitigate the fear and anxiety by empowering people with information that builds

self-efficacy—“This is what you can do...”—and that assures them that response will work. Fearful people need information they can process easily; that means nothing complicated. Keep the message sensitive and simple. Give anxious people specific instructions. Repeat the message as often as possible.

5.4.1.5 Risk, Stress, and the Communication Model

Communicating to an emotional and possibly untrusting or, worse, distrustful audience is one of the most difficult tasks you may ever face. Do it well and life may not be simple, but it will be a whole lot easier than if you do it poorly. The basic communication model includes the following components:

- *Sender*: communicator
- *Receiver*: public, partners, stakeholders
- *Channel*: medium used to convey information
- *Message*: content presented
- *Feedback*: receiver’s response message
- *Noise*: barriers that may interfere with reception (e.g., physical, receiver’s stress level)
- *Environment*: time and place

During normal risk communication situations when stress is low, trust in the communicator is based on that person’s level of competence and expertise. Covello’s research (2002) indicates that as much as 85% of trust may be based on these credentials (see [Figure 5.6](#)).

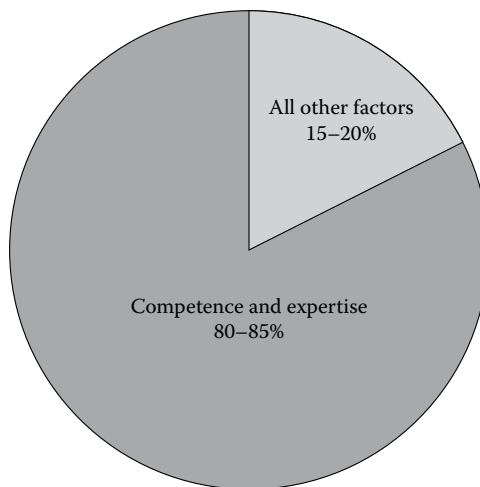


FIGURE 5.6 Trust factors in low stress situations. (From Covello V. 2002. Message mapping, risk and crisis communication. *Invited paper presented at the World Health Organization Conference on Bioterrorism and Risk Communication*, Geneva, Switzerland. http://www.orau.gov/cdcynergy/erc/Content/activeinformation/resources/Covello_message_mapping.pdf)

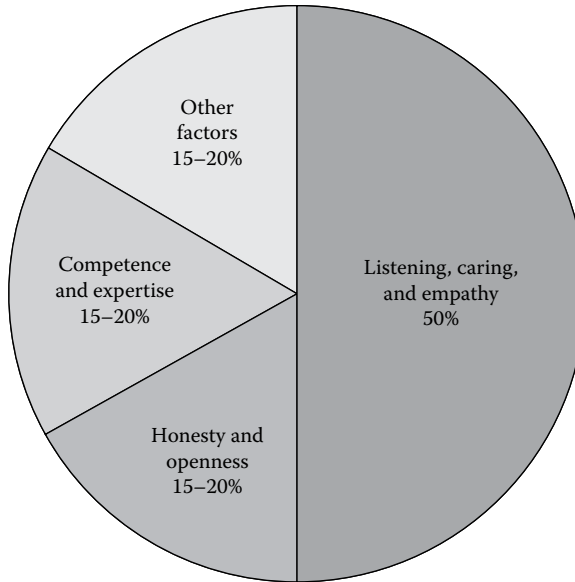


FIGURE 5.7 Trust factors in high stress situations. (From Covello V. 2002. Message mapping, risk and crisis communication. *Invited paper presented at the World Health Organization Conference on Bioterrorism and Risk Communication*, Geneva, Switzerland. http://www.orau.gov/cdcynergy/erc/Content/activeinformation/resources/Covello_message_mapping.pdf)

When risks are perceived as high or in crisis situations, communication takes place in high-stress circumstances. Trust factors change rather dramatically during times of high stress, as seen in [Figure 5.7](#). Competence and expertise become far less important, while listening, caring, and empathy become the primary factors for establishing trust. Honesty and openness also appear as important factors. These trust factors are routinely assessed within the first 30 seconds of communication. There is no second chance during stressful circumstances.

The basic communication model changes during high-stress conditions, as summarized in [Table 5.2](#). The effectiveness of the sender now depends on credibility and trust. The receiver's ability to process complex information is reduced, so the messages must be simplified. Feedback is essential to gauging the public's response.

People process information very differently during high-stress situations. We can handle fewer bits of information at a time, and we process it in a different order. Newspapers tend to write for an eighth-grade reading level. If that is the average grade, then during high-stress situations, information is processed at a fourth-grade level.

Mental noise caused by the stress of fear impedes the receiver's ability to accurately process information. To counteract these changes, risk communicators should:

- Simplify the message by lowering the reading level.
- Reduce the number of message points to a maximum of three.
- Use short sentences.

TABLE 5.2
Communication Shifts in Low- to High-Stress Situations

Low Stress	High Stress
Process an average of seven messages	Process an average of three messages
Information processed linearly (1, 2, 3)	Information processed in primacy (1, 3, 2) or recency order (3, 2, 1)
Information processed at average grade level	Information processed at 4 levels below average grade
Focus on competence, expertise, knowledge	Focus on listening, caring, empathy, compassion

Source: Covello, V. 2002. Message mapping, risk and crisis communication. *Invited paper presented at the World Health Organization Conference on Bioterrorism and Risk Communication*, Geneva, Switzerland. http://www.orau.gov/cdcynergy/erc/Content/activeinformation/resources/Covello_message_mapping.pdf

- Use numbers carefully.
- Use pictures or graphics to present ideas.

RECOMMENDED TIME LIMITS

- 20 minutes combined for all speakers at a public meeting
- 2 minutes to answer a question at a public meeting
- 8–10 second soundbites for answering media questions during an interview
- 3 minutes for interacting with the public for every minute you speak

Source: Eisenberg and Silverberg (2001).

5.4.1.6 Three M's of Risk Communication

Given the potential role of stress in risk communication, there are three categories of tools to consider in risk communication. Referred to as the *three M's of risk communication* (Eisenberg and Silverberg, 2001), they are:

- *Message:* What to say
- *Messenger:* Who should say it
- *Media:* How it should be presented

5.4.1.6.1 Message

There can be many different purposes for a risk communication (Fulton and Martinez, n.d.), including:

- Raising awareness
- Educating/informing

- Achieving consensus
- Changing behavior
- Changing perception
- Receiving input

The message needs to be consistent with your purpose.

During the initial stages of message development, there are three helpful questions (Eisenberg and Silverberg, 2001) to consider:

1. What are the three most important things you would like your audience to know?
2. What three things would your audience most like to know?
3. What are the three points your audience is most likely to get wrong unless they are emphasized and explained?

Avoid messages that convey only technical facts. Convey empathy, caring, honesty, openness, dedication, and commitment in your verbal and nonverbal messages. To maximize the information your audience hears, understands, and remembers:

- Structure and organize your message.
- Limit your information to three key messages.
- Keep your messages short.
- Present each message in 7–12 words followed by two to four supporting facts.
- Repeat your key messages: Tell them what you are going to tell them; then tell them; and finally tell them what you told them.

5.4.1.6.2 *Messenger*

The best spokesperson is not always the topic expert. You need someone who can show empathy, stay organized, understand the audience, and speak clearly—someone with credibility and expertise. Credible speakers have the requisite expertise, but they are also trustworthy and likeable. They are similar to the audience and communicate well nonverbally. Recall that credibility is based on the mix of trust factors identified previously and in the following paragraphs. Expert speakers have advanced knowledge and/or degrees in the area they are speaking about, and they speak with authority, assured in their knowledge. However, the best messenger in a low-stress situation may not be the best messenger in a high-stress situation.

People need to know that you care before they will care about what you know. Active listening skills including paraphrasing, providing active feedback, and controlling nonverbal cues are an important part of being perceived as a trustworthy speaker.

To be trustworthy, be balanced. Focus on a specific issue. Pay attention to what the audience already knows and be respectful in tone, recognizing the legitimacy of people's feelings and thoughts. Be honest about the limits of scientific knowledge.

AVOID

Humor
Negative terms
Guarantees and absolutes
Complex language
Jargon
Personal beliefs
Attack
Worst case speculation
Numerical details

Source: Eisenberg and Silverberg (2001).

If you make a promise or a commitment, keep it. Come early and stay late. Engage people one on one. Provide a phone number and an e-mail address where you can be reached.

BODY LANGUAGE

- Make eye contact while slowly sweeping the room
- Avoid darting eyes or staring
- Keep your hands open at about waist level
- Don't cross your arms, make a fist, clasp your hands, put your hands in your pockets or make large waving hand movements
- Lean slightly forward from the waist
- Avoid slouching and standing or sitting rigidly

Source: Eisenberg and Silverberg (2001).

Limit your use of notes and show a high level of organization and logic. Dress professionally; avoid over- or underdressing. Be assertive and avoid hedging. Make sure the audience knows your credentials.

5.4.1.6.3 Media

How will you be presenting the information? Media comprise vehicles, channels, and applications for your message appropriate to your audience. Communication vehicles may be written, oral, visual, interactive, computer-based, experiential, or technology-assisted. Channels include media, advertising, public meetings, one-on-one opportunities, Internet, word of mouth, speaker bureaus, and the like. Examples of applications include such things as fact sheets, pamphlets, reports, news releases, newsletters, web pages, Wiki spaces, public notices, flyers, posters, exhibits, videos, journal articles, fact sheets, tweets, and so on.

Message media are chosen on the basis of impact and influence. Impact refers to how widespread the impact of your message will be, while influence refers to

the kind of persuasive influence (e.g., credibility) the channel has. The choice of channel goes back to knowing your audience. Where are they? How do you reach them? Where do they get their information? Do they read newspapers, listen to radio and watch TV, or do they text, tweet, use instant message, e-mail, cruise the Internet, and rely on reference groups for information? Your message must meet them where they are.

5.4.1.7 Critical Differences in Crisis Communication

Risk communication has been defined in various ways, but most definitions include some version of a two-way exchange of information and opinion about risks. We have seen previously that when hazard and outrage are both high, we are often engaging in a crisis communication strategy. Glik (2007) defines crisis communication more narrowly as “the exchange of risk-relevant and safety information during an emergency situation.” The primary purpose of crisis communication is to motivate the audience to action.

The communication goals are different for more routine risks than for crises. Risk communication addresses what could go wrong and how it could happen. Crisis communication deals with what is happening right now. A crisis is a dynamic, usually unexpected event that involves a significant threat, ongoing uncertainty, and greater intensity than longer-term risk situations (Sellnow et al., 2009). There is not time for many of the best-practice techniques described in the risk communication literature during a crisis. The coordination, collaboration, consensus building, issue resolution, and public-involvement interactions often prescribed will not likely be possible.

CONSEQUENCES OF POOR CRISIS COMMUNICATION

- People may not make good choices or may make them too late.
- Public frustration (or outrage) may develop—once the public reaches an “outrage” state, it is very difficult to go back. Messages may be misinterpreted or misunderstood, causing bad feelings.
- The public may start to mistrust the organization.

Source: Risk Communication, Applications, and Case Studies (Neeley, n.d.).

Whereas risk communication can be planned, tested, and strategic, crisis communication is spontaneous. Risk communication usually takes place before an event occurs, while crisis communication is postevent. The risk communication model is multidirectional, proactive, and relatively certain. In a crisis, communication is unidirectional, reactive, and far more equivocal. Seeger and Ulmer (2003) summarize some other potential differences between the two strategies, as shown in [Table 5.3](#).

The person who is a good public relations communicator or even a good risk communicator may not be the best crisis communicator. The outrage can be expected to be greater, but the three M's still apply.

TABLE 5.3
Differences between Risk Communication and Crisis Communication

Risk Communication	Crisis Communication
Risk-centered: focuses on harm or risk occurring in the future	Event-centered: focuses on a specific event that has occurred and produced harm
Messages may include known probabilities of negative consequences and how they may be reduced	Messages address current state or conditions: Magnitude, immediacy, duration, control/remediation, cause, blame, consequences
Based on what is currently known	Based on what is known and what is not known
Long term (pre-crisis stage)	Short term (crisis stage)
Message preparation possible (campaign)	Less preparation (responsive)
Personal scope	Community or regional scope
Mediated: commercials, ads, brochures, pamphlets	Mediated: press conferences, press releases, speeches, web sites
Controlled and structured	Spontaneous and reactive

Source: Seeger, M.W. 2002. *Public Relations Review* 28 (4): 329–337.

5.4.1.8 Explaining Risk to Nonexperts

Explaining risk data is not the primary purpose of risk communication, but sometimes it is necessary. Risk assessors have to explain the risk to risk managers. Nonexpert stakeholders and the general public are also going to need scientific and technical information from time to time. There are three principles (Sandman, 1987) for accomplishing this difficult task: simplify, personalize, and use risk comparisons.

5.4.1.8.1 Simplify

The challenge is to make hard ideas clear. The best way to do this is to simplify the language rather than the content. You cannot tell the public everything you know, so we need some guidelines for deciding what to say and what to leave out. Sandman and Lanard (2003) suggest three rules of thumb for deciding what gets included and what gets left out.

First, tell people what they need to know. Answer their questions. Provide instructions for coping with a crisis. Stress these things. Second, tell people what they have to know to both understand and feel that they understand the information they are given. The trick here is to know what the audience might get wrong and provide the information that prevents that error. Testing messages is especially useful in this task.

Third, help people understand that there is more than what you are telling them so that additional information at a later date won't make them feel misled. You are building a framework to support an evolving understanding of the problem.

Explaining risk is difficult because people prefer hearing about things that are safe or dangerous. The public is more comfortable with these extremes. To avoid them, risk trade-offs and risk comparisons may be useful.

Although the nature of the risk may, itself, be complex and uncertain, people can understand risk trade-offs, risk comparisons, and risk probabilities when they are

carefully explained. Because of the way risk is perceived, the public can be expected to be resistant to the idea that their risk is modest when they are outraged or that it is substantial when they are not. In the long run, effective risk communication relies more on effective ways of addressing the anger, fear, powerlessness, optimism, and overconfidence of the public than it does on finding clever ways to simplify complex information.

The risk information you do prepare is most likely to reach the public through the mass media. Consequently, you are often simplifying risk information for journalists. Journalists are going to simplify the information for their readers. You are more likely to get a better result if you simplify complex information for them than you will if you give them the complex information to simplify. This is especially true for broadcast media that rely on short sound bites.

The greater concern then becomes to avoid oversimplifying the information and misleading the audience. Both your integrity and the public's trust are at stake. The key is to be prepared in advance of this communication with mass media. Know precisely what it is you want the journalist and their audience to take away from your message. In a crisis, you may have little time to prepare, but take the time you have and use it to prepare. If a journalist takes a different approach to the story, you can then quickly answer the less relevant question and follow with the longer prepared answer to the question that "should" have been asked. Alternatively, you are prepared to suggest a focus for the story or interview.

Make fact sheets part of your preparation. This can clarify your most important points without oversimplification. The greatest challenge is when reporters are demanding more information than you have and everyone is hurrying to respond to the crisis. In that case, be honest and warn reporters that you are in a rush and qualify your remarks by acknowledging that you are simplifying the response; then provide an overview of the sort of information you lack or are omitting for the sake of simplification.

Think about the things people are most likely to get wrong about your message and then provide information to prevent this mistake or discuss the mistake directly. As you and the public find out more about the situation, you want to make sure your simplification holds up as solid and accurate rather than as misleading. There is nothing wrong with being incomplete. Being incorrect is another matter.

5.4.1.8.2 Personalize

Make it personal, and the public is much more likely to understand the risk. Experts tend to gravitate toward the big (societal) picture and policy issues, while the audience for your risk information is interested in the smaller (personal) picture and their own options. Individual voluntary decisions are very different from social policy decisions. Ordering the city of Galveston, Texas, to evacuate is a fundamentally different kind of decision than deciding that you want to leave the island. You may be more concerned about the societal risk, but you should be prepared to talk about both.

It helps to understand the reporter's or the audience's viewpoint. Personalizing the issue brings it to life. It makes the abstract concrete. A focus on real people making

real decisions is the best way to personalize a risk. The personal judgments of the experts are often a powerful indicator for the public.

PERSONALIZE

“Persons not heeding evacuation orders in single family, one-, or two-story homes will face certain death.”

National Weather Service
Hurricane Ike warning for Galveston
September, 2008.

“The best way to guard against the flu is to get vaccinated, which helps to protect you, your loved ones, and your community.”

CDC official
Seasonal flu vaccination
September, 2006.

Sometimes the scientist must go against their instinct for the sake of good risk communication. Science is devoted to abstraction and deriving principles and theories from data. The public, on the other hand, wants concrete, specific, and personal information, especially when it comes to novel risks. Examples, anecdotes, and images help to personalize a risk.

Compare a leaking landfill to coffee grounds, a flood to a bathtub overflow, finding the source of a food-borne disease outbreak to finding a needle in a haystack. Good communication relies on vivid and memorable examples and images.

5.4.1.8.3 Risk Comparisons

Risk comparisons are controversial. Some experts like to avoid them; others embrace them as a useful tool for explaining risk to nonexperts. The alternative—providing the risk estimate details—is often not practical. In general, the public does not understand the scale or the units of measurement. What is 7×10^{-7} ? Who knows what a picocurie is or what CFS or CFU mean? For that matter, who knows if a milliliter is a little or a lot? Worse, the consequences and endpoints are often intimidating, threatening, or unattractive. Flesh-eating bacteria, increased lifetime risk of cancer, lost life expectancy, disease, habitat destruction, and so on, are hard to understand and unpleasant to contemplate.

The challenge is to find a middle ground between safe and dangerous and to present scientific facts that are comprehensible to the audience. Risk comparisons are an option. They help make risk numbers more meaningful and put risks into perspective by comparing this risk to other risks. Covello et al. (1988) have

RISK COMPARISONS CAN HELP WHEN...

1. The source of the comparison has high-credibility and is more or less neutral.
2. The situation is not heavily laden with emotion.
3. The comparison includes some acknowledgment that factors other than relative risk are relevant, that is, the comparison does not dispose of the issue.
4. The comparison aims at clarifying the issue, not at minimizing or dismissing it.

Source: Covello et al. (1988).

developed a taxonomy of risk comparisons that provides a useful guide to this option:

- The most acceptable risk comparisons are:
 - Comparisons of the same risk at two different times
 - Comparisons with a standard
 - Comparisons with different estimates of the same risk
- Less desirable risk comparisons are:
 - Comparisons of the risk of doing something versus not doing it
 - Comparisons of alternative solutions to the same problem
 - Comparisons with the same risk as experienced in other places
- Even less desirable risk comparisons are:
 - Comparisons of average risk with peak risk at a particular time or location
 - Comparisons of the risk from one source of a particular adverse effect with the risk from all sources of that same adverse effect
- Marginally acceptable risk comparisons are:
 - Comparisons of risk with cost, or of one cost/risk ratio with another cost/risk ratio
 - Comparisons of risk with benefit
 - Comparisons of occupational risks with environmental risks
 - Comparisons with other risks from the same source
 - Comparisons with other specific causes of the same disease, illness, or injury
- Rarely acceptable risk comparisons are:
 - Comparisons of two or more completely unrelated risks
 - Comparison of an unfamiliar risk to a familiar risk

Concrete examples of these can be found at <http://www.psandman.com/articles/cma-4.htm>.

SCALE COMPARISONS

One-in-a-million: One drop of gasoline in a full-size car's tankful of gas

One-in-a-billion: One four-inch hamburger in a chain of hamburgers circling the earth at the equator two and half times

One-in-a-trillion: One drop of detergent in enough dishwater to fill a string of railroad tank cars 10 miles long

One-in-a-quadrillion: One human hair out of all the hair on all the heads of all the people in the world

Source: Covello et al. (1988).

Comparisons must be relevant to your audience. Those rarely acceptable risk comparisons often turn out to be false arguments, based on a flawed premise. Risks have certain contextual characteristics for the audience, as we saw in the discussion of risk perceptions. The comparisons should not contradict any of the important risk characteristics. In other words, do not compare a familiar risk to an unfamiliar one or a voluntary risk to an involuntary one, and so on. The risk comparisons must be appropriate and truly comparable in the eyes of the audience. Use them with caution.

5.4.1.9 Explaining Uncertainty

Sometimes risk assessors are the risk communicators. There will always be uncertainty in risk assessment. When explaining uncertainty to risk managers, the job falls to the assessors. When explaining uncertainty to the public, professional risk communicators may be involved. In either case there are a number of simple rules of thumb (Sandman 2010a,c) that will make the task easier.

TWELVE TIPS FOR EXPRESSING UNCERTAINTY

1. Ride the risk communication seesaw.
2. Try to replicate in your audience your own level of uncertainty.
3. Avoid explicit claims of confidence.
4. Convert expert disagreement into garden-variety uncertainty.
5. Make your content more tentative than your tone.
6. Show your distress at having to be tentative and acknowledge your audience's distress.
7. Explain what you have done or are doing to reduce the uncertainty.
8. Do not equate uncertainty with safety—or with danger.
9. Explain how uncertainty affects precaution-taking.

10. Don't hide behind uncertainty.
11. Expect some criticism for your lack of confidence.
12. Don't go too far.

Source: Sandman (2004).

Acknowledge uncertainty from the outset. Do not wait for someone else to discover what you do not know. Bound your uncertainty with a range of possibilities that are credible.

Clarify that you are more certain about some things than others. Tell people:

- What you know for sure
- What you think is almost but not quite certain
- What you think is probable
- What you think is a toss-up
- What you think is possible but unlikely
- What you think is almost inconceivable

Tell people what has been done and what you continue or plan to do to reduce the uncertainty. If you are going to be unable to reduce the uncertainty further, say so. Report everyone's estimates of critical uncertain values, not just your own. Never hide behind uncertainty. If the existence of a problem is uncertain but likely, say so. Neither should you perpetuate uncertainty. If there are things you can do to answer the uncertain questions, do them.

No evidence of an effect is not evidence of no effect. Be especially careful not to say there is no evidence of a particular effect if you have not looked for the evidence.

Let people know when finding out for sure is less important than taking appropriate precautions now. Acknowledge that people disagree about how to respond to uncertainty and that different people may do different things. "Based on the information available I have decided I will not get the swine flu shot, but my wife is going to." Help people become involved in reducing uncertainty for themselves. Give them ways to learn about their own vulnerability. Tell them how to learn about their flood risk; let them know how to get up-to-the-minute information about the neighborhoods that may be affected by the spill. Show them how to find the batch number and date on the recalled peanut butter, and so on.

Research shows that acknowledging uncertainty diminishes the perception of your competence while it increases people's judgment of your trustworthiness. Rarely do we say things like:

I have no idea if the side effects of the swine flu vaccine are more or less dangerous than the risks of going unvaccinated. Because of the speed with which the vaccine was developed, no one has any data to estimate that yet.

The source of this latest outbreak of salmonellosis is not yet known; the evidence is mixed and very confusing.

Experts rarely say they do not know something, and they probably should do so far more often. No one likes to sound ignorant, so we often focus on what we do know, inadvertently leaving out important or useful information about what we do not know. Consequently, experts may sound more certain than they really are. If you sound certain and turn out to be wrong, credibility and trust can be grievously wounded. The best way to ensure that the media do not make you sound more certain than you are is to proclaim your uncertainty. Indeed, part of the risk assessor’s/communicator’s job is to be more precise about uncertainty and the level of confidence in their results and in what they are saying.

Another human trait is to be biased toward providing too much reassurance. Optimism is one of our fundamental biases. Uncertainty is not symmetrical: We tend to underplay negative outcomes and overplay positive ones.

5.4.2 PUBLIC INVOLVEMENT

As noted earlier, public/stakeholder involvement is sometimes considered part of risk communication and sometimes seen as a separate process. Its basic purpose is often to increase awareness or to build public support for a course of action. Public involvement is not going to be required for all risk management activities, whereas some amount of risk communication may be. Consequently, we will restrict our consideration of the topic to a brief review of some public-involvement practices.

The reasons for involving the public in a risk management activity vary, as shown in the public-involvement continuum in [Figure 5.8](#) (Creighton, 2005). The extent of the participation process varies with its purpose. Informing the public is far less intensive than is partnering and developing agreements.

Commonly stated goals for a public-involvement program include the following:

- Incorporate public values into decisions
- Improve the substantive quality of decisions
- Resolve conflict among competing interests
- Build trust in institutions
- Educate and inform the public

That the public should have a say in decisions that affect their lives is one of the core values of public involvement. The risk analysis team needs to seek out

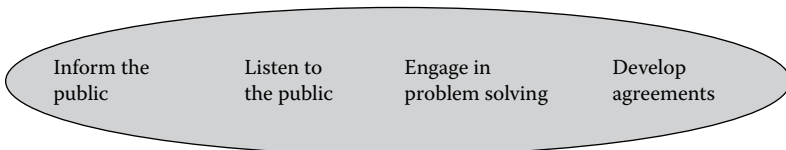


FIGURE 5.8 Varying intensity of different public-involvement activities. (From Creighton, J.L. 2005. *The Public Participation Handbook: Making Better Decisions through Citizen Involvement*. San Francisco: Jossey-Bass.)

and involve those potentially affected by the subject risks and their management decisions. In a good public-involvement program, the public’s contributions will help define the problems and the risk management objectives. They will have the opportunity to exchange information and opinions and influence decisions. A good public-involvement program communicates how that will happen. The program should convey the interest of the decision makers while it simultaneously meets the process needs of participants. The best programs let participants help define how they will participate.

Involving the public improves the quality of decisions and, through consensus building, it also minimizes cost and delay that can result from processes that exclude the public and leave them no option for participation other than adversarial ones. Public involvement builds trust and helps an organization maintain its credibility and legitimacy. A program that anticipates public concerns and attitudes is easier to implement.

5.4.2.1 Planning Stakeholder Involvement

Creighton (2005) offers a blueprint for developing a public-involvement program, which is summarized in Figure 5.9, where SH stands for stakeholder. The first step is the analysis of the decision context, a subject that was covered in Chapter 3.

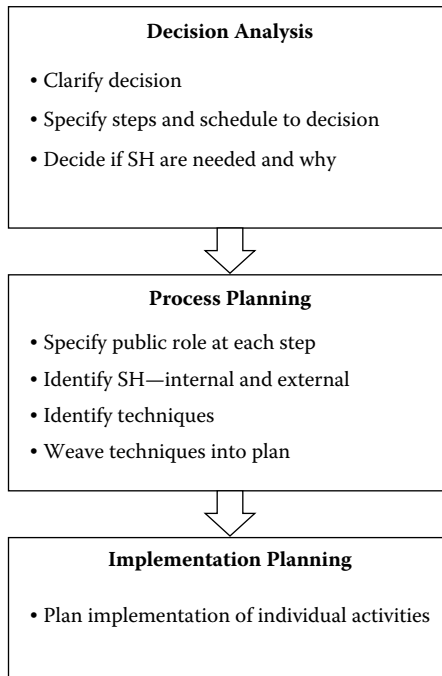


FIGURE 5.9 Blueprint for developing a public involvement program. (From Creighton, J.L. 2005. *The Public Participation Handbook: Making Better Decisions through Citizen Involvement*. San Francisco: Jossey-Bass.)

To adapt this step to include developing a participation program, a few more questions might be added, such as:

- Who needs to be involved in the decision analysis?
- Who is the decision maker?
- What is the decision being made or problem being addressed?
- What are the steps in the decision-making process?
- When will they occur?
- What institutional constraints or special circumstances could influence a stakeholder's participation process?
- Is stakeholder involvement needed?
- If so, what level of participation?
- Will the decision be controversial?
- Will the decision require trade-offs of one value for another?

A good process begins by being clear about why you want public involvement. Do you want a better-informed public? Is it to fulfill legal requirements or to give the public a voice before a decision is made? Do you need support or informed consent? Must you have buy-in for success? Are you trying to change behaviors or save lives?

Planning the participation process can also be guided by some questions:

- Who needs to be on the planning team?
- What are the issues?
- Who are the audiences/publics?
- What is the level of controversy and how do we prepare for it?
- What do we want to accomplish at each step?
- What are our stakeholder-involvement objectives?
- What do stakeholders need to know to participate effectively?
- What do we need to learn from stakeholders?
- Do special circumstances affect our techniques?
- What techniques are best?
- What will we include in the plan?

LEVELS OF PARTICIPATION

1. Unsurprised apathetics—do not participate, have little interest
2. Observers—keep abreast and generally do not participate
3. Commenters—very interested, will attend meeting or send letter
4. Technical reviewers—other agencies, peers
5. Active participants—commit time and energy in order to influence decisions
6. Co-decision makers—those who will make or veto a decision

Source: Creighton (2005).

Identifying stakeholders is especially important to ensure that no one is left out and to reach all parties interested in the issue. It is helpful to consider who benefits or loses in a given situation and who uses the relevant and affected resources. Different people and groups can be expected to participate in your process to varying extents. You need effective techniques to involve them all. Information exchange remains the goal of these activities.

You may need to explain the nature of the risk management activity and the decision process. You may want to know how different groups see the problem, who sees themselves as affected, as well as how the problem affects them. One key to good public involvement is to not let the issue slip from view. Although you cannot expect less active participants to sustain interest over a long time, bear in mind that suspicion often grows when an issue disappears. Use a variety of techniques to keep people productively involved in your process. Participation is especially important in the weeks leading up to decision points, and there may be many decision points in a risk management activity.

Implementing a good participation plan will take a mix of skills. You will need a spokesperson, technical experts, and facilitators. You may also need people with a wide array of communications skills. Do your homework and take care not to surprise elected officials or other community leaders and opinion makers. See to the needs of the media. If you are meeting with the public, visit the site in advance. Be sure to back up your technology, have a Plan B, and never outnumber the public.

There are many effective ways to communicate, and technology is growing the list of possibilities all the time. Even though communication is a two-way process, it is convenient to think of “to” and “from” techniques as seen in [Table 5.4](#).

Although one must remain aware of the digital divide that can separate different audience segments, it is exciting to consider the new possibilities for communication and participation that the Internet provides. Online learning classrooms, real-time chat, Twitter, instant messaging, podcasts, Wiki spaces, collaborative working environments, web conferencing, YouTube videos, Instagram, Facebook, interactive learning tools, data visualization techniques, Google, and all manner of emerging social networking techniques and tools make this an exciting time to be interested and active in public involvement.

The way people are working is changing. More and more collaborative work environments are popping up. More and more work is becoming defined by Tapscott and Williams’ (2006) four organizing principles:

- *Open*: all are welcome
- *Peered*: no one is in charge
- *Shared*: communal ownership
- *Global*: worldwide

Now is a great time to use technology to experiment, innovate, and collaborate. Imagine asking the world to help you solve your problem—and getting an answer! Think about using technology so that affected citizens can participate in a more

TABLE 5.4
Traditional and Internet To-and-From Communication Techniques

Traditional to	Internet to	Traditional from	Internet from
Briefings	Twitter, Facebook, and social media	Advisory group or task force	Twitter, Facebook, and social media
Exhibits and displays	Data, models, reports	Charette	Web conferencing
Feature stories	Hotline	Coffee klatsch	Wiki spaces
Repositories	Up-to-the-minute information	Computer simulation	Virtual communication
Mailings	Chatroom, discussion boards	Consensus simulation	Interactive web sites
Media interviews	Multimedia	Field trip	Interactive web sites
Media kits	Interactive	Focus groups	Shared spaces
Talk shows	Downloads	Hotlines	Blogs
News conferences	Distance learning	Interviews	Photo sharing
Newsletters	Published information about events	MCDA	
News releases	Podcasts	Shared vision planning	
Newspaper inserts and advertisements	Instant messaging Blogs Photo sharing	Large groups/small group meetings	
Panels			
Presentations			
PSAs			
Symposia			

active way. Spread your wings and fly, experiment with new technologies, and vary your approach.

5.4.3 CONFLICT RESOLUTION

There will be times when external risk communication includes public involvement, and some public involvement may require conflict resolution. Conflict resolution or consensus communication is often used to bring a number of parties to consensus on how to manage a risk. It is an effort to get people on “the same page.” It is most useful for addressing particularly contentious, controversial, or divisive issues (Neeley, n.d.). Although there are many reasons for conflict, three are almost inevitable (Deep and Sussman, 1997) in a risk management activity. Ours is a world of increasing complexity and rapid change. A consequence of that is growing diversity. Three television networks once exhausted the broadcast options for the United States. The amount of options now numbers in the hundreds, and each of these options has viewers in the many thousands or even millions. The first inevitability is that different people want different things. There are few risk management solutions that will satisfy everyone.

PRINCIPLES OF CONSENSUS COMMUNICATION

- Ensure stakeholder or audience participation early and throughout the risk analysis process.
- Listen to and honestly address the public's specific concerns.
- Convey the same information to all segments of your audience.
- When possible, allow stakeholders to participate in risk management decisions.
- Ensure there are effective feedback mechanisms between the communicators and stakeholders.
- Plan how you will balance the interests of various stakeholders.
- Address uncertainty.

Source: Neeley (n.d.).

Second, risk management activities involve and affect people. To affect people is inevitably to experience conflict. People will miscommunicate, misunderstand, jump to conclusions, suffer bruised egos, hold incompatible beliefs, and have incompatible needs. Humanity breeds conflict.

Third, limited resources mean even the winners in decision processes rarely get exactly what they want. Instead we are often "satisficing," that is, trying to get the best situation possible given the available options and constraints. For the losers in a decision process, the situation is more dire, so conflict flares readily. Given the inescapable nature of conflict, conflict management may at times be one of the risk manager's most needed skills and one of risk communication's critical tasks.

Deep and Sussman (1997) offer a treasure trove of practical lists for managing conflict productively. Eleven different lists comprising 105 different ideas are included in their conflict management chapter. It is a great place for the novice to begin. There is also a rich professional literature on conflict management (see, e.g., Burton, 1968; Kelman and Fisher, 2003; Kriesberg, 1998) and three forms of conflict management are addressed in the literature. These are conflict settlement, conflict resolution, and conflict transformation. Conflict settlement includes any conflict strategy that aims at a definite end of the conflict without necessarily addressing its basic causes (Reimann, 2004). Conflict-resolution approaches include strategies that can be used to find an exit from the conflict's damaging dynamic that aims at reaching a satisfactory solution for all parties involved. Galtung (2000), Lederach (1995), and others have suggested that the conflict context, its structure, the parties involved, and the general conflict issues may at times be transformed into a more agreeable situation.

Like the topic of public involvement, conflict resolution is too complex and too well developed elsewhere to address it in detail here. It is, however, important to understand that conflict resolution may be considered part of the risk communication program in the broadest constructions of the risk communication component.

5.5 SUMMARY AND LOOK FORWARD

Risk communication has both internal and external tasks. Internally, the coordination between risk managers and assessors is essential to the success of the risk analysis process. Not too many years ago, many thought managers and assessors may need to be separated almost to the point of sequestering the assessors so their objective work would not be tarnished by the subjective concerns of managers. Now we know better and recognize the importance of collaboration, coordination, and cooperation between managers and assessors.

The external communication task usually receives most of the emphasis in discussions of risk communication, and the extent of this task varies from one context to another. The narrower view of the risk communication component focuses on specific risk and crisis communications. An increasingly more common, broader view of this component includes those communications, but may also include public-involvement and conflict-resolution responsibilities as well.

The hazard and outrage dimensions of risk necessitate at least four types of risk communication strategies. These dimensions can affect the perception of risk, which is an important consideration for both risk managers and risk communicators. There are many unique challenges to effective risk communication, not the least of which is understanding the special challenges of communicating with people who are stressed and fearful. The three M's of risk communication—message, messenger, and media—are an important focus for any risk communication process.

Because the risk analysis process is for making decisions under uncertainty, risk communicators must develop skill at explaining risk and critical uncertainties to nonexperts. This is a task that is aided by simplifying, personalizing, and using risk comparisons. Learning to express uncertainty effectively and developing more effective techniques for communicating complex scientific information and its attendant uncertainty remains a challenge for all risk communicators.

With the three risk analysis components now described, let us once again draw a sharp distinction between the risk analysis sciences, as characterized by these three tasks, and the actual practice of the risk analysis sciences. The private sector has been increasingly, and in some instances aggressively, adopting and practicing enterprise risk management as a strategic and operational framework. Enterprise risk management uses risk management as the overarching concept that includes the three tasks risk management, risk assessment, and risk communication. As long as you draw a distinction between the science and the practice of risk analysis, the language is a little less confusing. [Chapter 6](#) presents an overview of the enterprise risk management process.

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6 Enterprise Risk Management

6.1 INTRODUCTION

The most difficult balance to strike in this text is that between the risk analysis sciences approach presented up to this point and the risk management in practice approach that may be best characterized by enterprise risk management (ERM), the subject of this chapter. The approaches are, I believe, more alike than not but there are significant differences in vocabulary, focus, and application. Risk management is the overarching and organizing concept for ERM, and the same three tasks of risk management, risk assessment, and risk communication are all found in the risk management framework. Science is not called out as often or as explicitly in ERM as it is in risk analysis, but ERM still relies on the objective truth. Uncertainty is important to both approaches but it is often subsumed by risk in the world of ERM. Risk assessments are more numerous and regular, as well as usually less complex, in ERM than compared to a public-sector risk assessment used as the basis for a regulation. Risk communication is a component of both approaches but it tends to be more elaborate in the “risk analysis world” than in ERM.

The working vocabulary is different in ERM because it emerged from the insurance, finance, and banking sectors, which have a more limited array of risks than the public sector. ERM uses terms now familiar to you from earlier chapters in different ways. Risk analysis, for example, is a step in risk assessment rather than an overarching term. A risk profile is no longer a summary of what is known about a risk; in ERM it is a description of any set of risks and, thus, it is what is known about the enterprise level risks an organization faces. In addition, ERM brings its own unique set of terms when it speaks of risk appetite, risk tolerance, risk source, and risk criteria. If you approach these differences a bit like you would a foreign language study you will find many more similarities than differences, because both of these approaches are derived from a common approach to decision making under uncertainty.

The purpose of this chapter is to present an introduction to the world of ERM. It begins by considering what ERM is and by looking briefly at its history. The chapter then presents two of the more popular models used by ERM practitioners followed by a discussion of risk appetite, risk tolerance, and risk profile before concluding with a summary.

6.2 WHAT IS ENTERPRISE RISK MANAGEMENT?

[Chapter 1](#) mentioned the many risk tribes and dialects in existence. Enterprise risk management is a very distinct dialect that first arose in the insurance industry from

which it quickly spread to financial firms. Early in the twenty-first century it has spread rapidly to nonfinancial firms of all types and now is making inroads with many public institutions like universities, schools systems, hospitals, and U.S. government agencies. In the pantheon of all things risk, ERM occupies its own hall. It has been distinguished enough by its nature and purpose to earn its own chapter, but it is not so distinguished in practice to be considered outside the risk analysis sciences. The risk analysis methods found in this text would be considered good ERM practice.

Enterprise risk management (ERM) is defined by the Committee of Sponsoring Organizations (COSO) as “a process, effected by an entity’s board of directors, management, and other personnel, applied in strategy-setting and across the enterprise, designed to identify potential events that may affect the entity, and manage risk to be within its risk appetite, to provide reasonable assurance regarding the achievement of entity objectives” (COSO, 2004).

ISO 73:2009 in its definition of terms defines risk management as “coordinated activities to direct and control an organization with regard to risk” (ISO, 2018b).

ERM is afflicted by the same misaligned and confusing terminology that plagues all of the risk sciences. Each tribe has a dialect they are loathe to give up. ERM has been described (Protiviti, 2006) as a “best-of-breed” approach to risk management that consists of different techniques that different companies have implemented in different ways. There is no shortage of risk management standards or ERM models in practice, and so there is no shortage of confusion about specialized ERM terms like risk appetite, risk tolerance, and such. Two of the most popular risk management models are the Committee of Sponsoring Organizations (COSO) of the Treadway Commission and International Organization for Standardization (ISO, 2018a) 31000 models, both are summarized later in this chapter. Although both are leaders in the field of ERM, the ISO 31000 model avoids the use of the term enterprise risk management and it eschews the use of other common ERM terms like risk appetite and risk tolerance.

ERM arises from a distinct business orientation and it adopts a more business-oriented spin to its language that includes such terms as risk capacity, risk appetite, risk tolerance, risk metrics, and risk portfolio, for a few examples. This alone distinguishes it from other risk management models.

Most businesses have mission and vision statements supported by a strategic plan that expresses strategic objectives for the organization. ERM is assumed to align with the strategic objectives of the entity. This requires the buy-in of the Board of Trustees and other top-level management of the organization, another distinguishing characteristic of ERM.

The diversity of business objectives guarantees a diversity of alignments of ERM frameworks well beyond what is found among public sector organizations. The value sets applied to risk management decision making also tend to be more pecuniary for ERM than for other risk management models. ERM takes great pains to assure

that organizations consider opportunities as well as risks, so risk taking is more commonly a risk management responsibility than in the public sector. Risk assessment is sometimes practiced primarily at the enterprise level through the preparation of a risk profile and it is not nearly as complex or involved as many public-sector risk assessments. Issues and debates about unacceptable, tolerable, and acceptable risks are replaced by risk appetites, tolerances, and management of the entity's portfolio of risks.

A singular accomplishment of ERM has been to encourage firms to put aside their traditional "silo" approach to risk management that compartmentalized and isolated the management of risk. In its place, ERM offers portfolio risk management, a unified, holistic structure that assesses and prioritizes risk in order to manage them in an efficient and more effective manner (Barton and MacArthur, 2015). For example, financial risks would no longer be managed in isolation from marketing, production, reputation, or operations risk. The tendency to overmanage some risks while undermanaging other risks would be eliminated by enterprise-wide risk appetites and tolerances.

There is little, if any, substantive difference in the practice of risk management between the generic model presented earlier and ERM. The devil, in this circumstance, is in how one interprets substantive. The language is different, the model's components have different names, acceptable and unacceptable risks are handled differently, but at the task level, at the thinking level, at the doing level, the two approaches to risk management are not significantly different.

So, think of ERM as the international private sector's adaptation of risk management to fit the needs of for-profit business firms. That system has proven robust enough to also be adaptable to the needs of not-for-profit organizations.

6.3 HISTORY

ERM is a relatively new development in the relatively young field of risk analysis/risk management. As risk analysis with risk assessment and risk management were being adopted and adapted as a decision framework for public sector regulatory and other decisions, private industry was also expressing interest in risk management. The insurance industry was possibly the first private industry to vigorously embrace ERM, and by the 1990s, financial and banking sector firms were equally immersed in the fledgling practice of ERM. Gradually, more non-financial firms took up the practice and today, ERM is widely practiced by a broad array of private industry. A brief timeline for the development of ERM is provided in the paragraphs that follow. Kloman's (2010) work provides the basis for the history prior to about 2000.

In 1955, Dr. Wayne Snider, University of Pennsylvania, suggested "the professional insurance manager should be a risk manager" to Dr. Herbert Denenberg, a colleague. A year later, in 1956, the *Harvard Business Review* published Russell Gallagher's article, "Risk Management: A New Phase of Cost Control." By 1966, the Insurance Institute of America had developed three examinations leading to the designation "Associate in Risk Management." This corporate insurance management designation broadened the risk management concept.

Gustav Hamilton, a risk manager for Sweden's Statsforetag, developed his "risk management circle" in 1974. His circle, summarized in [Figure 6.1](#),* may mark the first attempt to show the interaction of all the elements of the risk management process. The circle presented risks outside of production as dynamic risks (the top three risks in the figure) while risks inside of production or operational risks comprise the remaining risks. Hamilton recognized the wide variety of people who own the risks and must function as risk managers (the top line of each rectangle) as well as he recognizing the wide array of risks in each category (the bottom line offers examples). One year later, and two decades after Snider and Denenberg began their discussions, the American Society of Insurance Management changed its name to the Risk and Insurance Management Society (RIMS). That same year *Fortune* magazine published "The Risk Management Revolution," which suggested the need for coordination of risk management functions within an organization and board responsibility for organizational policy and oversight.

The Committee of Sponsoring Organizations (COSO) of the Treadway Commission was established in 1985 by five private organizations in the United States, as a joint initiative to combat corporate fraud. In 1986, the Institute for Risk Management in London began a program of continuing education that looked at risk management in all its aspects. A series of international examinations lead to the designation "Fellow of the Institute of Risk Management." Six years later, the Cadbury Committee issued a report suggesting that governing boards are responsible for risk management in the United Kingdom. That same year, GE Capital used the title "Chief Risk Officer" to describe an organizational function to manage all aspects of risk. Charles Sanford's 1994 paper entitled "The Risk Management Revolution," almost 20 years after the original paper by that name, argued that risk management was a keystone for managing financial institutions. Financial institutions follow a business model that relies on aggregating and disaggregating risk. They have been the cradle of modern ERM since the late 1980s (Pergler, 2012).

Government regulators provided a strong impetus for ERM. During the 1990s, several national standards began advocating that businesses should manage all risks as a portfolio across the enterprise. The first risk management standard, AS/NZS 4360:1995 appeared. This 1995 product of Australia and New Zealand was followed by similar efforts in Canada, Japan, and the United Kingdom. The standard has been revised several times since. In 1996, the Global Association of Risk Professionals (GARP) was established. It provides a global certification program for credit, currency, interest rate, and investment risk managers. In 2003, the Casualty Actuarial Society (CAS) defined ERM as the discipline by which an organization in any industry assesses, controls, exploits, finances, and monitors risks from all sources for the purpose of increasing the organization's short- and long-term value to its stakeholders.

COSO published its "Enterprise Risk Management-Integrated Framework" in 2004. In 2005, the International Organization for Standardization (ISO) undertook an effort to write a new global guideline for the definition and practice of risk

* Permission to present the circle could not be obtained but images of the circle are readily available on the Internet.

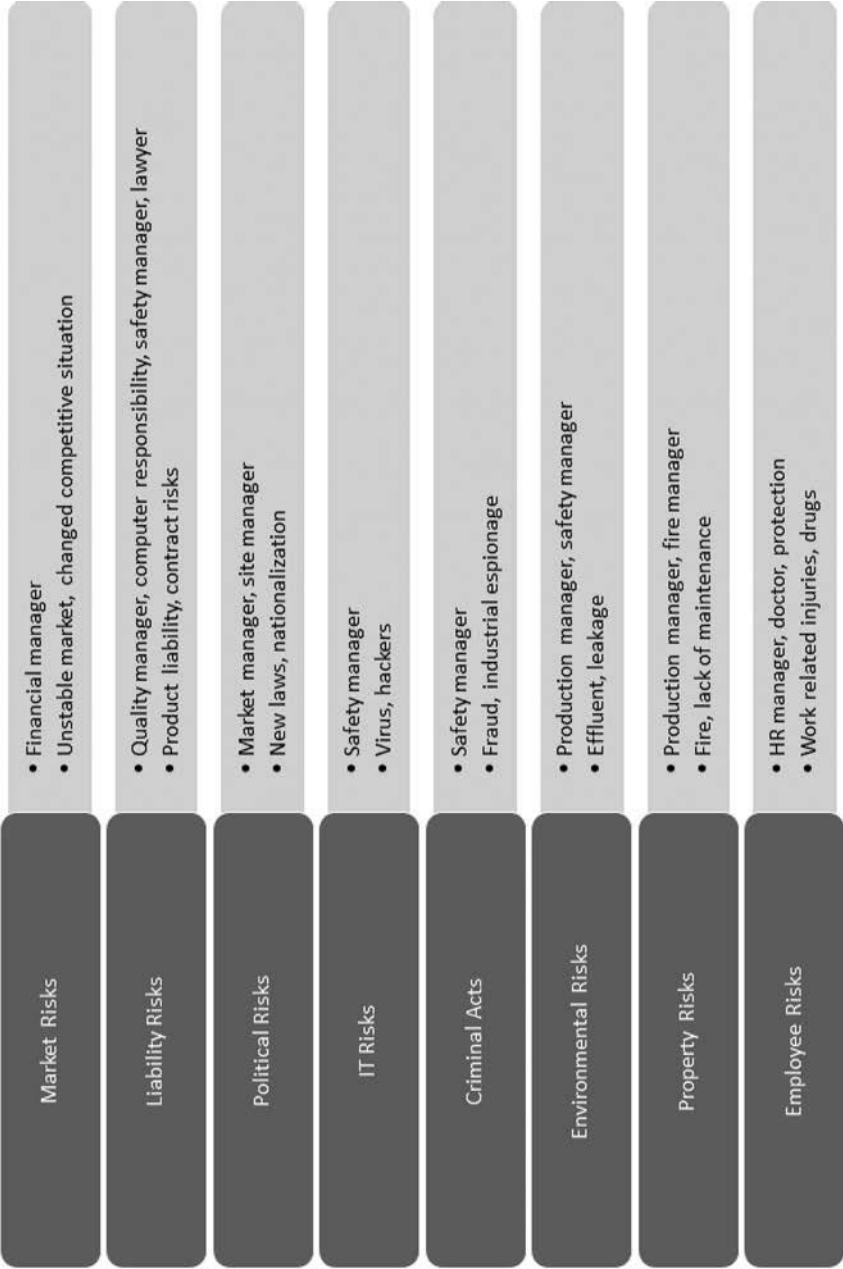


FIGURE 6.1 Summary of Gustav Hamilton's risk management circle.

management internationally. That guideline “Risk Management—Principles and Guidelines” was completed and released in 2009. It was updated in 2018. The RIMS Risk Maturity Model of 2006 is an online assessment tool recognized as a best practice ERM framework by several national organizations. In 2016, the U.S. Office of Management and Budget Circular No. A-123, “Management’s Responsibility for Enterprise Risk Management and Internal Control,” established the requirement for U.S. government agencies to implement an ERM capability in order to improve mission delivery, reduce costs, and focus corrective actions towards key risks. That same year, the Government Accountability Office (2016) published an ERM study on good risk management practices in government.

ERM is still evolving. Looking back, its drivers have been (Fraser and Simkins, 2010):

- Increasing consciousness that a more holistic approach to managing risk makes good business sense
- Studies by effective and authoritative groups that both promote ERM and demonstrate ways to implement and practice it
- Major legal developments which have placed greater responsibility on the board of directors to understand and manage an organization’s risk
- ERM’s ability to increase firm value

6.4 TRENDS IN ERM

This section reviews the contents of several risk management surveys in order to provide a current review of the state of ERM. All of the surveys cited are available online to download.

6.4.1 GLOBAL BUSINESS RISKS

The history of ERM tells part of the story about why interest in risk management has soared in the private sector of the economy. The nature of the risks that most concern the private sector tells another part of the story behind the rising interest in risk management. Although the risks of most concern can vary from location to location and from time to time, the annual *Allianz Business Barometer, Top Business Risks* (Allianz, 2018) provides an insightful view of some of the risks of greatest concern to the world’s global businesses.

TOP 10 GLOBAL BUSINESS RISKS

1. Business interruption
2. Cyber incidents
3. Natural catastrophes
4. Market developments
5. Changes in legislation and regulation

6. Fire, explosion
7. New technologies
8. Loss of reputation or brand value
9. Political risk and violence
10. Climate change/increasing volatility of weather

Source: Allianz Global Corporate and Specialty. 2018. Allianz Business Barometer, Top Business Risks for 2018. London.

TOP 10 RISKS

1. Damage to reputation/brand
2. Economic slowdown/slow recovery
3. Increasing competition
4. Regulatory/legislative changes
5. Cyber crime/hacking/viruses/malicious codes
6. Failure to innovate/meet customer needs
7. Failure to attract or retain top talent
8. Business interruption
9. Political risk/uncertainties
10. Third party liability

Source: Aon plc. 2017. Global Risk Management Survey. Aon Risk Solutions.

Business interruption (BI), including supply chain disruption, is the number one risk of concern to global businesses. BI can result from property damages resulting from several of the other top business risks (see text box) or from a break in the supply chain. The losses due to BI can be higher than the cost of physical damages. Cyber incidents were ranked as the most feared BI trigger in the 2018 survey.

In June 2017, the Petya ransomware attack halted production of a vital vaccine and it brought one of the world's busiest smart ports to a standstill. Businesses worry about the increasing sophistication of cyber attacks, which now go beyond the compromise of personal data and intellectual property. Cyber attacks have risen to the number two risk of concern to global businesses, and they are already the top concern in many countries.

From August to September of 2017, Hurricanes Harvey, Irma, and Maria caused \$215 billion in damages in the United States and the Caribbean, only \$92 billion of which was insured. Natural disasters including hurricanes, earthquakes, droughts, wildfires, windstorms, floods, and the like are the risk of third greatest concern to global businesses. The impact of natural catastrophes goes beyond physical damage to disrupt the dynamics of societal and industrial operations in affected regions and beyond. Natural disasters are presenting daunting challenges to the insurance industry as well as the organizations directly affected by the disasters.

The fourth-rated risk was market developments. The relatively strong economic performance of the world's three economic superpowers (the United States, Europe,

and China) has relegated market concerns to a lower rank than it experiences when the global economy is sluggish. Heightened political and policy uncertainty is strong enough to assure this risk remains an important concern.

Changes in legislation and regulation come next. The world continues a fragmentation trend with new protectionist measures growing in numbers with fewer global trade agreements and multilateral platforms. These trends are politically driven. Fire and explosion, the next concern, remain the second major cause of loss for businesses overall. The seventh risk is due to the technological advances of the last decade. Every industry has been penetrated by the digitalization of information; the same interconnectivity that fuels growth, cost optimization, and more flexible interconnectedness also poses significant risks of an inability to deliver products or services, cyber attacks, infrastructure breakdowns, and new liability scenarios.

Brand accounts for almost 25% of a company's value. Risks to reputation due to health and safety incidents, product recalls and data security breaches have grown exponentially in an age when a crisis can spread across the globe within minutes. When it comes to political risks, businesses are more worried about terrorism. They do not have to be the direct target of a terrorist attack to feel its effects. An attack in the surrounding area may close a business or impact tourism and spending. The final top ten risk is due to the perception that the frequency and severity of weather events is increasing.

6.4.2 THE FINANCIAL SECTOR

The financial and banking sectors have been leaders in developing and adopting ERM. Deloitte Touche conducts an annual survey of financial institutions around the world. The tenth survey (Deloitte Touche Tohmatsu Limited, 2018) found that risk management practices continue to gain wider adoption across the finance industry. Boards of directors devote more time and take a more active role in ERM oversight. The existence of a chief risk officer (CRO) is almost universal (92%) and the CRO is reporting directly to the board of directors and the chief executive officer (CEO). ERM programs are no longer novelties, 73% of institutions report having an ERM program. Another 13% said they are currently implementing an ERM program, while another 6% plan to create one in the future. ERM programs have been a focus of regulatory authorities in the United States/Canada (89%) and Europe (81%) and are more common than in Asia Pacific (69%) or Latin America (38%).

Table 6.1 shows the top risk management priorities for financial firms identified in the survey. The rapid growth of ERM has made attracting and retaining risk management professionals a significant challenge to the industry.

A significant majority of survey respondents rated their institutions as extremely or very effective in managing traditional risks of *liquidity* (84%), *underwriting/reserving* (83%), *credit* (83%), *asset and liability* (82%), *investment* (80%), and *market* (79%).

Risk management programs for these risks are established with proven methodologies, and analytics and relevant data are available. Operational risk proves a greater challenge with 51% rating their institutions as extremely or very effective. Newer types of risk are an even greater challenge because regulatory expectations

TABLE 6.1
Financial Industry Risk Management Priorities Identified in Deloitte Touche
10th Global Risk Management Survey

Priority	Firms Identifying this Priority (%)
Enhancing risk information systems and technology infrastructure	78
Collaborating between the business units and the risk management function	74
Enhancing the quality, availability, and timeliness of risk data	72
Attracting and retaining risk management professionals with required skills	70
Establishing and embedding the risk culture across the enterprise	69
Increasing regulatory requirements and expectations	67
Identifying and managing new and emerging risks	61
Collaborating between the risk management function and other functions	58
Attracting and retaining business unit professionals with required risk management skills	54

are less well-defined, and methodologies, analytics, and relevant data are not yet available. The progress has been undeniable, but in the years ahead risk management is likely to face a growing set of challenges.

6.4.3 THE STATE OF ENTERPRISE RISK MANAGEMENT

A major distinction of ERM is its tenant that opportunity does not exist without risk. Thus, when risk is taken strategically, new opportunities to accelerate organizational performance emerge. Deloitte (2017) surveyed 300 U.S.-based executives at large organizations about their views on risk management as a means of accelerating business performance. Four key insights were gleaned from the survey results.

First, a value-focused approach to risk strategy yields significant benefits. First among these is heightened financial and operational performance of the corporation. The second benefit is the competitive advantage that results because risk managing businesses manage costs better and improve customer relationships. A third category of benefits is enhanced brand and reputation due to improved risk protection and reputational resiliency.

A second insight is that with change comes challenge. Organizations struggle with risk strategy implementation. Even though 88% of respondents recognize value creation as a key goal of their risk strategies, only 40% believe they have been successful in creating value. The persistence of organizational silos was cited as a top risk-related failure that causes organizations to struggle with implementing a value-focused risk strategy.

The third insight is that timing is everything. Organizations must be prepared to react to a changing landscape. Important shifts are expected in the near future that make it imperative for business leaders to react quickly. Cyber security, for example,

TABLE 6.2
Selected Highlights of the RIMS 2017 ERM Benchmark Survey

Finding	Percent of Respondents Agreeing (%)
Have fully or partially integrated ERM programs in operation	73
ERM is being used to inform and influence strategy	61
Have a risk management department primarily responsible for ERM	62
Use ISO 31000 as their guide	25
Use COSO as their guide	29
Do not follow a particular standard or framework	20
Do not have risk appetite and risk tolerance statements	49

has risen to the top of the corporate mind. Interestingly, a little over half of the respondents say that cyber risk is both a threat and an opportunity. Building a risk-aware culture and identifying opportunities for loss avoidance are becoming more important, while improving compliance is becoming less of a focus.

The fourth insight concerns the road ahead for smart risk takers. This begins by breaking down the wall between risk management and strategic planning. Risk professionals and business leaders must share ideas. Business must create a culture where risk is everybody's business. Finally, risk leaders should adopt data analytics to measure risk and predict trends.

The RIMS (2017) survey had almost 397 respondents from 14 different industries, thus it is one of the best indicators of the current state of the ERM art in the entire private sector. [Table 6.2](#) presents selected highlights from the survey. A majority of firms responding have an ERM program in place and about three in five of them use it to influence strategy. About three in five organizations have a risk management department responsible for ERM. Better than half of all firms use either the ISO 31000 or the COSO model as their guide to ERM. Another 20% say they are not using a specific model. About half of the responding organizations do not have a risk appetite or risk tolerances.

The top three things executives expect ERM to deliver are:

- Reasonable assurance that major risks are identified
- Minimized operational surprises and reduced losses
- Aligned risk appetite and strategic risk management

Organizations were asked to rate their effectiveness on several ERM activities using a five-point scale where 1 = not effective at all and 5 = highly effective. [Table 6.3](#) shows the results with the average score for all respondents. Significant improvement is noted in all activities over the previous 2013 benchmark.

The top four values respondents gain from their ERM programs are (primary % and secondary %):

- Increasing risk awareness (24% and 42%)
- Avoiding and/or mitigating risk (24% and 33%)

TABLE 6.3
Effectiveness of Your Organization in Selected ERM Activities

ERM Activity	2017 Effectiveness Score (2013 Score)
Taking action on identified important and relevant risks	3.8 (2.2)
Anticipating and managing emerging risks	3.3 (2.6)
Instilling awareness of risk as a decision-making discipline	3.3 (2.5)
Linking risk management with corporate strategy and planning	3.2 (2.7)
Clearly articulating risk appetite and tolerances	3.1 (2.9)

Source: RIMS, the Risk Management Society. 2017. Enterprise Risk Management Benchmark Survey, Executive Report. www.rims.org.

- Eliminating silos, that is, viewing the entire portfolio of risks (20% and 29%)
- Increasing certainty in meeting strategic and operational objectives (16% and 28%)

Half or more of all organizations identify the following risks as among those that are addressed by their ERM programs, in order of frequency of mention:

- IT risk management
- Compliance
- Business continuity
- Operations/safety
- Strategic planning
- Legal
- Internal audit
- Human resources
- Security

Although ERM has made notable strides in penetrating private industry, the numerous surveys suggest both the need and desire for continued improvement.

6.5 ENTERPRISE RISK MANAGEMENT FOR DUMMIES

This text, to a great extent, describes the risk analysis experience of an organization that possesses stewardship responsibility for some public trust. This is the arena in which risk analysis began as a formal science-based approach to decision making. These organizations have often had a more open-ended approach to risk management, in the sense that they may have a wider and at times less well-defined purview of responsibility than private organizations, especially “for profit” private organizations.

There are some fundamental differences between public- and private-sector organizations (see [Table 6.4](#)) and these differences have influenced and differentiated the practice of risk management in these two sectors.

The fundamental objectives of these two kinds of organizations are different. Public-sector organizations focus on serving the general public and looking after their

TABLE 6.4
Selected Differences between Public and Private Sector Organizations

	Public Sector	Private Sector
Control and ownership of organization	Government	Private individual and corporations
Fundamental objectives	Serve people	Make profit
Strategic goals	Influenced by outside forces	Set by organization
Revenue	Public sources, tax, duty, penalty, fees	Stocks/loans/sales
Accountability	To public and political leaders	To ownership
Government influence	Full control	Varying degrees of influence
Job security	Greater	Lesser
Work environment	Some monopoly power	Competitive

Source: Adapted from Surbhi, S. 2015. "Difference between public sector and private sector." *Key Differences*. May 20. <https://keydifferences.com/difference-between-public-sector-and-private-sector.html> (accessed December 29, 2017).

changing interests. Private-sector organizations can have varied objectives but the profit motive is representative of most organizations. Private organizations answer to stockholders and boards of directors. Public organizations answer to stakeholders and customers. Because of the differing sources of revenue, public-sector organizations can survive inefficient operation, while poorly run private-sector firms can quickly go out of business. The public sector focuses on public concerns, but they are watched by interest groups and oversight committees. These differences affect the ways organizations in each sector operate.

Private-sector managers can hire quickly. Meeting personnel needs in the public sector can take months to years. Likewise, the timeframe for firing people differs by sector. Government budget processes are cumbersome, subject to political wiles, and are anything but adaptable. Purchasing processes are far more burdensome as well. Private organizations, by contrast, can use their revenue from sales and investments to buy things when they need them. They also have a quicker procurement process.

Public organizations are subject to a different kind of scrutiny due to the public eye they operate under. Leaders of private organizations do not face this level of scrutiny. They are accountable to their boards of directors and shareholders rather than the public.

Private organizations can set their own strategic goals and then focus resources on accomplishing them. Public organizations are buffeted by prevailing political winds. They are regularly challenged to meet legislative mandates, they face more outside forces, and have far more stakeholders who must be accommodated to some extent. Answering to public officials in pursuit of election victories further challenges accountability. The goals of public organizations can turn dramatically and quickly with the results of an election.

As a result of these differences the approach of these organizations to risk management is somewhat different too. The public sector tends to utilize a process

like that described in [Chapter 3](#). Private-sector organizations tend to favor ERM, although there are ample exceptions to each case. The differences between these two approaches are more semantic than substantive. But the semantics are important. This section offers a simplified interpretation of the major differences introduced by the ERM approach.

ERM begins with the strategic objectives of the organization. These will often be found in the strategic plan, and they describe what success looks like for the organization. A good strategic plan will provide metrics for measuring progress toward the achievement of these objectives. What a strategic plan does not do is identify those risks that can interfere with the achievement of those objectives. Nor does it identify new opportunities for achieving those objectives. ERM does this and it identifies metrics that can be used to manage those risks. These enterprise-level risks are typically managed by the senior leaders of an organization or its board.

The risks identified have to be assessed. This process of assessing enterprise-level risks is sometimes called creating a risk profile, which helps to identify the risks of greatest concern to the organization. Risk managers then establish an organizational risk appetite for these enterprise-level risks. The appetite identifies the amount of risk the organizations are comfortable accepting, while they pursue their strategic objectives. Some organizations may establish risk tolerances for these risks. A risk tolerance identifies the point at which a tolerable level of risk becomes unacceptable. It is usually an upper and/or lower bound on the risk appetite. Public organizations usually assess a risk and then must decide if that risk is acceptable, tolerable, or unacceptable. In a private organization a risk tolerance identifies the specific points at which risk management measures will be implemented.

Each entity will establish some sort of governance structure to undertake this enterprise-level risk management and to establish the policy, process, and procedures necessary to assure that ERM is implemented horizontally and vertically throughout the organization. Risks are managed jointly in a portfolio rather than individually in silos.

Beyond these distinctions and those in the introduction to the chapter, the process is actually quite similar to the process described throughout this book. An examination of the details of any ERM model will reveal different, if not unique, language and detail. There is much more that unites ERM to the generic risk management process presented here than divides it.

6.6 RISK MANAGEMENT STANDARDS AND GUIDANCE

A Google search on the title of this section produces over 123 million entries, many of which are actually directly related to the topic. There is no shortage of entries in this “best-of-breed” competition. A standard is an established norm that is usually voluntary in nature. It is generally promulgated by a standard-setting organization. By contrast, a regulation is generally mandatory. Guidance includes the presentation of customs, conventions, guidance documents, frameworks, or company products that may be developed outside of a recognized standard-setting body but which becomes generally accepted practice.

From the many standards and guidance candidates two are chosen for review in this chapter, they are the ISO and the COSO models. The ISO has issued four primary sources of guidance on risk management. They are:

- ISO Guide 73:2009 Risk Management—Vocabulary
- ISO 31000:2009 Risk Management—Principles and Guidelines
- ISO/IEC 31010:2009 Risk Management—Risk Assessment Techniques
- ISO 31000:2018 Risk Management—Guidelines

SELECTED STANDARDS AND GUIDANCE

RIMS (2011) provided an overview of six standards and guidelines. They are indicative of the dominant examples in ERM and are:

ISO 31000:2009 Risk Management—Principles and Guidelines
OCEG “Red Book” 2.0:2009 GRC Capability Model
BS 31100:2008 Code of Practice for Risk Management
COSO:2004 Enterprise Risk Management—Integrated Framework
FERMA:2002 A Risk Management Standard
SOLVENCY II:2012 Risk Management for the Insurance Industry

The introduction to ISO Guide 73 notes “that in addition to managing threats to the achievement of their objectives, organizations are increasingly applying risk management processes and developing an integrated approach to risk management in order to improve the management of potential opportunities.” Risk is defined as the effect of uncertainty on the objectives of an organization. An effect is a positive or negative deviation from the expected outcome.

Risk management is said to comprise the “coordinated activities to direct and control an organization with regard to risk.” A risk management framework is a set of components that provides the foundations and organizational arrangements for designing, implementing, monitoring, reviewing, and continually improving risk management throughout the organization. It is increasingly common for private industry to adopt an ERM model as its risk management framework. These models vary and are based more or less on the ISO risk management principles. The best ones provide for managing risk across the enterprise.

The COSO ERM framework is the second model summarized in this chapter. The primary reference for this framework is *Enterprise Risk Management — Integrated Framework* (2004). The underlying premise of COSO’s ERM framework is that every entity exists to provide value for its stakeholders and every entity faces uncertainty. Uncertainty presents both risk of loss and opportunity for gain. This uncertainty affects an enterprise’s ability to achieve its objectives. ERM provides a framework for management to effectively deal with uncertainty and its associated risk of loss and gain. COSO defined ERM as, “The culture, capabilities, and practices, integrated with strategy-setting and its execution, that organizations rely on to manage risk in creating, preserving, and realizing value.”

6.7 ISO 31000:2018 RISK MANAGEMENT—GUIDELINES

It bears repeating that this international standard never uses the term enterprise risk management, despite its status as one of the world's foremost ERM models. To be faithful to the document, risk management will be used in this discussion. However, if you hear ERM in its place no one will be offended. The substance of the standard is contained in its definition of terms, principles, framework, and process. [Figure 6.2](#) shows the relationship among the principles, framework, and process. Each component is described in a subsequent section. Eight risk-related terms, down from 29 in ISO 31000:2009, are defined in clause 3 of the standard. Many of these definitions have been adopted by other standards and guidance. The discussion that follows paraphrases ISO 31000:2018.

6.7.1 ISO 31000:2018 PRINCIPLES

Below and in [Figure 6.3](#) you will find the ISO principles, which define an effective risk management organization. Risk management is:

- Integrated
- Structured and comprehensive
- Customized
- Inclusive
- Dynamic
- Best available information

These mean that risk management is an integral part of all of an organization's activities. The process is structured and comprehensive in order to produce consistent and comparable results. The framework and process are customized to meet the needs of the organization. It includes appropriate and timely two-way involvement of stakeholders while it enables their knowledge, views, and perceptions to be considered. Risks can emerge, change, or disappear as the organization's external and internal contexts change. The inputs to risk management are based on the best available information and include appropriate consideration of any limitations and uncertainties associated with that information.

The ISO principles from ISO 31000:2009, still informative, are the following:

- Creates and protects value.
- Is an integral part of all organizational processes.
- Is part of decision making.
- Explicitly addresses uncertainty.
- Is systematic, structured and timely.
- Is based on the best available information.

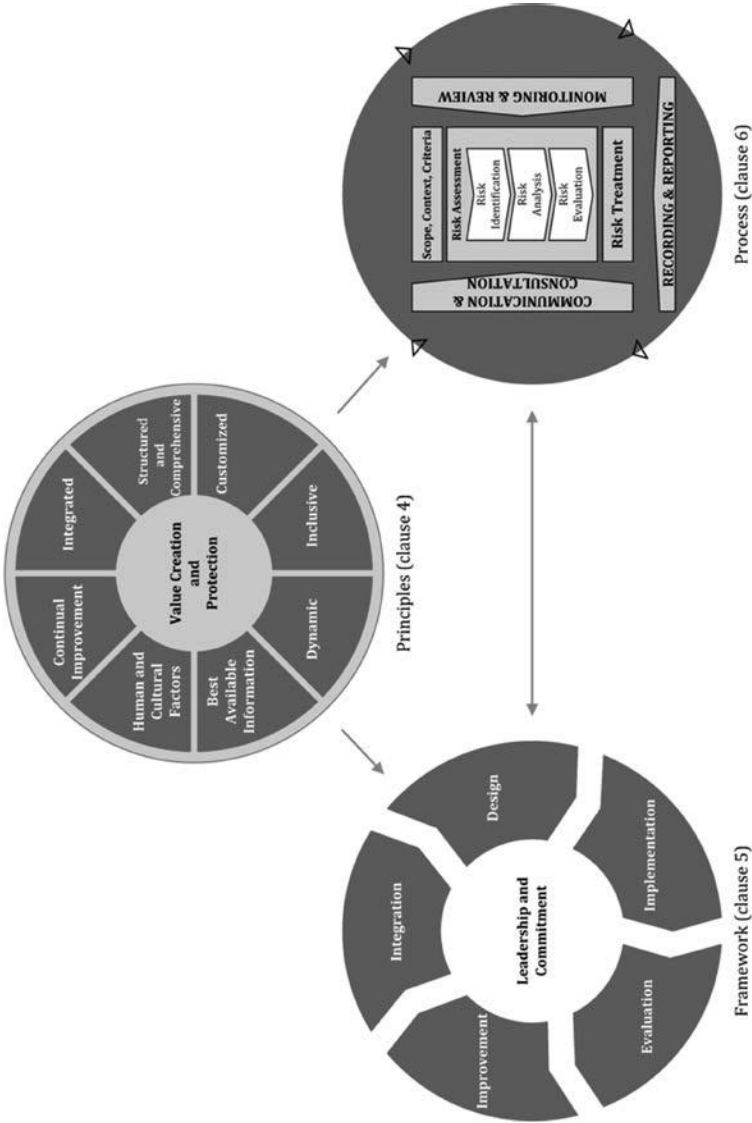


FIGURE 6.2 Relationship of the ISO 31000 principles, framework, and process. (Copyright ISO. This material is reproduced from ISO 31000:2018 with permission of the American National Standards Institute [ANSI] on behalf of the International Organization for Standardization. The complete standard can be purchased from ANSI at <https://webstore.ansi.org>. All rights reserved.)



FIGURE 6.3 ISO 31000:2018 Risk management principles summary. (Adapted from International Organization for Standardization. 2018. *ISO 31000:2018 Risk Management Guidelines*. Geneva: ISO.)

- Is tailored.
- Takes human and cultural factors into account.
- Is dynamic, iterative and responsive to change.
- Facilitates continual improvement of the organization.

6.7.2 ISO 31000:2018 FRAMEWORK

ISO describes the risk management framework as the set of components that provides the foundations and organizational arrangements for designing, implementing, monitoring, reviewing, and continually improving risk management throughout the organization. The framework helps to integrate risk management into the organization's activities and functions. Its effectiveness depends on the extent of its integration into the governance of the organization. The ISO framework comprises the elements of [Figure 6.4](#). The specific components of the framework and the way they work together should be customized to the needs of the organization. The organization's risk management leadership and commitment are embodied in the framework.

Integration. A strong and sustained commitment by the organization's management is the starting point for risk management. Chief among management's responsibilities are:

- Defining the risk management policy
- Aligning the strategic objectives of the organization with the risk management objectives

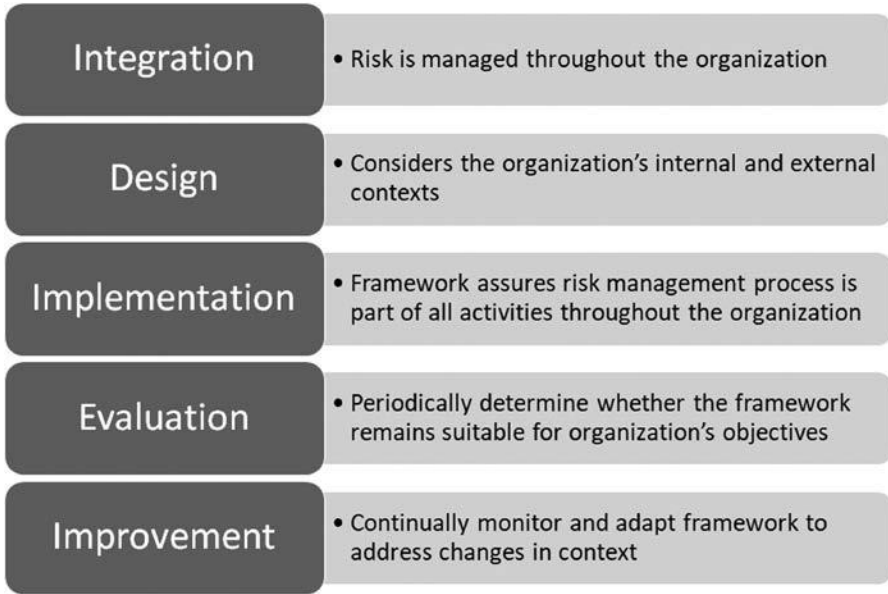


FIGURE 6.4 ISO 31000:2018-02 Risk management framework summary. (Adapted from International Organization for Standardization. 2018. *ISO 31000:2018 Risk Management Guidelines*. Geneva: ISO.)

- Assigning risk management accountabilities and responsibilities at appropriate levels throughout the organization
- Allocating sufficient resources to risk management
- Ensuring the risk management framework remains appropriate

Establishing the organization's risk management policy is a critical early step. This policy should be communicated appropriately throughout the organization. Management must assure that there is accountability, authority, and appropriate competence for managing risk. This must include identifying risk owners that have both the authority and the accountability to manage risks.

The risk management plan should be integrated into all the organizational practices and processes in a way that it is relevant, effective, and efficient. Sufficient resources must be allocated for risk management to assure the necessary people, skills, experience, and competence are available. Training programs must be a sustained integral part of the framework.

Integrating risk management into the activities and functions of an organization requires understanding the organization's governance, structures, and context. Governance guides the course of the organization and management structures translate governance direction into the strategy and objectives required to achieve the organization's desired levels of sustainable performance and long-term viability. Integrating risk management into an organization is a dynamic and iterative process that must be customized to meet the organization's needs and to serve its culture.

Design. Management is responsible for the design of the organization's framework for managing risk. This begins by understanding the organization and its context, most importantly the organization's policies and objectives, as well as the strategies put in place to achieve them. When designing the framework for managing risk the organization should:

- Understand the organization and its context
- Articulate its risk management commitment
- Assign organization roles, responsibilities, authorities, and accountabilities
- Allocate resources
- Establish communication and consultation

Implementation. Implementing the risk management framework is obviously one of the critical elements of the framework. Assuring that risk management policy and process are embedded in all organizational processes is a significant and continuous undertaking. Training personnel in the risk management process of the organization is critical to the success of that process. Risk management should be implemented at all relevant levels and functions of the organization as part of its practices and processes. Once it is properly designed and implemented, the risk management framework ensures that the risk management process is a part of all decision-making activities throughout the organization.

Evaluation. Monitoring and review of the framework are necessary to ensure that risk management is effectively supporting the organization's performance. Ideally, monitoring will include measuring the organization's risk management performance against indicators. The effectiveness of the framework also needs to be regularly reviewed and modified as warranted.

Improvement. The organization should continually monitor and adapt its risk management framework to changes in its external and internal contexts. Based on the results of this monitoring and review, the organization's risk management framework, policy, and plan can be continually improved. The organization should also continually improve the suitability, adequacy, and effectiveness of the risk management framework and the way it is integrated throughout the organization.

6.7.3 ISO 31000:2018 RISK MANAGEMENT PROCESS

The risk management process describes the manner in which risks are managed. The process can be applied at the strategic, operational, program, or project levels. It is a systematic application of policies, procedures, and practices to the activities of communicating and consulting, establishing the context and assessing, treating, monitoring, reviewing, recording, and reporting risk. This process should be an integral part of decision making that is integrated into the structure, operations, and processes of the organization.

The ISO risk management process comprises the five steps or stages and three processes seen in [Figure 6.5](#). Some of the sharpest differences from the terminology as used in the majority of this text are encountered here in the ISO risk management process.

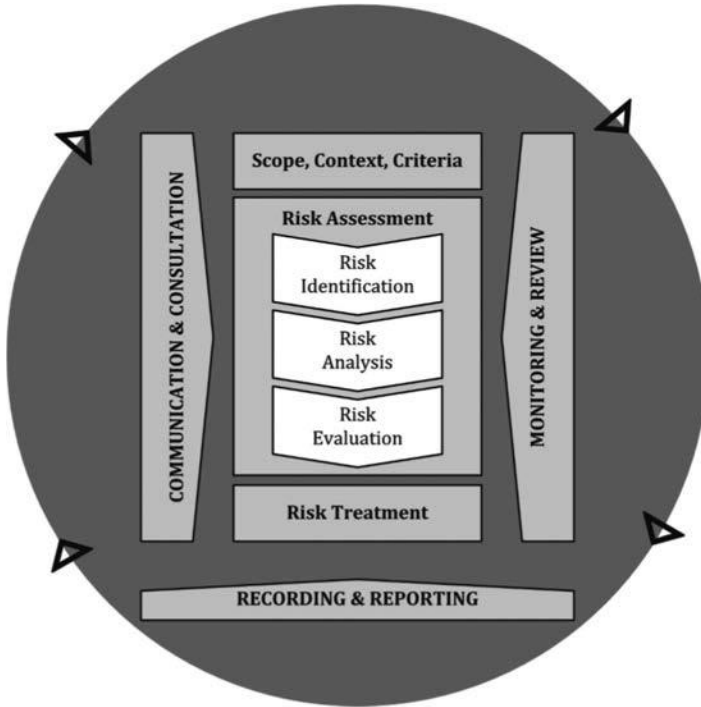


FIGURE 6.5 ISO 31000:2018-02 risk management process. (Copyright ISO. This material is reproduced from ISO 31000:2018 with permission of the American National Standards Institute [ANSI] on behalf of the International Organization for Standardization. The complete standard can be purchased from ANSI at <https://webstore.ansi.org>. All rights reserved.)

The risk management process is applied to a specific risk management activity. This all begins by establishing the scope, context, and criteria that customize the risk management activity. This includes articulating the relevant objectives of the activity. Risk managers will establish the external environment which may include but is not limited to the organization's social and cultural, political, legal, regulatory, financial, technological, economic, natural, and competitive environment, whether international, national, regional, or local. The internal context of the organization must also be established. The objectives and criteria of a particular project, process, or activity should be considered in the light of the objectives of the organization as a whole. Criteria should reflect the entity's risk appetite and tolerance. The organization should also recognize opportunities to achieve their strategic, project, or business objectives.

The objectives, strategies, scope, and parameters of each individual activity must be established. The ISO description of this particular context is quite extensive and includes identifying and specifying the decisions that have to be made as well as defining the risk assessment methodologies. The primary intent of this stage of the process is to ensure that the risk management approach adopted is appropriate to the circumstances, to the organization, and to the risks affecting the achievement of its objectives.

The ISO defines risk assessment as the overall process of risk identification, risk analysis, and risk evaluation. This differs from this text's definition of risk assessment. The ISO definition includes this text's risk assessment and some of its risk management process.

The ISO's definition of risk analysis is a process to comprehend the nature of risk and to determine the level of risk. This more closely resembles this text's definition of risk assessment.

In the ISO's dialect, risk analysis is a component of risk assessment. In this text's dialect, risk assessment is a component of risk analysis. The language of risk is very messy.

An additional task in this stage is to define appropriate risk criteria for the specific activity. This entails considering how to:

- Measure the nature and types of causes and consequences that can occur
- Define likelihood
- Determine the timeframe(s) of the likelihood and/or consequence(s)
- Determine the level of risk
- Ascertain the views of stakeholders
- Establish the level at which risk becomes acceptable or tolerable
- Consider combinations of multiple risks when applicable

The next three stages comprise the risk assessment. It begins with risk identification. The purpose of this stage is to generate a comprehensive list of risks based on those events that might create, enhance, prevent, degrade, accelerate, or delay the achievement of objectives. This should include identifying the risks associated with not pursuing an opportunity. Risk identification is a crucial step because risks not identified will not be analyzed further. Risk identification tools and techniques should be chosen based on what best suits the organization.

The next stage is called risk analysis. This is where an understanding of the risk is developed. In the ISO model, risk analysis provides an input to risk evaluation. It is used to decide whether risks need to be treated, and if so, the most appropriate risk treatment options. ISO's risk analysis is very much like the risk assessment described in [Chapter 3](#). It should consider such things as:

- The likelihood of events and consequences
- The nature and magnitude of consequences
- Complexity and connectivity
- Time-related factors and volatility
- The effectiveness of existing controls
- Sensitivity and confidence levels

Consequences and likelihoods may be expressed qualitatively, semi-quantitatively, or quantitatively depending on the type of risk, the information available, and the

intended use of the risk assessment output. Uncertainty should be addressed through a combination of techniques and communicated effectively to decision makers and other stakeholders.

Risk evaluation is ISO's third and final stage in the risk assessment. In risk evaluation, decision makers compare the level of risk determined during the risk analysis process with risk criteria established during the context step. The need for treatment can be determined based on this comparison. Decision making about which risks need treatment and the priority for treatment implementation begins here. All decisions should be made in accordance with legal, regulatory, and other requirements. The purpose of risk evaluation is to support decisions. Risk evaluation can lead to a decision to:

- Do nothing further
- Consider risk treatment options
- Undertake further analysis to better understand the risk
- Maintain existing controls
- Reconsider objectives

Once the assessment is completed, the final stage is risk treatment. Risk treatment is an iterative process of formulating and selecting risk treatment options and implementing one or more options for modifying risks. Risk treatment options include:

- Avoiding the risk by deciding not to start or continue with the activity that gives rise to the risk
- Taking or increasing the risk in order to pursue an opportunity
- Removing the risk source
- Changing the likelihood
- Changing the consequence
- Sharing the risk with another party or parties (including contracts and risk financing)
- Retaining the risk by informed decision

Choosing the best treatment option involves balancing the costs and benefits of implementation. ISO suggests these decisions should include consideration of risk treatment that is not justifiable on economic grounds. Treatment options can be considered and applied either individually or in combination. The risk treatment must be planned and implemented. Once the treatment has been assessed, a risk treatment plan should be developed to document how the chosen treatment options will be implemented.

The information provided in the treatment plan should include:

- The selection rationale, including the expected benefits
- Identification of those accountable and responsible for approving and implementing the plan
- The proposed actions
- The required resources

- Appropriate performance measures
- Relevant constraints
- Reporting and monitoring requirements
- A schedule for taking and completing actions

The effectiveness of the treatment must be assessed. A risk treatment can introduce risks. One such risk is the failure or ineffectiveness of the risk treatment measures. Treatment can also introduce secondary risks. Both of these classes of risk need to be assessed, treated, monitored, and reviewed. Then it is necessary to decide whether the remaining risk is acceptable, and if it is not, the process should be iterated to prescribe further treatment.

The first process is communication and consultation with internal and external stakeholders. Communication should address the risk itself, its causes, its consequences (if known), and the measures being taken to treat it. Consultation provides input and feedback opportunities to support decision making and it suggests that a team approach to risk management will be employed. Plans for communicating and consulting need to be developed at the outset of a risk management activity. Communication and consultation with appropriate external and internal stakeholders should take place within and throughout all steps of the risk management process. Communication and consultation is intended to facilitate truthful, relevant, accurate, and understandable exchanges of information.

The second ongoing process is monitoring and review. Both activities have to be planned and implemented, with responsibilities for monitoring and review clearly defined. These activities are to ensure that risk controls are effective and efficient in both design and operation as well as to assure and improve the quality and effectiveness of the risk management process design, implementation, and outcomes.

The third and final process is recording and reporting. This process is intended to:

- Communicate risk management outcomes and activities across the organization
- Support decision making with information
- Improve risk management activities
- Assist interaction with stakeholders

6.8 COSO'S ENTERPRISE RISK MANAGEMENT INTEGRATED FRAMEWORK

COSO describes ERM as a process that is executed strategically by the people of the enterprise. It is applied horizontally and vertically throughout the organization, and it is geared toward the achievement of objectives. The process is designed to identify events that could affect the enterprise and it manages those risks within its risk appetite. ERM is not an event or a circumstance, but a pervasive continuous series of actions that permeate the way management runs the business. It is not something added on to an enterprise's way of doing business. ERM is intertwined with the entity's operations and management. The basic framework is illustrated in [Figure 6.6](#). The right face of the cube shows that risk management occurs across the enterprise. The top face illustrates the enterprise objectives that are served by ERM.

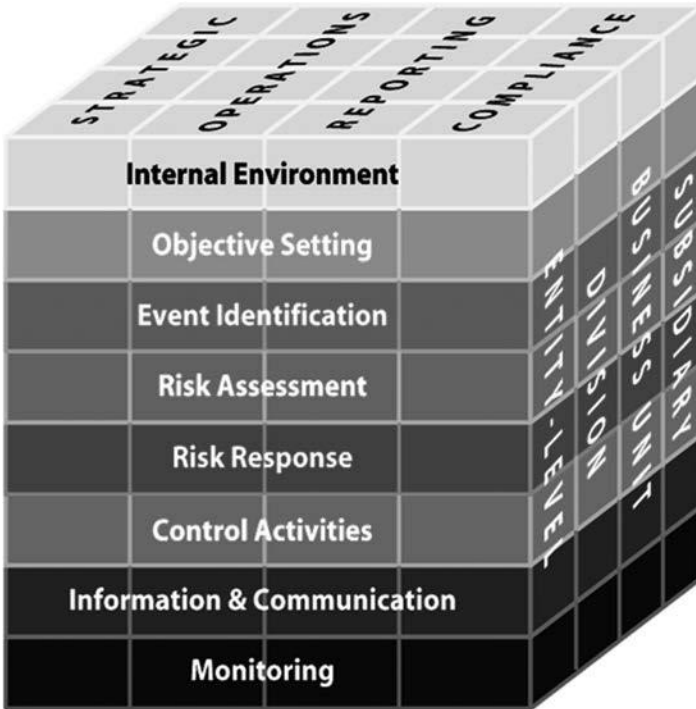


FIGURE 6.6 COSO ERM framework. (Copyright 2004 COSO. All rights reserved. Used by permission.)

The presenting face summarizes the steps in the process. Each cube face is discussed in turn below.

6.8.1 ACROSS THE ENTERPRISE

ERM helps a firm’s management select strategy consistent with the company’s risk appetite. Risk appetite is the amount of risk a firm will accept in pursuit of value. Different strategies expose the entity to different risks. For example, pursuit of foreign markets is a high-risk position in which to put one’s self. Conversely, failure to pursue foreign markets may severely limit a firm’s profits and growth. A firm’s risk appetite guides its resource allocation. Management allocates resources across business units in consideration of the firm’s risk appetite and the individual business units’ strategies for generating a desired return on invested resources (COSO, 2016). Management considers its risk appetite as it aligns its organization, people, and processes, and designs infrastructure necessary to effectively respond to and monitor risks.

Successful ERM requires an entity to consider its entire scope of activities. Every division, business unit, and subsidiary (see right face of Figure 6.6) must be engaged in risk management. That means there is a risk management hierarchy. ERM encompasses the entire scope of the firm’s activities. This includes enterprise-level activities like strategic planning and resource allocation and business unit activities

like marketing, production, new customer development, special projects, and new initiatives that might not yet have found a home in the firm's structure.

Most ERM frameworks, including COSO's, require a portfolio view of risk. This gives rise to the Rubik's Cube structure of the framework. Each business function in the entity (right face) has objectives (top face) and must follow the ERM process (presenting face) assessing the risk for each function or unit. It is management's responsibility to manage the entity's overall risk portfolio to ensure it is commensurate with its risk appetite. This requires them to consider interrelated risks from a portfolio perspective. Risks for an individual purchase decision, for example, may be within the unit's risk tolerances, but taken together with other purchases they may exceed the risk appetite of the firm as a whole. In a portfolio view, management considers potential events to understand how they can affect the enterprise.

6.8.2 ACHIEVEMENT OF OBJECTIVES

Risk is defined by COSO as the possibility that events will occur and affect the achievement of strategy and business objectives. ERM is designed to achieve an entity's strategic, operational, reporting, and compliance objectives. These distinct categories of objectives overlap, that is, a particular objective may address different needs and could be the direct responsibility of several executives. Strategic objectives include the firm's high-level goals that are aligned with and support its mission. Operations objectives assure the effective and efficient use of the firm's resources. Objectives relating to reliability of reporting and compliance with laws and regulations are within the firm's control, so ERM should be reasonably assured of meeting those objectives. Strategic and operations objectives are influenced by external events that make their achievement more uncertain. The key idea, at this point in the discussion, is that ERM permeates the firm's vertical and horizontal structure and the objectives of each of those elements. This is what makes ERM enterprise wide.

6.8.3 COMPONENTS OF COSO'S ERM FRAMEWORK

Figure 6.7 provides an effective summary of the nuts and bolts of the COSO ERM framework. There are eight interrelated ERM components derived from and integrated with the way management runs an enterprise. The ERM process begins by understanding the firm's internal environment, which influences the risk consciousness of its people and provides discipline and structure for all other components of ERM. The internal environment comprises the firm's risk management philosophy, its risk appetite, and risk culture, among the other factors listed in the figure. This internal environment shapes and influences strategies and objectives, how business activities are structured, and how risks are identified, assessed, and managed.

Objectives must exist before they can be achieved. Every firm faces risks from a variety of external and internal sources. Which of these risks will be assessed and responded to depends critically on the firm's objectives. Strategic objectives provide a basis for establishing operations, reporting, and compliance objectives. When these objectives are aligned with the firm's risk appetite they drive the risk tolerance levels for the company's activities.



FIGURE 6.7 COSO ERM components. (Copyright 2004 COSO. All rights reserved. Used by permission.)

Internal and external events that can affect achievement of the firm’s objectives must be identified. Then management identifies the risks of loss and opportunities for gain among them. These and other events with potential negative or positive impacts on the firm’s objectives will require management’s assessment and response. It is important that management consider the full scope of the organization when identifying events that could influence achievement of organizational objectives. Likewise, management must recognize the uncertainties that can influence these events.

Firms undertake risk assessment to anticipate the extent to which potential events might impact the achievement of objectives. Both the likelihood and consequence of the risk needs to be assessed using either qualitative or quantitative methods. The positive and negative impacts of potential events need to be assessed across the enterprise. The likelihood and consequence of risks that emerge from the identified events are analyzed to form a basis for determining how they should be managed.

The firm chooses whether or not to respond to the risks that have been assessed. Management can accept, avoid, reduce, prevent, share, or live with the assessed risk, according to the firm's risk tolerance and risk appetite. Costs and benefits can be expected to weigh heavily in the firm's response. The risk that remains after a risk response is implemented, that is, the residual risk, should be assessed. This enables the enterprise's risk managers to bring the expected likelihood and consequence of a risk within the firm's risk tolerances.

Control activities are the policies and procedures enterprise risk managers put into place to ensure the risk responses are carried out. With ERM, control activities occur at all levels and in all functions of the organization. They can include changes in business processes, production process changes, compliance changes, and so on. A single control activity could help achieve firm objectives in several categories.

Information is needed at all levels of an organization to run a successful business. Likewise, information is needed to identify, assess, and respond to risks. Businesses use their internally generated data and information about external events to manage enterprise risks. Effective risk communication requires that all personnel receive a clear message from top management that ERM responsibilities must be taken seriously. Each person must understand their own role in ERM, as well as how their role affects or is affected by the work of others. Firms need an effective means of communicating information upstream and they must establish effective communication with external parties. All of this information must flow in a form and timeframe that enables everyone to carry out their ERM responsibilities.

ERM decisions must be monitored to assure that the desired effects on objectives are being achieved. This is ordinarily done through ongoing monitoring activities or in separate evaluations. A firm's ERM framework changes over time. Risk responses that were once effective may become irrelevant. Control activities may become less effective or may no longer be performed. The firm's objectives may change. Management needs to determine whether existing ERM measures continue to be effective, in the face of such change, and to respond accordingly.

6.9 THREE ENTERPRISE RISK MANAGEMENT CONCEPTS

It is important to note once again the genesis of ERM in the for-profit business sector. The terminology was generated there to meet the needs of that sector. As is often the case, terms generated for a specific context can be appealing to those laboring in a different context. The terms are adopted, adapted, and the confusion begins. Efforts to adapt the ERM language to government and non-profit sectors have been hampered by an inability to seamlessly translate some of the key concepts of ERM to these new contexts. This has led to no small amount of confusion about the meaning of these terms. The Internet is rife with explanations that point in many conflicting directions.

As with all other terminology turf battles there is no illusion that they can be resolved here. It is, however, important to be clear about what the terms mean as they are used here. Three key terms have been selected for discussion, they are risk profile, risk appetite, and risk tolerance. Risk appetite and risk tolerance are frequently incorrectly interchanged. A solid understanding of the definition of these related yet different concepts has eluded the greater Internet community, despite the confidence

of each individual source of information. Perhaps this discussion should begin with some *caveat emptor*. Here is my short take on these concepts. A risk profile is an objective representation of an organization's overall exposure to a group of risks at a given point in time. Risk appetite is an entity's policy for taking risk. Risk tolerance defines the upper and lower limits on risk that will initiate a risk response. Each of these concepts is discussed in the pages that follow.

6.9.1 RISK PROFILE

A risk profile is, at a minimum, a description of a set of risks of concern to an organization. This description can extend to a high-level assessment of the types of risks an organization faces. It is a representation of an organization's overall exposure to some specific risk or group of risks at a given point in time. The purpose of a risk profile is to provide an objective understanding of an organization's enterprise level risks.

A risk profile is quite different from a risk assessment; they are very different risk management tools. The risk profile is usually a high-level effort, conducted at the enterprise, business unit, product, or branch level. It may be closer to a risk prioritization process than to a risk assessment, which, by contrast, has a narrower focus and is more detailed and specific. The outputs are intended for different purposes. Risk profile results identify high level areas of risk that require management attention, which may include additional assessment of the risk. A risk assessment focuses on the consequence and probability of a risk and how effective risk controls can be against that risk. The familiar green, amber, red heat map or risk matrix (see [Chapter 10](#) for examples) is a common tool for conducting a risk profile.

The risk management team should be able to measure the gaps between the organization's risk profile and its risk appetite to understand the organization's risk landscape. An effective risk profile reflects the nature and scale of the entity's risk exposures across each relevant risk category.

6.9.2 RISK APPETITE

The risk appetite guides the enterprise in determining the types and amount of risk it is willing to accept in pursuit of its strategic and business line objectives. Every organization must take risks to achieve its objectives. The critical ERM question is how much risk do they need to take? Taking risks without intentionally managing them can lead to the organization's failure. The COSO ERM framework defines risk appetite as "the amount of risk, on a broad level, an organization is willing to accept in pursuit of stakeholder value." ISO Guide 73:2009 defines it as "the amount and type of risk that an organization is willing to pursue or retain." Risk appetite, therefore defines an organization's desired pursuit of risk. This includes its willingness to accept losses and its desire for upside risk.

The Internet is teeming with definitions and explanations of risk appetite. Unfortunately, it is not teeming with consistency. Aven (2012) provides an academician's review of some thirteen different definitions. He argues that effective use in practice requires clear and understandable concepts, noting that risk management struggles

with the nomenclature, with a number of diverging ideas and conceptions of risk and related concepts in use. Different environments and people support different interpretations, and this affects the use of the term “risk appetite.” He argues that risk appetite should be used to express the entity’s willingness to take on risky activities in pursuit of value. It is a term used for describing a policy for risk taking.

Afforded the opportunity to observe organizations in various stages of transition to ERM, a striking constant has been the quickness with which employees latch on to the notion of a risk appetite. They want to know from their bosses, “How much risk can we take?” Their motivations may be more concern for personal culpability than for the strategic objectives of the organization, but their need is transparently clear. They need the top management of the organization to take charge and articulate the risk it is okay to take.

An organization’s risk appetite should be prepared by its top management. It then needs to be carefully communicated throughout the organization. There does not appear to be any fixed or defined format for a risk appetite statement. Appetites will vary depending on the sector, culture, and objectives of the organization. A range of appetites may exist for different risks within a single organization and these appetites may change over time or with circumstances. Typically, a risk appetite statement is provided for enterprise-level risks. Operationalizing the risk appetite for enterprise-wide risks requires that the appetite statements become more specific as one drills down into the layers of the organization.

For example, an organization may express a low risk threshold for human life, health, and safety throughout the enterprise. That appetite statement will be applied quite differently aboard an oil drilling rig than it would be in an office environment, although both operations would be tasked with protecting human life, health, and safety.

Examples of qualitative risk appetite statements for single risks from a variety of organizations follow:

- A computer gaming organization has a higher risk appetite for virtual reality products and is willing to accept higher losses in the pursuit of higher returns.
- A franchising organization has a low risk appetite related to risky ventures and therefore is willing to invest in new business but with low appetite for potential losses.
- A health service organization has a low risk appetite related to patient safety but a higher appetite related to response to all patient needs.
- A manufacturer of engineered wood products has adopted a higher risk appetite relating to product defects in accepting the cost savings from lower-quality raw materials.
- A government agency has a low risk appetite for life safety but a higher appetite related to transportation cost savings and ecosystem restoration benefits created.
- A liberal arts teaching college has a low risk appetite for teaching reputation and a moderate risk appetite for research reputation.

Quantitative statements of risk appetite are also common.

The organization is, then, expected to evaluate alternative strategies to bring its risk profile in line with its risk appetite as part of its ERM strategy. Strategies are evaluated in order to understand the potential efficacy and implications of the chosen strategy for the organization's risk profile. The RIMS 2017 ERM Benchmark Survey reported:

- 37% of respondents had an enterprise level risk appetite
- 15% of respondents had a business unit or divisional level risk appetite
- 8% of respondents had a departmental level risk appetite
- 49% have developed no risk appetite

There would appear to be room for considerable improvement in the use of the risk appetite.

6.9.3 RISK TOLERANCE

The organization will define acceptable variation in pursuit of its strategic and business line objectives. Acceptable variation in performance is closely linked to risk appetite and is sometimes called "risk tolerance." Risk tolerance describes the range of acceptable outcomes for achieving a strategic or business line objective within the risk appetite. It also provides an approach for measuring whether risks to the achievement of strategic and business line objectives are acceptable or unacceptable.

Risk appetite identifies the level of risk the organization will pursue to meet its objectives. Inevitably, organizations may wander outside their appetites, but how far? Risk tolerance statements identify the specific minimum and maximum levels beyond which the organization is unwilling to go. These define the upper and lower levels of risk the organization can absorb without significantly impacting the achievement of its strategic objectives. Exceeding these limits triggers a risk response. Deviations within the expressed boundaries would be bearable, exceeding them would not be.

The COSO ERM framework says risk tolerance "reflects the acceptable variation in outcomes related to specific performance measures linked to objectives the entity seeks to achieve." ISO Guide 73:2009 defines it as the "organization's or stakeholder's readiness to bear the risk after risk treatment in order to achieve its objectives." These may do more to contribute to the confusion over this term than to clarify it.

Risk tolerance appears to be a relatively simple concept. Depending on the organization, it presents a series of limits that may be absolute in the sense that the organization will not exceed them or they may be thresholds that alert the organization to a breach of tolerable risks (IRM, 2011).

Tolerance levels can be depicted graphically as shown in [Figure 6.8](#). Call all the risks the organization might face the risk universe. Risk appetite defines the subset

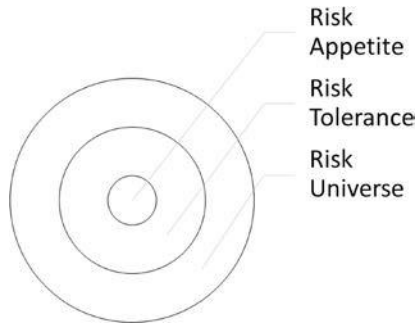


FIGURE 6.8 Relationship of risk appetite and risk tolerance to an organization's risk universe.

of risks with which the organization wants to actively engage. Risk tolerance defines those risks, which if push comes to shove, the organization could reluctantly live with. In general, an organization with any options at all wants to operate within its appetite and it will not exceed its tolerance. Or, exceeding its tolerance triggers an immediate risk response to return the organization within its tolerance, if not its appetite.

Examples of risk tolerances to match the risk appetite statements above follow:

- A computer gaming organization seeks an expected return of 20% on virtual reality investments, but is not willing to take more than a 25% chance these investments will lead to a loss of more than 25% of the organization's existing capital.
- A franchising organization will not accept more than a 5% risk that a new line of franchises will reduce operating earnings by more than 5% over the next 5 years.
- A health service organization will treat all emergency room patients within 2 hours and all critically ill patients within 15 minutes.
- A manufacturer of engineered wood products has targeted production defects at one flaw per 1,000 board feet.
- A government agency has a zero lives lost tolerance for the operation of its projects. It seeks an increase of two new transportation cost savings and ecosystem restoration projects per year over the next 5 years.
- A liberal arts teaching college expects to stay the same or rise in quality of teaching surveys, while it will accept up to a 10% decrease in its research rankings.

Risk tolerances are often easier to quantify than risk appetites.

Deloitte Touche (2014) presents a convenient way to think about these three concepts. [Figure 6.9](#) is adapted from their work. Imagine a risk profile that falls beneath the lower tolerance limit. Such an enterprise is not taking enough risk and corrective action must be taken. A risk profile that lands in the risk appetite area is in a desired position. A risk profile that is above the appetite but below the tolerance

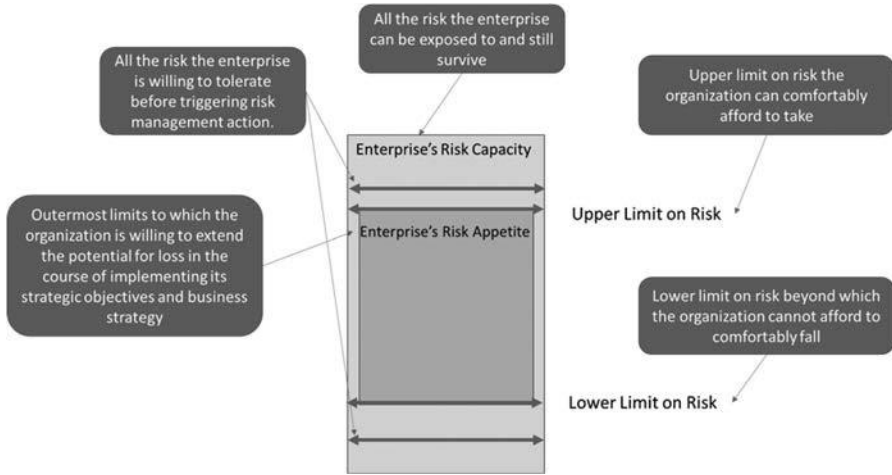


FIGURE 6.9 An enterprise’s risk capacity, tolerance, and appetite. (Adapted from Deloitte Touche Tohmatsu Limited. 2014. Risk Appetite Frameworks, how to spot the genuine article. <https://www2.deloitte.com/content/dam/Deloitte/au/Documents/risk/deloitte-au-risk-appetite-frameworks-financial-services-0614.pdf> [accessed April 13, 2018].)

level has risks that have escalated beyond the desired range, corrective action can be expected. If the upper tolerance limit is exceeded by the risk profile, corrective action is required and risk must be reduced. Finally, if the risk profile exceeds the enterprise’s risk capacity, the organization is no longer in a sustainable position.

6.10 SUMMARY AND LOOK FORWARD

ERM includes the methods and processes used by organizations to manage risks and seize opportunities related to the achievement of their objectives. Insurance and financial firms gave birth to ERM in the mid-twentieth century. ERM arises from a distinct business orientation that distinguishes it from other risk analysis and risk management models. Since its humble beginnings, ERM has spread rapidly to nonfinancial firms of all types and is now making inroads with many public institutions. One of its principle distinguishing characteristics is the buy-in of the board of directors and other top-level management of the firm who integrate risk management with the achievement of the organization’s strategic objectives.

Two of the most popular risk management models are the COSO and ISO models. These models establish a standard and provide guidance for the conduct of ERM. Many alternative standards and models have been established for risk management.

Three important concepts of ERM were stressed: risk profile, risk appetite, and risk tolerance. A risk profile is an objective representation of an organization’s overall exposure to a group of risks at a given point in time. Its risk appetite is likened to the organization’s risk-taking policy and guidelines. Its risk tolerance defines the upper and lower limits on risk that will initiate a risk response. Although the language of ERM is quite distinctive, in principles and substance it is very compatible with the

risk management model presented in [Chapter 3](#). If you follow the process of that chapter you will be practicing good risk management whether in an ERM, a public policy, or some other context.

With the generic risk management and the enterprise risk management frameworks now described, we turn our attention to a more detailed look at problem identification. Getting the right problem(s) identified is the critical first step for any risk management activity.

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7 Problem Identification for Risk Management

7.1 INTRODUCTION

There is a great chapter in Morgan D. Jones's (1998) book *The Thinker's Toolkit*. It is called "Thinking about Thinking," and its primary thesis is that the human mind is not analytical by nature. He explores the fallibility of human reasoning and suggests that the best remedy for the mind's ineffectiveness is to impose some structure on the way we think. This is what risk analysis does well. Jones argues, persuasively in my opinion, that structuring our analyses is at odds with the way our minds work naturally.

He argues that, left to our own devices, we often begin a problem analysis by formulating our conclusions, thus beginning where we ought to hope to end our analysis. With an intuitive preference for one solution, often the first one that seems satisfactory, we tend to give insufficient consideration to alternative solutions. We tend to confuse the gathering and analysis of data with the process of thinking about a problem.

Jones identifies seven traits that get in the way of our ability to analyze and solve problems. Risk analysis attempts to influence our thinking by making it more analytical. This can simultaneously limit the "damage" our fallible human reasoning can inadvertently do to decision making. The first of these traits is the emotional dimension to our thoughts and decisions. Emotion can hijack our ability to reason, as anyone who has thrown a broken item across a room has discovered. Serious mistakes can be made if decisions are made when emotions are hot. Risk analysis avoids emotional decisions.

Our minds are constantly taking shortcuts. We do not teach our minds how to work. They work as they work, and most of us rely on such shortcuts as stereotyping, personal bias, prejudice, hunches, jumping to conclusions, intuition, and the like. Risk analysis strives to replace shortcuts with science and evidence.

A third trait is that we are driven to see patterns in the world around us. We are conditioned to fill in missing information and to edit out what does not fit the pattern. The mind is not objective; it can construe random events as nonrandom or, when convenient, reverse the process and see no pattern where there is one. This compulsion to see patterns can mislead us when we analyze problems. Risk analysis requires evidence to support patterns.

DO YOU SEE A PATTERN?

The numbers 9/11 (9 plus 1 plus 1) equal 11
American Airlines Flight 11 was the 1st plane to hit the World Trade Center
There were 92 people on board (9 and 2)
September 11 is the 254th day of the year (2 and 5 and 4)

There are 11 letters each in “Afghanistan,” “New York City,” “the Pentagon,” and “George W. Bush”
The World Trade Center buildings themselves formed the number 11

Then what of the second flight, United Airlines Flight 175, or American Airlines Flight 77 that hit the Pentagon, or United Flight 93 that crashed in Pennsylvania? If you see patterns you may have a ready answer, these did not involve New York!

We rely on our biases and mind-sets for much of our decision making. Bias is the unconscious belief that conditions, governs, and compels our thinking and our behavior. It is instinctive and beyond the reach of our conscious mind. Our biases ensure that we give high value to information that reinforces our biases and assumptions, and they encourage us to discount or reject inconsistent information. We are unwitting slaves to our biases and the perspectives they create. They constrain and bound what we think and see. Consequently, our minds often operate analogically, and our logic is largely superficial. New experiences are interpreted in light of old ones, and our inferences are based on similarity. When we rely on bias, our reasoning only needs to be plausible to satisfy us. Good risk analysis avoids bias.

Fifth, we need to provide explanations for this uncertain world, regardless of the accuracy of those explanations. Jones calls us an explaining species: An eclipse is a dragon eating the moon or, in the twentieth century, rocket launches cause weather extremes. We seek cause and effect even when there is none. We want our perceptions to mean something because knowing is pleasing and not knowing is not. When an event has no particular meaning, we find one anyway. Subconsciously, we do not care if it is valid; it enables us to move on, and that is often sufficient. We are quite adept at coming up with explanations that do not fit the evidence very well, and our stunning indifference to the validity of our explanations is profoundly telling. Explanations need not be true to satisfy our need to know and explain. Risk analysis seeks sound, evidence-based explanations for what we see and what we do about what we see.

We tend to seek evidence that confirms our beliefs while devaluing what does not. In other words, we naturally prefer what confirms our existing views. When that causes us to (subconsciously) seek out evidence that supports our beliefs and judgments while eschewing information that does not, decision making can suffer. We focus by nature. In fact, our very survival is aided by our ability to focus. The problem often is that we tend to see in a body of evidence what we expect to see, that is, what we are looking for, and we do not see what we do not expect or want to see. The mind is very good at reconfiguring evidence to make it consistent with our expectation. This advocacy position is the basis of our political and judicial systems. Advocates are trained to take a position and marshal supporting evidence to defend that position while doing their best to weaken all other perspectives. Our systems reward subjective argument more often than objective analysis. When the advocate is also the decision maker, advocacy can be destructive. Risk analysis does honor values

and the explanations they can lead us to, but it also seeks a scientific explanation whether it conforms to social values or not.

Finally, Jones asserts that we can stubbornly cling to untrue beliefs. In fact, we often treat beliefs like prized possessions. They make us feel good, and so we cherish and protect them, but many of our most cherished beliefs are untrue because we often prefer to believe what we prefer to be true. Our willingness to embrace untrue beliefs can have disastrous effects on our ability to analyze and resolve problems. Risk analysis challenges beliefs. It separates what we know from what we do not know and then identifies key uncertainties and addresses them. It identifies assumptions and challenges them. It forces us to consider different perspectives and challenges the way we think. Risk analysis is analytical decision making, and it asks us to change the way we think about things.

This is where people often struggle. We humans are prone to reacting to what we think the problem is instead of seeking to understand what the problem really is. As a consequence, we often treat symptoms and ripple effects of problems instead of the problems themselves. You have got to get the problem right. Then you have to write the problem down. Risk analysis is oriented toward finding the right problem. If you solve the wrong problem, well, you've still got problems. Remember that risk comes in two "flavors": loss and opportunity. A successful process depends on your ability to find the right problem or the right opportunity.

You are the risk manager and your boss has just said, "We have to do something about..." How do you begin to do that? You begin by asking, "Why? Why are we initiating this activity?" If your answer involves the words authority, regulation, law, previous studies, the boss, and the like, you may be technically correct, but you're missing the point. There is a reason for every risk management activity. You face problems or have opportunities. Risk management begins by identifying and clearly articulating those problems and opportunities, which we call risks. This comes before budgets, schedules, milestones, profits, stakeholders, shareholders, politics, or any of the other pressing duties you might have with a risk management activity.

Assemble as many of the risk analysis team members as you can identify, sit down together, and begin where you are: "What are the problems here?" "What opportunities do we have to improve conditions here?" In some cases, you may have to rely on the vague and generic wording of a higher authority that set you in motion. In other cases, you may have three full hard drives and a bank of file cabinets full of information about a situation that has been bedeviling you for the last 30 years. At times, the problem may kick down your door unexpectedly. Wherever you are, this is where you begin.

Take a piece of paper. At the top of your paper write "Problems and Opportunities." Date the page, because this is going to change many times before it is finalized. Risk analysis is an iterative process, and so is the identification of problems and opportunities. Your first entry is, "Waterfowl are disappearing in the Babylon Ranch area of the Voodoo River." In time you will learn what kind of waterfowl are disappearing, and you will understand why they are disappearing. But today you are beginning, and you work with what is available to you.

It is easier to identify problems than opportunities. Human nature finds it easier to point out negatives than positives. But on day one, while you have your team

assembled in one place, you also need to begin to think about the opportunities you might have to improve conditions. Write them down, too. Your second entry might be, “Preserve wildlife at Babylon Ranch on the Voodoo River.” Never mind that you might not have the authority to do this. Never mind that you are not sure anyone “out there” wants to do this. You need a place to start, and this is it. Now you have the first draft of your “Problems and Opportunities Statement.”

When people ask why you are doing this risk management activity, you can say, “Because waterfowl are disappearing from the Babylon Ranch area of the Voodoo River and because we are exploring the possibility of preserving wildlife there.” The takeaway point here is that you must have a clear understanding of why you are doing what you are doing. At this point it is better to be clear than to be right. It is day one.

There will be time to understand the problems and the opportunities better. In time you can be both clear and right. Risk management is always best when its purpose is clear. In an iterative process, that purpose will and should change and evolve as uncertainty is reduced. That is okay. That is a good risk management process.

If it is day two of your activity and you do not yet have the first draft of your problems and opportunities statement, you are not managing as well as you could. That piece of paper is the “why” of what you are doing. Do not neglect it.

Problem identification was defined earlier as a three-part process of problem recognition, problem acceptance, and problem definition as seen in [Figure 7.1](#). Problem identification is the “seemingly” simple act of recognizing that a problem exists and figuring out what it is. It is also the subject of this chapter.

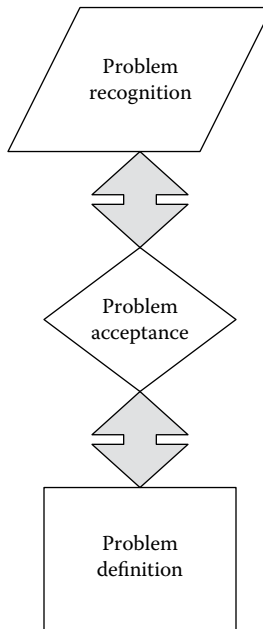


FIGURE 7.1 Problem identification elements.

Following this introduction, we spend some time describing and differentiating problems and opportunities. Next, we consider how people become aware of problems and opportunities by focusing on the notion of triggers and inputs. The chapter presents a number of different techniques for identifying problems and opportunities and concludes by considering the problems and opportunities (P&O) statement, an essential part of risk identification.

7.2 WHAT'S A PROBLEM? WHAT'S AN OPPORTUNITY?

Merriam-Webster's New Collegiate Dictionary defines a problem as follows:

prob•lem

1 a : a question raised for inquiry, consideration, or solution; **b** : a proposition in mathematics or physics stating something to be done

2 a : an intricate unsettled question; **b** : a source of perplexity or vexation synonyms, see MYSTERY

In risk management, we might informally think of a problem as a situation that we would like to address and solve. Most of us are pretty good at recognizing problems. A risky problem is going to involve a potential loss and usually a hazard, while a risky opportunity is going to involve the potential for an uncertain gain.

The most common kinds of problems are well-structured problems. Facts play a larger role than judgment with these problems. With well-structured problems the existing state and the desired state are both clear, and the methods needed to reach the desired state are fairly obvious. Textbook problems are archetypical examples of well-structured problems that simply require you to apply a set of principles to reach a solution. Another example would be when a piece of equipment fails that we know how to fix. We can figure out how many people we need, how long it will take, and what the costs will be. Thankfully many of our problems are well-structured. In an uncertain world, however, a good number of problems are not so well-structured.

Risk analysis is well suited to these poorly structured problems, which tend to be situational and emergent dilemmas. Judgment often plays a bigger role than facts when solving these problems. As the amount of uncertainty increases, the role of judgment increases. Poorly structured problems have existing and desired states that are unclear, making it more difficult to confidently identify the method(s) for reaching the desired state. They are poorly structured because one or more of the problem elements are unknown or not known with any degree of confidence (Wood 1983).

These problems may require the integration of numerous knowledge domains, and there are often no explicit means for determining an appropriate action. The parameters of the problem may not lend themselves to ready manipulation. Understanding them may require people to express their personal opinions or beliefs about the problem (Jonassen 1997). Decision makers must make judgments about these problems and then defend them. Their solutions may require uniquely human interpersonal activities (Meacham and Emont 1989). Complex problems with values in conflict are much more difficult to solve. Understanding the nature of the ill-structured problem is, then, necessarily an essential starting point for problem solving.

We are less adept at recognizing opportunities. An opportunity is defined by Webster as:

- op•por•tu•ni•ty
- 1 : a favorable juncture of circumstances
- 2 : a good chance for advancement or progress

Informally, we might define an opportunity as a gain or situation we would like to realize or a target we'd like to hit. It is useful to clearly distinguish the terms opportunity and problem so that we can intentionally identify both when initiating a risk management activity. See [Table 7.1](#) for some differences between problems and opportunities.

A problem is usually an existing undesirable condition perceived as negative or objectionable. People, resources, or other assets of value are usually adversely affected under existing or expected future conditions. The implicit objective of responding to a problem is to return to a problem-free circumstance or to create a future condition that is not objectionable. In contrast, an opportunity is usually a positive condition that does not yet exist and will not likely exist unless we take intentional steps to make it happen. Under existing conditions, the absence of an opportunity does not adversely affect other assets, even though their full potential may not be realized.

Management's implicit objective with respect to opportunities is to create a future condition that will realize those opportunities.

TABLE 7.1
Differences between Problems and Opportunities

Characteristic	Problem	Opportunity
Focus	Existing undesirable condition; a description of what is or might be	Future desirable condition; a description of what could or should be
Core message	Negative—an objection	Positive—a desire
Occurrence	Past: usually occurred Existing: usually occurs Future “without action”: usually expected to occur	Past: usually did not occur Existing: may or may not occur Future “without action”: may or may not be expected to occur
Relationship to other assets	An existing condition that may adversely affect other assets	Existing condition does not affect other assets
Implicit objectives of action	Return to a past condition that was not considered objectionable Create a future condition that would not be objectionable	Create a future condition considered to be desirable Return to a previous condition considered to be desirable
Consequences of doing nothing	Usually direct, immediate, and adverse	Usually indirect and long term due to benefits foregone

Source: Yoe, C., and K. Orth. 1996. *Planning Manual*. IWR Report 96-R-21. Alexandria: Institute for Water Resources.

There are also similarities between problems and opportunities, as seen in [Table 7.2](#). They are both often multiple in number, identified by people and through analysis, and stated in practical specific terms. They are measurable in the sense that we can at least tell the difference between better and worse conditions. They are achievable, and ideal situations can sometimes be described for both of them.

A problem statement need not be elaborate. It can be as simple as the example in [Table 7.3](#). The representation or definition of these problems will take considerably more explanation. Each problem needs to be thoroughly developed by the risk managers using a risk identification process like that presented in [Chapter 1](#). It is

TABLE 7.2
Similarities between Problems and Opportunities

Characteristic	Similarity
Number	Variable, few to many
How stated	In practical, meaningful, operational terms in a single statement
Source	Developed from people, observation, analysis, and documentation
Specificity	Specific, narrow; essentially limited
Specific subject	Usually limited to a specific asset
Specific location	Usually found in a particular place or locale (example: “study area”)
Specific measurability	Moderate to high; usually measurable or easy-to-recognize change that would result in a “better” or “worse” condition
Ability to achieve	High; problems can be solved, opportunities can be realized
“Ideal”	An “ideal” usually exists and can be identified The “ideal” is not the same as the existing condition The “ideal” is not the same as the long-term “without” condition

Source: Yoe, C., and K. Orth. 1996. *Planning Manual*. IWR Report 96-R-21. Alexandria: Institute for Water Resources.

TABLE 7.3
Simple Problem Statement Examples

Redlands Creek Basin Problem Statement

The problems in the Redlands Creek Basin are:

1. Loss of fish habitat in Redlands Creek due to urbanization
2. Flood damages in the industrial section of Central City
3. Stream bank erosion along Campus Park
4. Saltwater intrusion in the Redlands Bay estuary
5. Loss of coastal wetlands along the South Ditch section of Redlands Bay

Food Safety Agency Problem Statement

The problems of concern to the regulatory agency are:

1. Increasing resistance of *Campylobacter* in chicken to fluoroquinolones
2. Declining efficacy in the use of fluoroquinolones for the treatment of campylobacteriosis in humans

TABLE 7.4
Simple Opportunity Statement Examples

Redlands Creek Basin Opportunity Statement

There are opportunities in the Redlands Creek Basin to:

1. Increase wildlife habitat along Campus Park
2. Restore indigenous fish species in the upper basin
3. Provide increased recreational opportunities along the waterfront

Food Safety Agency Opportunity Statement

There is an opportunity for the regulatory agency to:

1. Reduce incidence of all campylobacteriosis in humans due to consumption of chicken
2. Provide a healthier work environment for on-farm employees
3. Reduce disease in flocks

important that risk managers and assessors understand exactly what problems they are addressing and that other interested parties can also see a clear statement of the problems under consideration.

Opportunities should, likewise, be clearly stated. An opportunity statement need not be elaborate. It can be as simple as the example shown in [Table 7.4](#).

7.3 BECOMING AWARE OF PROBLEMS AND OPPORTUNITIES

Some problems come bursting through your door at 4:30 on Friday afternoon and set up camp on your desk. Other problems are subtler and do their best to avoid detection. Some are as familiar as the faces of our parents or children, while others we have never seen before nor will we see them again. Some problems stay only a brief while and others refuse to leave. Among these extremes are infinite varieties of ways for problems to be discovered. Although the precise manner in which a problem is identified will vary from one organization to the next, there are some useful generalizations that can be made about the origins of problems and how we initially become aware of them. Likewise, the same is true for opportunities. To avoid the tedium of constantly repeating “and opportunities” after each mention of a problem, I will stop coupling the two terms. The techniques presented here for problem identification are equally adaptable for identifying opportunities.

7.3.1 TRIGGERS AND INPUTS

Some events trigger or initiate a process or reaction that identifies a problem. The *Deepwater Horizon* explosion, melamine in milk products, landing a plane in the Hudson River, or the Grenfell Tower fire in London are examples of problems that force themselves upon us and cannot be ignored, although they can be misidentified. Passive problem identification is sufficient for the more aggressive issues that come to you. Other problems only become apparent as inputs (information, reactions, events, opinions, and the like) accumulate over time; you must look for these kinds of problems.

Triggers and inputs are indicators of problems or opportunities that may require a risk management activity. A trigger may be a single event (e.g., a decision made by a higher authority, a natural disaster, infrastructure failure, terrorist attack, disease outbreak) or an accumulation of inputs into the program manager's continuous program assessment and evaluation. When triggers or early warning signs indicate that a risk cannot be addressed within the current program capabilities, it is reaching a point of importance and urgency that may require a risk management activity.

Triggers come from a variety of sources and can be thought of in several broad types (FDA 2003). They are:

- Authority triggers
- Crisis triggers
- Science and technology triggers
- Emerging or "on the horizon" triggers
- Strategic plan triggers

EXAMPLES OF INPUT SOURCES

Academia
Professional literature
Environmental monitoring
Toxicity testing
Disease surveillance, epidemiological studies
Lack of compliance with standards
Permit applications
Inspection
Community reaction
Legal action
Media or interest group reporting
What other nations do
Research
Staff feedback
Strategic planning

Authority triggers are "pulled" by higher authorities in an organization. Someone with decision-making authority directs what we consider a situation. Examples include Congressional authorizations and appropriations, new policies, ERM risk profiles, and the like.

A real or perceived crisis can trigger a risk management activity. Examples include a message from the media alerting you to an issue, a public outcry and subsequent media involvement, natural or manmade events, and adverse comments by stakeholders, critics, or others. Crisis triggers can also result from growing public awareness of an apparent risk, the concerns of susceptible subpopulations, decreased consumer confidence in your organization and what it does, geopolitical events, natural disasters, accidents, and the like.

Science or improved scientific methodology can act as a trigger. Newly acquired scientific knowledge that reveals previously unknown risks of specific hazards or a technological improvement that presents new opportunities may act as triggers. Examples include emerging concerns like climate change, new information that indicates that a problem or hazard is of greater concern than previously thought such as the “discovery” of acrylamide in fried foods, and new technology that makes new solutions viable, for example, nanotechnology, artificial intelligence, and genome mapping.

A well-planned, forward-looking forecasting practice can identify emerging or on-the-horizon triggers. This entails scanning your organization’s risk landscape to see how emerging events might affect you now and in the future. How might recent or future earthquakes, storms, floods, or civil unrest in the world affect your programs and opportunities? What trends and global events now on the horizon could affect your organization in time? Strategic plan triggers are the things we choose to address in order to realize the organization’s goals and, therefore, its vision.

Among the inputs that may accumulate and steer the risk management process are some recurring elements. Some potentially important inputs include:

- *Science (including research findings)*: We need to understand the facts contributing to a problem. Many organizations intentionally collect data and/or evidence and develop or assemble an understanding of the hazards, opportunities, or other risk factors of the situations or issues that may negatively or positively impact their organizational mission.
- *Policy/precedent*: The institutional history of an organization is an important source of information. Standard operating procedures (SOPs), formal policy, and informal ways of doing things can be important sources of input. When SOPs become insufficient, for example, that is useful information that is beginning to accumulate.
- *Legal issues*: The underlying legislative history, authorities, laws, precedents, regulations, programs, and such that support the potential responses of your organization can be important. Furthermore, they can change.
- *Economics*: Costs, benefits, and cost/risk trade-offs are practical elements of any risk management activity that must be considered.
- *Political issues*: Awareness and knowledge of key state, local, Congressional, media, consumer, and international geopolitical concerns with respect to a presenting issue are essential inputs to consider in a risk management response.
- *Cooperation and collaboration*: Working with knowledgeable and expert stakeholders, partners, academicians, industry, other governments, and international expert(s) to ensure that a shared vision of the problems and their solutions is developed is an essential input source.

An accumulation of inputs from any combination of these areas can surface a problem or opportunity and trigger a risk management activity.

When a problem first comes to your attention it is likely to be poorly structured. Once it reaches your radar screen, the next task is to decide whether you will accept the problem or not. In the public sector this decision may be based on authorities, and in the private sector resources or an organization’s mission may provide the basis for

accepting or rejecting a problem. Acceptance is usually the most straightforward of the three problem identification tasks, and it is not considered further here.

The National Levee Database (NLD), developed by the U.S. Army Corps of Engineers, provides an excellent example of a science trigger. The database contains information to facilitate and link activities, such as flood risk communication, levee system evaluation for the National Flood Insurance Program, levee system inspections, flood plain management, and risk assessments. The NLD is a dynamic database with ongoing efforts to continue to add levee data.

Think of problem recognition as articulating the initial understanding or description of the problem. Once an identified problem is accepted as an appropriate issue to pursue, a more detailed problem definition can follow. Problem identification, getting the problem right, is one of the most important steps in the risk management task. To aid you in accomplishing this task, a number of problem identification techniques are offered. These may be applied in the problem recognition or problem description stages of problem identification.

7.4 FRAMING THE PROBLEM

A recent survey (Wedell-Wedellsborg 2017) found 85% of 106 executives strongly agreed or agreed that their organizations were bad at problem diagnosis. Managers, quick to want to take action, slip into solution mode often without really understanding the problem. Frame blindness results in solving the wrong problem because our mental framework causes us to lose sight of important objectives or to overlook the best decision options (Russo and Shoemaker 1989). Framing a decision sets boundaries on a decision just as choosing a window to look through influences how much of the landscape we will see. The way we frame a problem influences the solutions we will ultimately choose.

Wedell-Wedellsborg offers a seven-step process for framing a problem; I add an eighth one. First, establish the legitimacy of framing as a method for problem identification. Get buy-in on finding questions before providing answers. Relating the slow elevator problem (see box) is one way to introduce the notion of framing.

Second, bring outsiders into the discussion. Look for “boundary spanners,” people who understand what you do but are not fully part of your world. Expect input, not solutions; outsiders are not experts so they will rarely be able to solve the problem. Outsiders are present to help the problem owners to think differently. This is the single most helpful framing practice.

Third, before the meeting, get each person to define the problem in writing. To understand what people think, you need to hear from them. Bring these definitions to the meeting. It’s not unusual to leave a meeting thinking there is agreement on what the problem is following a discussion, only to discover later some people had very different views of the issue. Opportunities for reframing the problem may be found in one of those definitions.

THE SLOW ELEVATOR

A classic example of problem framing is the slow elevator. The tenants in a building are complaining about the speed of an old elevator. Tenants have requested replacing the elevator, installing a stronger motor, or upgrading the algorithm that runs the elevator. These suggestions share assumptions about what the problem is—a slow elevator.

The building manager suggests a more elegant solution: put mirrors next to the elevator. People tend to lose track of time when they have something utterly fascinating to look at—namely, themselves.

The mirror is not a solution to the stated problem. It does not make the elevator faster, rather it offers a different frame through which to understand the problem. The point of reframing is to find the best problem to solve.

Source: Wedell-Wedellsborg (2017).

Fourth, ask what is missing, that is, what has not been captured or mentioned in these definitions. People tend to discuss what has been said in detail and pay less attention to what has been left out.

Fifth, consider the category of problem they think they are facing. Then consider multiple categories. Is it a property damage problem, life safety, production, expectations, attitude? It is easy to think of a problem too narrowly. Is the problem a hazard or an emotional reaction to the existence of a hazard? Highlighting how the group thinks about a problem (metacognition, i.e., thinking about thinking) can help the group reframe it. It may be helpful to arrange the written definitions in broad categories in advance of the framing meeting.

CHALLENGING YOUR PROBLEM FRAME

1. Challenge it yourself—does it make sense?
2. Seek other opinions—have others challenge your frame.
3. Role-play your adversaries—take your competitors viewpoint.
4. Welcome diversity—include a wide array of perspectives.
5. Brainstorming—look for ways to change the problem frame.
6. Lateral thinking—side-step or redefine the problem.
7. Synectics—think via analogy to seemingly unrelated elements.
8. Consider alternative metaphors—is your company an army, a football team, an orchestra, or a Japanese garden?
9. Find out how the other guy does it—has someone already solved this problem?
10. Monitor the changing world—track frame shifts that are occurring.

Source: Russo and Shoemaker (1989).

Sixth, analyze positive exceptions. Look for examples where the problem did not or does not occur. Explore what is different about those situations. Exploring positive exceptions makes the discussion less threatening, avoiding confrontation and defensiveness. These bright spots might uncover hidden factors the group may have overlooked. A positive exception makes it easier for individuals to consider their own role in problem situations.

Seventh, question the objective. Question the predefined and long-standing objectives of the organization. Pay explicit attention to the objectives of the parties involved. Begin by clarifying their objectives and then challenge them.

Eighth, reiterate the process as often as is necessary to explore a number of frames and arrive at an acceptable framing of the problem.

7.5 PROBLEM AND OPPORTUNITY IDENTIFICATION TECHNIQUES

Focus on the major things, circumstances, events, and conditions that cause something to happen or not happen. These are the factors that cause issues to arise, and therein lie your problems and opportunities. Focus on the factors that drive situations. Do not waste time on subtleties, as they are not significant. When a subtlety becomes important, it is no longer a subtlety (Jones 1998).

What is not as it should be? Be specific. Are you sure you have identified the actual problem and not just its symptoms? Some problems are relatively routine and quite familiar. They require little problem identification effort. When the needle on your fuel gauge is at or below E and the car engine chokes and dies, there is little uncertainty about what the problem is or how to solve it. Other problems are a little harder to solve; there is a lack of information and some general uncertainty about what the problem really is. Often, we can modify existing problem frameworks to accommodate these. The most difficult problems are those that are complex and ambiguous, the ill-formed problems spoken of earlier. They are accompanied by little information and a lot of uncertainty. These poorly structured problems require the most effort to identify.

A team has some leeway in how they define a problem. Consider [Figure 7.2](#), which depicts the food supply chain from-farm-to-fork as consisting of seven components. Food safety problems may be identified at any step in the process. Government regulators may define the problem as occurring in the food processing step, perhaps because of their regulatory authority over this step in the process. Consumers may define it in the preparation and consumption stage. A holistic view of the problem might consider the entire supply chain. Varying perspectives give rise to alternative views of the symptoms and causes of problems. A cause in one view, such as *E. coli* on carcasses in a meat processing plant, may be a symptom of a food production problem, for example, a contaminated water supply, in another perspective. Thus, it is critically important to clearly define the problem you will be seeking to solve. Unless real causes are addressed, a solution may be temporary at best.

When a diverse group of people, however large or small, is expected to come to a common understanding of anything, process is important. Problem identification requires at least the risk managers and their assessment team to have a common view of

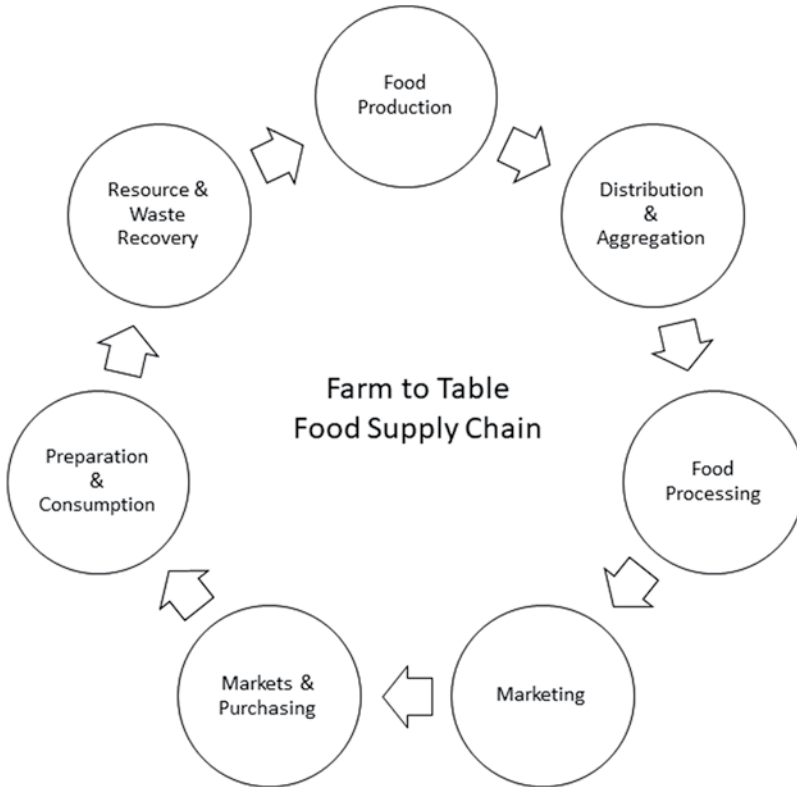


FIGURE 7.2 The farm-to-table food supply chain.

the problem(s). In the cases where the risk management activity is being undertaken by a government organization in some stewardship role (think post-Katrina New Orleans, H1N1 flu, food safety, airport security), it can involve a great many more people.

In my experience, many adults have little use for a formal process, especially well-educated adults. We are all adults, some with advanced degrees; certainly, we can identify a problem, right? Maybe we can't, at least not easily. Communication is still our species' greatest challenge, and a formal process can greatly aid communication.

The techniques presented in this section will help you better understand complicated and difficult situations. Having a structured and methodical way to accomplish this all-important first step for risk managers keeps problems from seeming huge and overwhelming. If we cannot provide certain structure to the problem itself, we can at least provide structure to the search for that problem. Techniques often help provide the laser-like focus needed for a successful problem identification process. (See [Chapter 3](#) for a description of this process.)

This section presents 13 examples of techniques that can be helpful in identifying problems and opportunities. There are many more than that identified in the literature (see VanGundy 1988). Use these techniques. Invent your own. Be systematic in identifying problems and you will never regret it. Haphazard approaches are often

regretted. Look through the summaries of the techniques presented here. Find a couple you like and give them a try the next time you need to identify a problem.

7.5.1 RISK IDENTIFICATION

[Chapter 1](#) introduced a risk identification technique. It consisted of four core steps and a bonus step. They are:

- Identify the trigger event.
- Identify the hazard or opportunity for uncertain gain.
- Identify the specific harm or harms that could result from the hazard or opportunity for uncertain gain.
- Specify the sequence of events that is necessary for the hazard or opportunity for uncertain gain to result in the identified harm(s).
- Identify the most significant uncertainties in the preceding steps.

These steps are explained in [Chapter 1](#).

7.5.2 PROBLEM DEFINITION PROCESS

Spradlin (2012) offered an updated four-step problem definition process in the *Harvard Business Review*. That process is summarized below.

Step 1: Establish the Need for a Solution—you articulate the problem in the simplest terms possible. This initial framing answers three questions:

- What is the basic need?
- What is the desired outcome?
- Who stands to benefit and why?

Step 2: Justify the Need—you explain why your organization should attempt to solve the problem. This is done by answering the following questions:

- Is the effort aligned with our strategy?
- What are the desired benefits for the company, and how will we measure them?
- How will we ensure that a solution is implemented?

Step 3: Contextualize the Problem—you examine past efforts to find a solution to save time and resources and generate highly innovative thinking. This is done by considering these questions:

- What approaches have we tried?
- What have others tried?
- What are the internal and external constraints on implementing a solution?

Step 4: Write the Problem Statement—you write a full description of the problem you are seeking to solve and the requirements the solution must meet. This requires answering these questions:

- Is the problem actually many problems?
- What requirements must a solution meet?

- Which problem solvers should we engage?
- What information and language should the problem statement include?
- What do solvers need to submit?
- What incentives do solvers need?
- How will solutions be evaluated and success measured?

7.5.3 APPRECIATION

Appreciation (Mind Tools 2007) is used to extract maximum information from the sparse facts that are available. Simply start by stating a fact about your problem or opportunity and ask the question, “So what?” What are the implications of this fact as far as the problems it may present? Keep on asking the question until the team has drawn all the inferences possible from the fact. Turn to the next fact and repeat the process. The inferences and facts can then be used to provide an initial description of the problem. This technique is useful when little information is available about a problem.

This technique is especially useful for unanticipated events like the explosion at the *Deepwater Horizon* oil-drilling rig in 2010: There has been a fire and explosion aboard the platform. So, what? So, lives may be lost. So, what? The answer to this question can lead down many paths. Another response may be that we do not yet know its cause. So, what? We do not know the risks to which we may still be exposed. So, what? And so it goes.

7.5.4 BE A REPORTER

Investigative reporters identify and describe problems and opportunities all the time. You can do a lot worse than to ask somewhat, where, how, why, when, and who questions to help you identify problems. What makes you think there is a problem? Where is it happening? How is this problem occurring? Why is there a problem? When is it happening? Who is involved with this problem? Be as specific in answering these questions as you can be.

When you have answers to these or similar questions, write the lead to the newspaper story describing this problem. If you do not have a unique “hook” for the story, consider one of these: “This is what is happening and it should not be happening.” or, “This is what is not happening that should be happening.”

Do not leap to fixing blame for a problem. Understand the facts of the problem first. Once BP was blamed for the Gulf oil spill in 2010, our attention was divided between stopping the oil spill and blaming BP at a time when perhaps addressing the oil spill was the greater of the two concerns. When a person’s temperature spikes into a dangerous fever, it is more important to bring the fever down than to pinpoint the cause. Sometimes you must treat the symptoms as the problem because you are unable to address the cause, but never confuse the symptoms with the cause.

Often the solution is more important than the cause. Nonetheless, there are times when understanding the cause is essential to solving the problem. So, provide the most specific answers to these questions that you can. Specifics make a better story and they define the problem more precisely.

Good reporters follow a good story. You should feel free to continue to ask additional questions once you have the basic facts. If the problem involves an asset or resource, for example, we might zero in on an aspect of the story and ask: What happened or will happen to the resource/asset? What is or will be that event's impact? Who or what does that impact affect? When did or will that impact happen? How did it or will the impact occur? Why did it or will it occur? What could be done about what happens, its impact, who or what it affects, and when, how, or why it occurs? Ask and answer good questions. Write the lead to the story. Follow the story. These three simple steps will give you a good start on identifying a problem.

PITFALLS IN PROBLEM DEFINITION TO AVOID

1. No focus: Definition too vague or broad.
Example: Lack of biodiversity in the watershed.
2. Focus is misdirected: Definition is too narrow.
Example: How can we improve conditions for the mottled duck?
3. Statement is assumption-driven.
Example: How can we stop harmful human disturbances?
4. Statement is solution-driven.
Example: Mallow Marsh needs a water control structure.

7.5.5 UTOPIA

Problems may affect an organization, a system, a process, a population, or any other number of targets. A problem may be an event, a situation, or an ongoing issue. For the next several techniques it will help to develop a little shorthand for all these possibilities. So, when you hear the word "situation," feel free to think any or all of the causes of problems discussed here. Likewise, the decision context is generalized to an organization to keep the language simple.

Look at your organization's situation. Create an idealized or utopian situation for your organization. What do you want to see happen? What do you want to ensure does not happen? What does an ideal future look like? Now compare the existing situation to this utopian ideal. What are the differences? Why do these differences exist? What do the differences suggest to you about the problems and opportunities in your situation? Use the insights gained through a comparison of your situation to a utopian situation to articulate your problems.

7.5.6 BENCHMARKING

Xerox is credited with developing this technique for comparing practices among businesses. It can be easily adapted to any situation. Who is the very best at what they do in your situation? Who sets the standard for performance? What is that standard? In benchmarking, you identify a situation similar to your own in significant resources, size, and other important aspects that is considered the best there is. Then you compare your situation to the benchmark.

Just as with the utopia technique, you are looking for deviations, that is, the gap between where you are now and where the benchmark situation is. These deviations should be described as specifically as possible. What are the deviations? Where are they occurring? When do they occur? How large are the deviations? Can you explain the deviations? What factors explain them? What are the possible explanations for the most important deviations?

Make each possible cause stand on its own or in combination with others to satisfactorily explain the deviation. Now choose the most likely cause(s) of the deviations and you have an initial problem identification.

This technique differs from utopia in that it uses an actual situation as the benchmark for comparison rather than a utopian ideal. Utopia is used when there is no benchmark for your organization or situation.

7.5.7 CHECKLISTS

Examine your situation with checklists in hand. The best checklists provide a comprehensive set of questions to ask, conditions to monitor, factors to consider, and the like. Deep and Sussman (1997) provide a set of 140 lists to aid in decision making. *That's a Great Idea* by Tony Husch and Linda Foust (1986) has several situation analysis checklists. Many of these lists are designed to help you identify problems and opportunities. Arthur B. VanGundy's (1988) *Techniques of Structured Problem Solving*, though out of print, is well worth the search; it offers 105 different creative problem-solving techniques. James T. Higgins (2005) offers some very practical techniques in his excellent book, *101 Creative Problem Solving Techniques*.

The best checklists may be the ones you develop specifically for your own situation. Many food processors, for example, have adopted the Hazard Analysis and Critical Control Point (HACCP) plan approach to food production. This approach breaks the production process down into its basic elements and identifies those points at which things can go wrong. Such an analytical process helps identify classes of problems associated with the production process. The medical profession provides many excellent examples of checklists useful in diagnosing health problems. You may have to develop your own checklists initially, but once developed they can prove to be an invaluable aid in identifying recurring kinds of problems.

7.5.8 INVERSE BRAINSTORMING

Inverse brainstorming unleashes the destructive energy in us that we have been suppressing since childhood! In this technique, you begin by considering your situation satisfactory. Then you nitpick it. See how many things you can find wrong with it. These potential obstacles and shortcomings become the bases for your problem identification.

Inverse brainstorming can be especially useful in dealing with opportunity risks. With this technique you look at an opportunity and brainstorm all the things that might prevent it from being fully realized. Why can't ecosystem habitats be increased? The technique can be particularly good at exposing the implicit assumptions that lie in our unconscious minds. When only one person or when like-minded people look for what can go wrong, beliefs and values may limit our ability to see the reality of a

situation. These beliefs can often be exposed by expanding the inverse brainstorming circle to include those outside your organization or the immediate situation.

Little gets people's creative juices flowing faster than deconstructive criticism. Ask people to find ways to create problems with your situation. Do a *premortem* on your situation and think about what can go wrong. Ask people how we can decrease habitat, increase cases of food-borne illness, introduce radon into our homes, cause the structure to fail, and so on. Get into a destructive problem-causing mode. Think like a bad guy or at least a severe pessimist. The insights gained from this process can help you identify the things that can go wrong as well as the ways they can happen.

7.5.9 BITCHING

Closely related to the inverse brainstorming technique is bitching. This gives full reign to the negative energy of humans. It differs in that while it can consider obstacles to opportunities, it may be more useful for problems. It simply invites people to let it rip and tell us what is wrong with our situation.

As a practical matter, you gather as many people as possible who know the situation and brainstorm (see [Chapter 8](#)) their lists of complaints. As the number of complaints begins to grow, they can be organized into subject areas. The subject areas are in turn grouped as necessary to get to a definition of problems.

7.5.10 DRAW A PICTURE OF THE PROBLEM

Draw a picture of the problem to make sure you are identifying the real problem. Drawing pictures taps into the creative side of the brain. Seeing the problem in a picture is a useful way to gain insights into the problem and its linkages with other ideas. The picture can be a flow diagram or a crude symbolic drawing; do not let a lack of artistic sense stop you from drawing the problem. Many problems often lend themselves nicely to visualization. There are no further rules to this technique. In one version of this technique, each member of the group is invited to draw a picture of the problem. The group then develops a consensus picture from the various individual versions. In another version, the group is tasked with developing a drawing jointly from scratch. The pictures are explained to everyone's satisfaction, and this explanation becomes the basis for the problem description.

7.5.11 MIND MAPS

Mind maps are a specific kind of problem picture that is growing in popularity and ease of use. Mind maps are diagrams used to represent many ideas and their linkage to a central concept. They are extremely useful for visualizing, structuring, and classifying ideas. They are also useful for analyzing, comprehending, synthesizing, recalling, and generating new ideas as well as for illustrating problems. Mind maps can be done by hand. The basic steps for creating a mind map are:

- Write the key problem word or phrase in the middle of a blank sheet of paper. Draw a circle around it.

- Think of as many related subtopics as you can. Write them down and connect each of them to the center with a line.
- Treat each subtopic as if it is the central idea in its own mind map. Identify facts (or, for a complex model, another tier of subtopics) for your subtopics and repeat the process. Generate as many of these lower-level subtopics as you see fit. Connect each one to its corresponding topic.
- Be as visual as you can be. Use colors, photographs, stick-figure drawings, sketches, and symbols generously.
- Limit your words. Keep your topics, facts, and phrases as short as possible. One word is good; a picture is better.
- Engage your brain; use variety. Different-size print or script, colors, thickness, lengths, curvature, alignments, and so on should be used. They encourage our creativity.

Figure 7.3 shows how a mind map aids thinking about the problem of the Asian carp reaching Lake Michigan in the United States. There is concern that this invasive species may become established in the Great Lakes. Once a map like this is drawn, it becomes easier to see the complexity of the problem and to develop a well-focused problem statement from it.

The example here is kept intentionally simple. The map suggests ways to frame the problem in terms of pathways, impacts, science, or even solutions. The map shows entry pathways, impacted areas, structures on the waterways, and even the species itself. The pictures are often more effective than words in stimulating thought. The eventual problem description can be developed by integrating the key insights from the mind map.

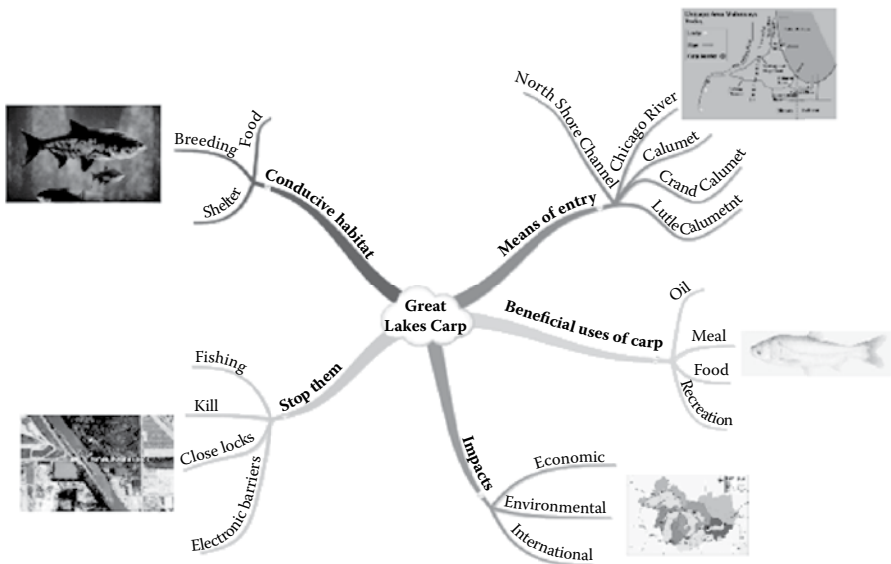


FIGURE 7.3 Mind map example for Asian carp entering Lake Michigan.

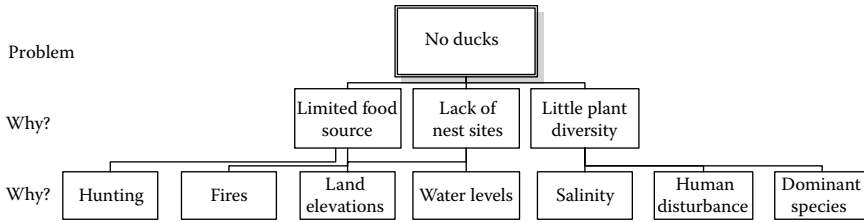


FIGURE 7.4 Why-why example for mottled duck habitat.

7.5.12 WHY-WHY DIAGRAM

The why-why diagram identifies possible causes of a problem, and when done well it quickly sorts ideas into useful categories. It is sometimes called a cause-and-effect diagram, fishbone diagram, or Ishikawa diagram. This technique is most useful when causes are important to know. It helps the team think through the causes of a problem in a thorough manner. It pushes the team to consider all potential causes of a problem rather than focusing too quickly on a single cause, a symptom of the problem, or on affixing blame. The why-why approach is a useful tool for moving from an early recognition of the problem to a more mature description of the problem.

It can be done simply. Divide a piece of paper into at least three horizontal sections. Write the problem in one section of the paper. In the middle section ask why this is a problem, ask why it happens, and list as many reasons for the problem as possible. The third section is the second level of “whys.” Here you write the reasons for the factors identified in the middle section. Add as many subsequent why sections as you need to sketch and understand the problem. An example, explaining the absence of ducks at a marsh site, is shown in [Figure 7.4](#).

Convenient and easy-to-use software tools have been developed to assist more sophisticated why-why models. Such tools can be easily found on the Internet by using the search term “fishbone diagram.”

7.5.13 RESTATEMENT

Once you have begun to define a problem or opportunity, restate it in as many ways as you can. Look at and imagine your situation from as many different perspectives as possible. The basic idea is to see your problem through many different sets of eyes to broaden your perspective of a problem.

The obvious place to begin is with your situation’s different stakeholders. Consider the problem of public elementary education in the United States. How would school administrators phrase the problem? What would politicians, students, teachers, administrators, janitorial services, the local newspaper, textbook makers, neighbors, crossing guards, and so on say?

Once you have exhausted the list of stakeholders, it can be helpful to think about how different professions and demographic groups would state the problem? What would engineers say? What about medical doctors, police officers, African-Americans, Asians, liberals, conservatives, the uneducated, the wealthy?

Imagine how different media would characterize your problem. What would CNN say? What about Fox News or ESPN? How would the magazines *Time*, *All About Beer*, *Vanity Fair*, *Popular Mechanics*, *Mad*, or *Home and Garden* state your problem? Finally, you might consider how specific individuals, real or not, might state the problem. What would the mayor or governor say? How about the president of the company or your fourth-grade teacher? What would JFK, Aristotle, Bart Simpson, Popeye, or Superman say about the problem?

This technique can be a lot of fun when an honest effort is made to explore the different perspectives on a problem. It is especially helpful for identifying biases and assumptions when your original problem description is compared to those you

TECHNIQUES FOR PROBLEM RESTATEMENT

Every problem can be viewed from multiple perspectives. Restating a problem as many ways as possible is a good way to explore these perspectives and the dimensions of a problem. To obtain a good definition of the problem, restate it in as many ways as possible. Here are a few ways to restate a problem that have proven effective. Restating should take no more than 5 or 10 quality minutes when you start with a basic statement of a problem.

Initial statement: Freshwater fish and invertebrate species are being eliminated.

1. Paraphrase: Restate the problem using different words without losing the original meaning.
Paraphrased: How can we preserve and restore freshwater fish and invertebrates?
2. 180 degrees: Turn the problem on its head.
180 degreed: How can we eliminate freshwater fish and invertebrate species?
3. Broaden the focus: Restate the problem in a larger context.
Broadened focus: How can we achieve greater biodiversity?
4. Redirect the focus: Boldly, consciously change the focus.
Redirected focus: Saltwater fish species are on the increase.
5. Use the why-why approach: Ask “why” of the initial problem statement. Then formulate a new problem statement based on the answer. Then ask “why” again and restate the problem based on the answer. Repeat this process a number of times until the essence of the “real” problem emerges.
Why? Because salinity levels are changing in the marsh.
Restatement: Salinity levels are changing in the marsh.
Why? Because salt water has entered this formerly freshwater marsh.
Restatement: Salinities in the freshwater marsh are increasing.
Why? Because the navigation channel has introduced a saltwater wedge to the river that feeds the marsh.
Restatement: Dredging has increased salinities in the marsh, eliminating freshwater fish and invertebrates.

identify. The goal is simple: Identify as many different ways of seeing and expressing the problem as possible. Write them down. Do you see the problem any differently? Do you understand it better? How can you best consolidate these views into a cohesive statement? The preceding text box (Techniques for Problem Restatement) offers a slightly different approach to the restatement technique.

7.6 THE P&O STATEMENT

Your problems and opportunities (P&O) statement is not real until it is written down. Your risk management activity should never be without a written list of current problems and opportunities. Once your list starts to take shape, it takes very little time, for example, in a team meeting, to ask if there are any revisions or evolutionary changes to be made to the P&O statement. Keep it current and up to date. Make sure every team member and all the significant stakeholders always have access to a current copy.

Publish it on your web page. Tell people that these are the problems as you see them. Ask them, “Do you agree? Did we get them right? Have we missed anything? Is there anything here that does not belong?” If your risk management activity is not in the public sector, ask your risk analysis team these same questions. Vet your work. It takes some time, but it takes less time to do it right than to do it over.

What should the P&O statement look like? It is short, a page or two at most if you have multiple problems and opportunities. Each problem and opportunity is succinctly stated in a sentence or two at most. They are numbered for convenience. Eventually, you may develop an expanded definition and description of each item, but you need not do so for the P&O statement. This is where risks are initially documented.

None of this brevity is intended to reduce you to sound bites and clichés. It is intended to focus the risk management activity and crystallize the attention of managers, assessors, and stakeholders. The statement enables you to say why you are conducting a given risk management activity. The risk assessment can still weave a story and explain the problems and opportunities in as much detail as necessary. Your P&O statement needs to be clear, concise, and complete. It is the reason for the risk management activity. In this respect, it is like a mission statement for the activity. Continuing the analogy, the objectives and constraints statement, then, is like the vision statement for the activity.

An optional step between the P&O statement and the risk assessment’s full definition of the problem is to prepare a fact sheet or problem profile, not to be confused with the risk profile. For example, a profile might identify the source that first recognized the problem, the public or extra-organizational concerns about the problem, as well as a few technical details to help flesh out the problem a little more. A simple template for a problem profile is shown in [Table 7.5](#).

How do you know you have a good P&O statement? When people understand it. If you show it to someone and they understand why you are doing an assessment, you have succeeded. How do you know if they understood it? You must vet it, publish it, communicate it, and seek feedback on it. How do you know when it is final? When people agree with it or at least accept it. It is final when you no longer find a reason to change it.

Do not wait until you have a good P&O statement to begin using it. A good statement takes time to develop, but a useful statement is the one you have. There are two things to do with a useful P&O statement: you can improve it or you can use it.

TABLE 7.5
Problem and Opportunity Profiling Template

Problem/Opportunity Profile

1. Source: What source first identified the problem or opportunity? Examples: higher authority, media, stakeholders, conversation with elected officials, experts, field observations.
2. Public concerns
 - a. Advocate: Who is the spokesperson for the problem or opportunity? Identify specific groups, agencies, and individuals.
 - b. Basis: What is the advocate's basis for the problem or opportunity? Examples: homeowners who have experienced flooding, state agency legally mandated to oversee wildlife resources.
 - c. Background: In the advocate's view, what is the problem or opportunity, and what are the causes and effects?
 - d. Other stakeholders: Who else believes the problem or opportunity does or does not exist? Why or why not? Identify specific groups, agencies, and individuals.
3. Technical analysis
 - a. Subject: State the problem or opportunity.
 - b. Location: Describe the location of the problem or opportunity; map it if possible.
 - c. Measurement: Identify one (or more) measurable indicator that is used to measure change in the problem or opportunity.
 - d. Conditions: Describe past, present, and future conditions related to the problem or opportunity:
 - (i) Historic condition
 - (ii) Existing condition
 - (iii) Future "without project" condition
 - e. Decision criteria: Identify any standard, target, or other criteria that may be used to define the magnitude of a problem or opportunity. For example: state water quality standards, design specifications, legislated targets, strategic plan goals, profits, costs, and so on as appropriate.
 Causes and effects: Describe causes and effects of the problem or opportunity.
 Conclusion: Does the technical analysis support the public concerns about the problem or opportunity? Why or why not? How do the historic, existing, and future conditions compare to any applicable decision criteria?
4. Problem/opportunity statement: Write a clear and brief description of the problem or opportunity.
5. Information

Sources: List sources of information about the problem or opportunity.

Information needed: Briefly describe the types of additional studies needed to address the problem or opportunity.

Source: Yoe, C., and K. Orth. 1996. *Planning Manual*. IWR Report 96-R-21. Alexandria: Institute for Water Resources.

7.7 TWO PROBLEM SOLVING TRAITS

Once the problems are identified, it remains to solve them. That, to a great extent, is what risk analysis is all about. Cognitive diversity and psychological safety can help you do that. Reynolds and Lewis (2017) report that increased diversity of gender, ethnicity, and age is apparent on executive teams. Popular wisdom suggests that more diverse teams are more creative and productive. Their research found no correlation between this type of diversity and team performance but it found *cognitive* diversity—differences in perspective or information processing styles—to be a good predictor of performance.

Information processing is the extent to which individuals prefer consolidating and deploying existing knowledge to generating new knowledge, when facing new situations.

Perspective is the extent to which individuals prefer deploying their own expertise to orchestrating the ideas and expertise of others, when facing new situations.

Source: Reynolds and Lewis (2017).

It is common practice to recruit in our own image. We gravitate toward the people who think and express themselves as we do. As a result, organizations can end up with like-minded teams. Functional bias is a problem for teams that face the new uncertain and complex situations that present themselves to risk managers. With little cognitive diversity, teams have limited ability to see things differently, engage in different ways like experiment versus analysis, or create new options. Cognitive diversity could generate accelerated learning and performance in the face of new, uncertain, and complex situations. When everyone agrees on what to do about your problem, find someone who disagrees and cherish them.

In more recent research, Reynolds and Lewis (2018) identify cognitive diversity and psychological safety as the two traits of the best problem-solving teams. Groups that perform well treat mistakes with curiosity. They share responsibility for the outcomes—an admirable trait for risk management organizations. This climate of psychological safety encourages people to express themselves, their thoughts, and ideas without fear of social retribution. [Figure 7.5](#) provides a taxonomy of four types of problem solving organizations. Characteristic behaviors and emotions of these organizations are described below (Reynolds and Lewis 2018).

Oppositional teams with high cognitive diversity and low psychological safety tend to be cautious, controlling, flexible, hierarchical, reasoned, and resistant. Defensive teams with low cognitive diversity and low psychological safety tend to be cautious, conforming, controlling, directive, hierarchical, and resistant. Uniform teams with low cognitive diversity and psychological safety tend to be appreciative, considered, controlling, competitive, flexible, and hierarchical. Generative teams, the best performers, have high cognitive diversity and psychological safety, and they tend

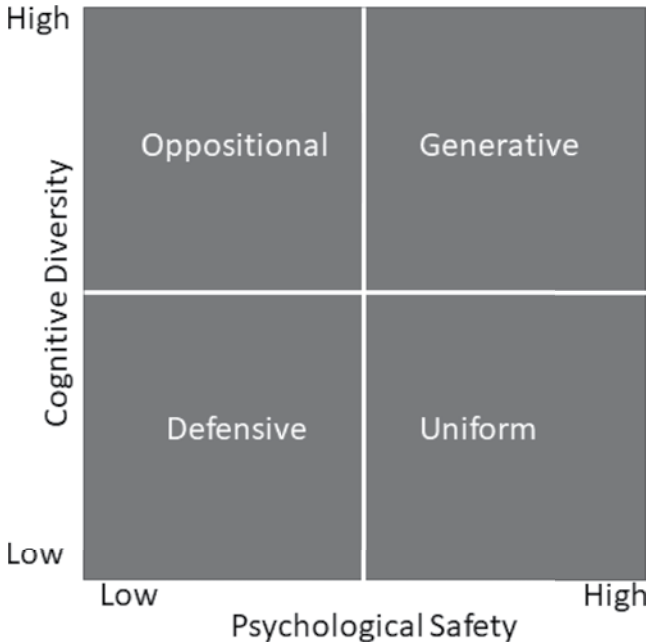


FIGURE 7.5 Reynolds and Lewis typology of team types.

to be curious, encouraging, experimental, forceful, inquiring, and nurturing. To be an effective risk managing organization, cultivate generational teams.

7.8 SUMMARY AND LOOK FORWARD

Problems are undesirable conditions we want to avoid. They usually require risk-avoidance strategies. Opportunities are desirable conditions we seek to capitalize upon. They usually require risk-taking strategies. It is critically important that problems and opportunities be as clearly and carefully identified from the outset of a risk management activity as possible. One of the most common and most avoidable weaknesses of a poor risk management activity is solving the wrong problem or failing to realize an opportunity.

Identifying problems and opportunities is important, these are your risks. Risk managers would be well served to know and use one or more problem-identification techniques. Several techniques to help you prepare an effective problems and opportunities statement have been offered in this chapter.

Many professionals are wary of techniques; they tend to regard them as gimmicky and unnecessary. My experience says some parts of the risk management process can be vastly improved with a good technique or two. Problem and opportunity identification is one such instance. Another instance is at the points in the risk management process where divergent thinking is needed. This is where brainstorming, another useful tool for the risk manager's toolbox, can be very helpful. Brainstorming is the topic of the next chapter.

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8 Brainstorming

8.1 INTRODUCTION

Good risk management begins with divergent thinking: lots of ideas and lots of different perspectives. Too often we are prisoners of our own beliefs, biases, mind-sets, organizational cultures, and authorities. We have difficulty seeing and accepting other perspectives on a problem and its solutions. We see more obstacles to opportunities than we see possibilities.

Every organization faces limitations on what it can and cannot do, but no organization should face a limitation on what it can think. If the best ideas are beyond your authority, new authorities may be obtainable. If they are really good ideas, someone else may be willing to implement them on their own. We can never be sure we have the best idea unless we have selected it from among many other good ideas.

Brainstorming is a proven effective methodology for generating ideas. In my experience, it is rarely used and when it is, it is not always used effectively. Follow-through and follow-up are often missing. Virtually everyone has heard of or used brainstorming techniques at one time or another, and most people have an opinion about brainstorming. With no research behind me and only my own gut instinct, I again offer my own pet theory. Adults, especially well-educated adults, do not like to use techniques. They seem gimmicky and unnecessary for smart people. Serious people often have difficulty thinking in an uninhibited fashion. So, despite its proven benefits, many people do not seem terribly fond of using group techniques like brainstorming.

There seems to be at least some support for this idea in the literature. Isaksen (1998) reports a National Science Foundation official at a conference saying, “We all know that brainstorming is nothing more than executive entertainment.” De Bono (1998) said of brainstorming, “It was designed for use in the advertising industry... Novelty and gimmicky does attract attention... I find that people who have a brainstorming background tend to perform rather poorly...they are always looking for the way out, exotic idea and often miss the simple, practical idea which is at hand.”

That is an unfortunate experience, if literally so, because I have used brainstorming consistently and always with good results. I have no solutions to help those uncomfortable with brainstorming feel more comfortable with it, beyond trying it a few times. It can be an invigorating and productive experience.

This chapter begins by considering some of the things you can brainstorm. The four cornerstones of brainstorming are identified, followed by four pitfalls to avoid. Suggestions for things to do both before and during the session are offered to help avoid the pitfalls and other problems during the session. Once this background is completed, we'll consider a range of oral and nonoral brainstorming techniques and follow this by carefully considering my favorite technique. This is followed by a description of the colored-dots evaluation process, which works well with large

groups. The chapter concludes by considering whether you need a professional facilitator or not.

8.2 WHAT CAN YOU BRAINSTORM?

Brainstorming can help us find solutions to problems, and risk managers often need to find creative solutions to problems. Actually, brainstorming can be used for a wide variety of purposes in a risk management activity. It may be helpful to use brainstorming techniques to frame and represent the problems and opportunities. Once the problem is articulated, brainstorming can obviously be used to formulate risk management options that could solve the problem.

Brainstorming can also be used to identify hazards of concern, opportunities for improvement, and stakeholders for an issue, or you can use brainstorming to figure out what the appropriate decision criteria or risk metrics might be. Brainstorming is a flexible tool that does not require a highly organized process. Once you master a few techniques, you'll find many opportunities to apply them.

8.3 BACKGROUND

Alex Faickney Osborn (1963), an advertising manager, is credited with at least popularizing, if not introducing, the brainstorming methodology in his book, *Applied Imagination: Principles and Procedures of Creative Problem Solving*. In the third revised edition of his book, Osborn offered four basic rules for brainstorming that are still valid today. They are presented here as the cornerstone concepts for a good brainstorming session. They are followed by four barriers to a good brainstorming process.

8.3.1 NO EVALUATION

Brainstorming is for generating ideas, not for evaluating them. Fear of criticism or of looking foolish is one of the major reasons people hold back their thoughts and ideas in open forums. To provide a safe and fun environment for generating ideas, there is no criticism of any idea during the brainstorming session. Neither is there praise for an idea. Divergent thinking is the goal of a brainstorming session and ensuring that people feel comfortable with the notion of generating unusual and incomplete ideas is essential to achieving that goal. In time, the ideas will need to be evaluated, but that does not occur during the idea-generation stage of brainstorming.

Related to the idea of no evaluation is the no censoring rule. Not only should individuals not evaluate the ideas of others, pro or con, they should not evaluate their own ideas. Do not censor your thinking; make an effort not to exclude or keep an idea to yourself. If it pops into your head and expressing it aloud will not land you in jail, then by all means share the idea.

8.3.2 UNUSUAL IDEAS

Brainstorming is not just after ideas; it is especially interested in unusual ideas. Creating an enthusiastic and fun atmosphere that encourages participation by all team

members will loosen the creative juices. Unusual ideas are welcomed for a couple of reasons. First, the seed of a solution is often found in an unusual idea. Some of our best solutions come from new ways of looking at the world. Second, unusual ideas often inspire others to generate unusual ideas of their own or to build on another's idea. Unusual ideas are contagious. Third, it is easier to back off from the weird ideas than it is to step up the tame ideas. Encourage everyone to exercise their creativity. Encourage people to consider wild ideas.

Work is serious. But work can be fun, too. The fun atmosphere is an important element of successful brainstorming, in my experience. In a serious atmosphere, wild ideas are just stupid, a waste of time. A bad experience with brainstorming is likely to sour one on the potential for this technique. So, do not overlook the importance of tending to the relaxed, fun aspect of brainstorming.

8.3.3 QUANTITY COUNTS

Another goal of brainstorming is generating the greatest number of ideas in the least amount of time possible. The more ideas generated, the more likely we are to have some really good ones. To get more ideas "out there" in a given period of time, don't worry about the details. A germ of an idea is sufficient. A word is often enough. Brainstorming is not the time for details. The best techniques are those that generate the longest list of ideas.

8.3.4 COMBINE AND IMPROVE IDEAS

Stealing and plagiarizing are encouraged. Take someone else's idea and tweak it. Take two ideas and combine them. Build on the ideas of others and add to their thoughts. Look to other ideas for your own inspiration. Hear a silly idea? Out-silly it. Keep the process going; feed on the creativity of the group. Adapting and improving an idea is every bit as valuable as generating an original idea.

8.3.5 FOUR PITFALLS

In addition to my own pet theory about an aversion to seemingly gimmicky techniques, the literature (Beasley and Jenkins 2003) identifies four common hurdles to brainstorming's effectiveness. These are group domination, free riding, "groupthink," and "groupshift."

Because the purpose of brainstorming is to involve the entire group in generating and sharing as many ideas as possible, group domination is one of the most deleterious problems that can arise. It occurs when one or a small number of participants from the group dominate the process and squash the creative energy of the group. This obviously reduces the likelihood that the effort will produce results of value.

The more hierarchical the structure of the organization, the more susceptible a group is to this pitfall. Junior, especially newer, employees are often inclined to defer to senior employees or supervisors. Intimidation is still the style of senior staff in some organizations. Some group members may defer to those with more responsibility for the effort, believing they have had an opportunity to think in more

detail about the issue and are better qualified to speak to the issues. In addition to the hurdles of hierarchy and responsibility, there are also individuals with, shall we say diplomatically, great confidence in their ability and a determination to present their views. The benefits of brainstorming may never materialize if any of these conditions are present.

Fortunately, brainstorming techniques like the “3× Yeah” process described later in this chapter can be designed to minimize the opportunities for group domination.

Free riding, sometimes called social loafing, can also limit the success of a brainstorming activity. It occurs when people fail to engage in or choose to disengage from the process. Free riders expect others to do the heavy lifting in the process. This phenomenon is more likely when a group is large and it is easy to hide or get lost in the crowd. People may disengage for a number of reasons, however, including the absence of a motive to participate, the lack of incentives for active participation, lack of buy-in to the team, and feelings of futility possibly even related to group dominance.

One of the more insidious reasons for free riding is fear of evaluation. There is often a strong negative reaction to this sort of group exercise, especially among those who fear they could lose dignity, standing, or credibility. These kinds of fears may prevent people from offering creative or even goofy ideas. They can also make people less likely to voice an unpopular idea or opinion. Some people may feel they lack the experience or qualifications to speak about a topic, or they may be afraid to do so in front of a more experienced group. Self-censoring and censoring can cause free riding in a group process. Prior notice of a brainstorming session and its agenda, accompanied by clear ground rules, an encouraging environment, and small groups can often offset a tendency to free ride.

Groupthink can arise from the snowball effect when a group is anxious to reach a consensus for any reason at all. It is another impediment to the creativity of a good brainstorm. Groupthink limits the number of ideas that are generated or, if the brainstorm includes an evaluation step, the number of ideas evaluated.

Any number of group dynamics may limit the members’ willingness to offer new or additional ideas. Some groups may be inclined to align too quickly with a single viewpoint on an issue. When this happens, it is easy for new ideas to reinforce the central idea and give rise to that snowball effect. Others, perhaps anxious to limit the pain of a brainstorming session, may quickly abandon their perspective in favor of the group’s emerging consensus. Groups are particularly susceptible to this effect when the individuals have not bought into the process and are anxious to get back to their “real” work. This dynamic can create a rush to judgment that counters the benefits of brainstorming.

Polarization or groupshift is a fourth pitfall to a successful group process. Consensus building is often a desired outcome of a brainstorming process. We would like to think that reaching a conclusion on an issue is a desirable thing. Groups can at times harden their positions on an issue. Those with a certain view of a problem, upon hearing the quite different views of others, may dig in their heels and harden their positions. Conservatives on an issue become more conservative and liberals on an issue become more liberal. Extreme views become more extreme, and the benefits of brainstorming are limited. Keeping evaluation out of the idea-generating portion of a brainstorming process is the best way to avoid groupshift.

8.4 AVOID PROBLEMS IN YOUR PROCESS

The best way to avoid the problems described in the previous section is with a well-defined process. That would be a process based on Osborn's four principles and one that intentionally seeks to minimize the manifestation of the four pitfalls described in the preceding discussion. A number of useful ideas can be gleaned from the literature (Panitz 1998; Beasley and Jenkins 2003; Sutton 2006) and from practical experience with the process. Some simple preparations will help with virtually any brainstorming technique.

There are a few things to do prior to the brainstorming session. First, know why you want to hold a session. You need a very specific topic, so carefully define the focus of your session. Someone or some group must identify the problem that needs to be solved by the brainstorming session. Make sure everyone is clear on the focus of your session.

Second, decide what kind of session you will run, who will run it, and whom to invite to it. There are any number of brainstorming techniques, as a quick Google search will confirm. A few specific techniques I have found success with follow. Every session needs a leader, and that person needs to be familiar with Osborn's principles, the things that can go wrong, and the technique being used. We will return to the idea of a facilitator near the end of the chapter when we discuss whether you need a professional facilitator or not.

Make sure you have the right people at your session. A small group is usually six or fewer (Aiken et al. 1994); a large group is more than six. A small group tends to complete tasks more quickly. It also minimizes the potential for group domination and free riding. A larger group tends to provide better solutions to problems and more ideas because there are more people thinking about the topic. The downside of a large group is that it tends to deter some people from participating. Although there are some specific large-group brainstorming techniques, a common compromise when faced with the need or desire to involve many people is to divide the large group into subgroups and to work at the subgroup level. You can have several small groups working at once.

Third, assign homework. Let everyone involved know what the problem is well in advance of the scheduled brainstorming session so that they can begin to think about it. Providing a context for the brainstorming session is important. This is also a good first opportunity to allay fears and to begin to create a comfortable environment for all to work in. The session leader should encourage all group members to use their different experiences and knowledge to enhance the process. Stress the value of fresh eyes from new employees and address other easily anticipated obstacles to openness at the time the session is announced. Also, let people know that this session will not be time-consuming.

Fourth are the logistic concerns. Secure a meeting space and prepare any necessary materials. These requirements will change with the type and size of your session. It is usually desirable to schedule the brainstorming session as a stand-alone meeting rather than as part of a larger meeting. Once the presession preparation is done, you can turn your attention to what needs to be done during the session. Six suggestions are offered.

First among the session tasks is to establish ground rules. The importance of this task is difficult to exaggerate. Establishing the ground rules is an essential part of providing a comfortable environment for the sessions,

which, in turn, is the best way to combat the pitfalls of brainstorming. Each group member should know what is expected of themselves and others. All participants should feel that their input is valued and that their voices will be heard. To that end, participants should understand how the session will proceed and how the ideas generated during the session will be used by risk managers.

Second, set the tone for the session. Value each individual and all ideas. Not everyone enters the session with the same expertise or commitment to the process, so it is vitally important to establish that comfortable environment. The leader must establish a tone that invites and encourages all members to contribute to the session. An open mind is to be valued over conformity during the session.

Third, establish a “zero tolerance” on all criticism, defensiveness, and commentary during the idea-generation stages of the session. Nothing can shut down the productivity of a brainstorming session faster than a laughing supervisor, rolling eyes, or a stern rebuke. Criticism can quickly put an end to one’s willingness to participate in the process. Comments and cross talk can also divert the session from its purpose to other topics, so they are best avoided. The facilitator needs to make it clear that no criticism of any idea will be tolerated during the session, without doing so in a heavy-handed way. One of the best ways to ensure this is to establish and enforce rules barring evaluation and cross talk during the oral brainstorming session.

Fourth, always encourage more ideas, not less. The group should make an effort to produce the largest number of ideas possible. A skilled facilitator may find it useful to reframe an issue to spur a growing number of ideas.

Fifth, credit the group, not individuals. Brainstorming is a group activity, and a good facilitator will recognize the group process and group ownership of ideas. Stressing the group process is more likely to increase the group’s interest in and commitment to the process than does recognizing individual contributions to the process.

Sixth, follow the rules or “it ain’t brainstorming!” The facilitator cannot remain silent if the group begins to lose its focus or if rules are violated. One of the reasons people are not fond of brainstorming is a prior experience in a poorly run session. We have all been asked to brainstorm when there were no rules or when the few rules that were in place were not followed.

8.5 A FEW GOOD TECHNIQUES

The variety of brainstorming techniques have been covered too well in too many places to compete with here. What I would like to do is distinguish between oral brainstorming and nonoral brainstorming techniques, then offer a more detailed consideration of a technique I have found easy and effective to use. Some, like Aiken et al. (1997), consider brainstorming to be oral idea generation, and they would call nonoral idea generation brainwriting. This distinction works well enough to adopt here.

8.5.1 BRAINSTORMING

Open brainstorming (Beasley and Jenkins 2003) is a process with few rules and procedures. It is characterized by its unstructured technique. Think of the leader standing at the front of a room writing down ideas as they come to mind in a free-for-all kind of *gestalt*. That is open brainstorming. It is frequently the first experience many of us have with brainstorming, and it often comes about when a meeting bogs down, someone says, “let’s brainstorm,” grabs a marker, and steps to the flipchart. Open brainstorming is prone to ignorance of Osborn’s simple tenets as well as to the pitfalls discussed previously (and many others not mentioned) that result from poor preparation. In general, open brainstorming is not going to be terribly effective.

SCAMPER

Alex Osborn posed questions to help spur brainstorming creativity that was adapted by Eberle (n.d.) into an easy-to-remember acronym:

- *Substitute*: What if I used a different ingredient, material, person, process, power source, place, approach, or tone of voice?
- *Combine*: Could I use a blend, an alloy, an assortment, or an ensemble? Could I combine units, purposes, appeals, or ideas?
- *Adapt*: What else is like this? What other idea does this suggest? Does the past offer a parallel? What could I copy? Whom could I emulate?
- *Modify*: Could I add a new twist? Could I change the meaning, color, motion, sound, odor, form, or shape? What other changes could I make?
- *Magnify*: Could I add something, such as more time or greater frequency? Could I make it stronger, higher, longer, or thicker? Could I add more ingredients? Could I duplicate, multiply, or exaggerate it?
- *Minify*: Could I subtract something? Could I make a condensed or miniature version? Could I make it lower, smaller, shorter, or lighter? What if I omit something, or streamline, divide, or understate it?
- *Put to Other Uses*: Are there new ways to use this as it is? Does it have other uses if I modify it?
- *Eliminate*: Could I remove anything? Could I disaggregate or decompose it?
- *Rearrange*: Could I interchange components? Could I use a different pattern, layout, or sequence? What if I transpose the cause and effect? What if I change the pace or the schedule?
- *Reverse*: Could I transpose positive and negative? What if I tried the opposite or reversed roles? What if I turn it backward, upside down, or inside out?

Round-robin brainstorming is a somewhat more structured technique that provides each group member with a turn to present his or her ideas. Turns do help minimize group dominance problems, but they can also stifle creativity and spontaneity.

Waiting for one's turn can lessen feelings of connectedness to the group, and it leads to productivity gaps as people wait for their turn. A common variation of the round robin is to ask for one idea at a time, going around the group until the supply of ideas is exhausted. Those who are out of ideas simply pass.

These techniques encourage social interaction and a high level of group cohesion. The disadvantages are that: people must take turns, a significant concern with large groups; ideas must often be summarized, and content is lost; the process lacks anonymity, so some people may not contribute or say what they really think.

8.5.2 BRAINWRITING

Brainwriting has been devised as a group of techniques that help overcome some of the problems with oral brainstorming. Brainwriting can be done in a face-to-face setting or in nominal group settings. Electronic brainwriting, using digital technology, has developed as a nominal group brainwriting technique in the last two decades. Brainwriting is characterized by individual and silent idea generation followed by written communication of these ideas. The greatest advantages of this technique are: no one needs to await a turn, so the group may be more productive; all ideas are recorded; anonymity can be preserved for all group members.

Brainwriting is less likely to require a professional facilitator, and it can work with people who have little experience with brainstorming. It is also useful when group domination is a real concern or when there is conflict among individuals in the group. Its principal limitation is that it may not meet the social interaction needs of group members, which could cause groupshift and the attendant hardening of polarized opinions (Aiken et al. 1997). There are probably as many brainwriting techniques as there are brainstorming techniques, so we will focus on two broad categories of techniques: poolwriting and gallery writing.

8.5.2.1 Poolwriting

Poolwriting pools ideas. Although the details of this technique vary widely, the basic steps are some version of those described by Geschka et al. (1981). Assuming the preparation has been done, poolwriting consists of:

1. Each individual silently writes down their ideas about the topic on a sheet of paper.
2. The papers are all placed in the center of the table (or some other pool).
3. Each individual takes a sheet of paper from the pool, reads the ideas on the new sheet, and uses them to stimulate new ideas, which are added to the sheet.
4. Once new ideas are added to the sheet, it is exchanged for another sheet from the pool. Often there may be a rule that at least one new idea must be added to a sheet before it can be returned to the pool.
5. Each individual continues to write down ideas and exchange sheets for three or more iterations.
6. An optional step would include reading aloud the ideas and evaluating them, once the writing is completed.

Anonymity is preserved by not signing the uniform sheets of paper. Everyone can work at the same time, so no time is spent waiting for a turn or listening to others. There is a permanent record of each idea generated. The downside of poolwriting is that individuals do not get to see all of the ideas generated during a meeting. Different people are likely to see different things. Some of these limitations have been overcome, and some advantages have been enhanced, by electronic poolwriting.

8.5.2.2 Gallery Writing

An interesting innovation of the poolwriting technique is to make the process a bit more open in a technique called gallery writing (Aiken et al. 1997). This also helps overcome the problem of limited exposure to the ideas generated in brainwriting. It involves some version of the following steps:

1. Flip chart papers are attached to the walls of a room, or the flip charts themselves can be placed around the sides of a room.
2. Each individual silently writes down their ideas about the topic on a sheet of paper.
3. Individuals wander around the room and record their ideas on the flipcharts.
4. Individuals then read others' ideas and add new ideas to the sheets of paper.

This technique moves people around the room instead of moving paper like poolwriting does. Gallery writing enables people to write and view comments simultaneously. This is believed to increase group cohesion, but at some cost of anonymity, as others can see what an individual is writing.

8.5.2.3 Electronic Brainwriting

Brainstorming techniques are being combined with software technology. Brainwriting techniques have been readily adapted to digital technologies in what has come to be called electronic brainwriting. Electronic brainwriting improves over the manual version by increasing anonymity. No one will recognize your handwriting, and no one needs to see what you write. This helps to remove organizational politics and personalities from the brainstorming process. Flexible scheduling and/or extended time periods can be offered for the session. This can enable better-developed contributions if participants have time to collect their own thoughts, read those of others, and reflect more on the topic after hearing new perspectives on an issue.

Some software systems may offer creative incentives to participants. Free-rider problems can be overcome, for example, by offering points based on the quantity and quality of ideas that enable participants to share in real (e.g., cash, compensatory time) or symbolic (e.g., plaques, candy bars) rewards. Incentives have been shown to be effective in improving idea generation outcomes (Toubia 2006). Electronic techniques are well suited to larger groups. For example, it is possible to open a process for an extended period of time, say two weeks, that enables participants to post ideas anonymously and continuously from anywhere in the world. They can work on their own schedule whenever an idea strikes them. Internet searches for electronic brainwriting software and electronic meeting systems will introduce you to some of the available options.

8.6 3× YEAH

The available brainstorming techniques are numerous. I learned my favorite one from Ken Orth, a planner and friend. It closely follows Olson's method, and although the use of a professional facilitator would no doubt improve the process, I do not believe that one is required. What is required, however, is a champion of the technique familiar with the approach who will be able to make the participants feel safe enough to get a little creative. The process, called "3× Yeah" (as in the Beatles' "Yeah, yeah, yeah"), is designed to add a little fun to it. It works like this:

- Provide materials
- Identify the question
- Explain the process
- Silent idea generation (brainwriting)
- Group idea generation (brainstorming)
- Preliminary evaluation
- Award prizes
- Follow up

You will need a workspace that is flexible enough to provide individuals with a private writing surface and enough room to break out into small groups of six or less. Paper and pencils are needed for private idea generation and a flip chart with markers (or some other communal form of recording, like a digital file) is needed for each group. Post-it flipcharts or some means to display the group results (e.g., LCD projector) are also needed.

The issue you are brainstorming needs to be clearly stated and well-focused. People need a specific task, a single question to which to respond. Brainstorming is not so good for ill-defined problems and general tasks. Every process begins with a well-defined question on which the group will focus.

For the purposes of better illustrating the process, we will use a learning example I have used in many classes: pizza tongue burn. We have all scalded our tongue or the roof of our mouth on a hot piece of pizza. We will call this problem "pizza tongue burn." Our task is simple: Identify as many ways to manage the risk of pizza tongue burn as possible.

The process itself is simple to explain. It has the following simple rules:

- No evaluation
- No judgment
- Quantity counts
- Time is limited
- Follow the process
- Generation of ideas is separate from judgment of ideas

Explain the importance of not evaluating or judging ideas. Stress the importance of not censoring one's thoughts. If something comes to mind, write it down; do not worry if it is a good idea or a bad one, a complete one or a germ of one. Capture it.

The goal is generating as many ideas as possible that are related to the problem we are solving. Let people know that this is a time-limited process. The entire process should take well under one hour. It is important to follow the process and to give it a chance to work. Let everyone know they will get a chance to evaluate the ideas when they are done generating them.

Group dynamics, as we now know, are a common impediment to a brainstorming process. When bosses, opinion leaders, or other strong personalities are in the room they can intimidate the other members, sometimes intentionally, sometimes inadvertently. To try to avoid this effect, the process begins with each individual silently generating a list of ideas. This is essentially a brainwriting task.

Make sure that everyone has several index cards or a piece of paper and something to write with. Ask them to write legibly because their ideas will be collected. Begin the process by telling them they have three minutes to list 10 ideas for managing pizza tongue burn. During this time, they are to work silently. If they can go beyond 10 ideas, please do so. After three minutes have passed, ask if anyone got more than 10 ideas. If anyone did, ask how many ideas they got. Then ask if anyone got 10, nine, and so on until most of the group has raised their hands. If you would like to inject a little fun into the process, toss the person with the most ideas a token prize of a candy bar or some other trinket that would be regarded as fun without crossing over into competitiveness or jealousy.

Congratulate folks on their efforts and results. Tell everyone to draw a line beneath their last idea and explain that the first time through we are getting all the obvious stuff, the easy ideas. Give them three more minutes and ask for 10 new ideas. Let them continue adding the ideas to their lists. After three minutes repeat the query of your group, asking if anyone got more than 10. Before moving on, ask if anyone failed to get any new ideas. It will be rare that someone did not; be gentle with anyone who comes up blank. Take the process seriously but have fun with it.

An experienced facilitator can decide if it is time to move into groups or to try one more round of silent idea generation. The basis for this decision will be the number of new ideas generated in the second go-round. If there are people getting five or more new ideas, it may be worth mining the group one more time. This time give them one minute and ask for three ideas. You never want to ask people to generate their own ideas more than three times.

The next step is to form small groups for some oral brainstorming. Use a random process of some sort to do this (see box). Counting off is a simple way to break the chosen seating patterns and to form groups. You want no fewer than three in a group and no more than six, but these are suggestions and not requirements.

COUNTING OFF

Instead of counting off by 3s or 5s to form small groups, try instead to ask someone for their favorite letter of the alphabet, TV show, city to visit, color, beer, or any random thing you can imagine. Write their response down for all to see. Then ask your next goofy question of another person. When you have as

many answers as groups you want to form have them count off by the answers, for example, A, *Leave It to Beaver*, Berlin, green. These become your group names and the exercise usually throws enough people that it can provide a few laughs along the way.

Warning—never attempt humor if you are humor impaired.

The group's charge is for people to take their lists of ideas with them and, as a group, to make the longest list of unique ideas they can, no repeats allowed. These ideas will be numbered and recorded by the group on flipchart paper, a computer, or some other medium that others will be able to see. The usual process is for everyone to offer one idea from their list going around the group until no one has any new ideas left. A freewheeling style is an acceptable alternative in this step of the process.

Everyone is encouraged to add new ideas to their list as they listen to others. If an idea gives them a new idea, interrupt, shout it out, add it to the list. If you can combine two or more ideas in a novel way, write it down, have the groups number their ideas. Offering the group with the most ideas a prize—ice cream on a stick, candy bars, an hour off with pay—can spur some friendly competition among the groups. Usually twenty minutes will be sufficient for this task. If you need more time, take it.

When the group idea generation is completed, ask each group to select their best idea, their worst idea, and their wildest idea. For a variation and to get people to read the ideas of others, have the groups exchange lists and vote these “honors” to another group's list. Have the group report back on its selections, collect the individual lists and flip chart paper, award prizes if you use them, and call it a productive hour.

The critical question now is what are you going to do with all of this information? If there is no productive follow-up, then you have just wasted an hour of everyone's time. What you have likely done, if you follow this process, is generated a lot of ideas from a lot of people in less than an hour.

Compile the suggestions and feed them back to all participants and interested others as swiftly as you can. Now it is time for convergent thinking, going from the many ideas to weeding out the weaker ideas to get to the best ideas. There are many creative problem-solving (CPS) techniques that can get you from your long list of ideas to a short list. You can even adapt some of the qualitative risk assessment approaches of [Chapter 10](#) to the task. Two good resources for this evaluation task include VanGundy's (1988) out-of-print book on structured problem solving and Mind Tools Limited's (2008) e-book. Two less modest recommendations include Yoe and Orth's (1996) chapters on evaluation, comparison, and selection of plans and Yoe's (2002) introduction to multicriteria decision analysis.

8.7 GROUP EVALUATIONS WITH COLORED DOTS

Group decision making is a complex topic supported by its own rich literature, a literature I choose to overlook here in favor of a simpler technique that has proven quite useful for group consensus finding. It is often useful to learn how a group

of stakeholders, the risk analysis team, or decision makers seem to think about an issue with alternative courses of action before more formal action is taken. One of the simplest ways to gauge the relative importance or desirability of a number of alternatives is to rank them.

The problem is there are a great many more-or-less sophisticated ways to do that. One of the more useful ones is to let everyone whose opinion is valued vote the strength of their preference. So, imagine that our 3× Yeah process has generated a great many ways to end the scourge of pizza tongue burn. How would the restaurant owners in a given chain decide which of these ideas should be implemented? Colored-dot voting is a simple visual way to quickly develop an idea as to whether consensus exists or not.

Ideally, the options would be arrayed on flip chart paper on the walls of a room. Each participant would be allocated a limited number of colored dots with which to vote. For simplicity, suppose each person got three different colored dots: blue, green, and red. Assign points to each color. Let blue = 3, green = 2, and red = 1. Allow the group time to roam about the room to examine the various alternatives that have been proposed. Ideally, this process might follow a reading of the ideas accompanied by a chance to clarify the meaning of each.

Each stakeholder has six points with which to vote. They may cast all their votes for a single alternative if they feel strongly enough about it, or they can distribute their votes across three different alternatives. When the voting reveals a clear preponderance of dots for a relatively few ideas, it is easy to quickly see the group's consensus. An absence of dots for an alternative is an equally compelling piece of evidence about the group's consensus. See <https://dotmocracy.org/> (Accessed January 2, 2018) for more on this technique.

The technique is neither sophisticated nor foolproof. But it can be compelling. If the only votes my favorite idea got were my own, I can quickly gauge its popularity. If it is subsequently eliminated from consideration, I may be unhappy about that fact, but in a democratic decision-making environment I can readily see that this was going to happen and that it is not the arbitrary whim of faceless risk managers.

8.8 DO YOU NEED A FACILITATOR?

Osborn's original description of the brainstorming process was designed with a facilitator as an essential part of the process. So, you might wonder whether you need a professional facilitator or not. There is literature that suggests that a group facilitator is necessary to get the most from a brainstorming session. No doubt this is true. Managing and facilitating the group's behavior is important if we hope to get the group's best effort. Oxley et al. (1996) found that groups with facilitators generated more ideas than those without. However, Isaksen (1998) reviewed related literature that showed facilitators were used relatively infrequently, in seven of 50 reviewed studies, to no ill effect.

Someone has to champion the process and be familiar with the brainstorming technique you are using. You are better off using a different problem-solving technique than using a poorly planned brainstorming session. If your idea of brainstorming is to go around the room and have everyone give you ideas, you'll probably be better

off with a facilitator. But brainstorming is not brain surgery, and you can get pretty good at it by doing it a few times and having it add value to your decision-making process. Planning and organizing the sessions, keeping it on subject and on schedule while trying to steer it toward some practical solutions is basically the job description for a session leader.

A facilitator becomes most valuable when a process bogs down or fails to find its energy. Being able to unstick a process is a skill an experienced facilitator can bring to a process. Keep in mind that each office or team has its own dynamic as well. Sometimes a group will respond differently to an expert than they will to you, even though you and the expert may do exactly the same things.

If the stakes are high, a facilitator can be useful. On the other hand, there is much to be said for building the capacity for brainstorming within your organization. Between VanGundy and the Internet you should have no problem finding a wide variety of techniques and tricks to keep a brainstorming session productive.

8.9 ADDENDUM

I have used the pizza tongue burn issue as a classroom exercise many times. One of these was during an online food safety risk analysis course. Although a discussion board is far from an optimal setting for a brainstorming session, participants offered more than 200 distinct solutions to the problem. When you have 200 ideas, a few of them have to be good, even if only by accident. The list was long and multicultural, but it was undeniably creative. I have culled 25 of the more “interesting” ideas, unedited, to give you a flavor for the results of a brainstorming process.

1. Remove tongue to avoid pizza “tongue.” (This is to echo a Chinese saying: “Chopping off your toes to avoid being bitten by sand worms.”)
2. Consume pizza without touching the tongue by feeding blended pizza through a stomach tube.
3. Have a pizza fool try the pizza first to ensure the pizza is not burning the tongue.
4. Make a wish or pray that the pizza will not burn your tongue, then eat the pizza with faith that the wish is granted or the prayer is heard.
5. Convey warning messages on package or on display such as, “Be careful to eat it when you are an old person or a child!”
6. Serving pizza on a cold plate.
7. [Let’s be serious for a moment.] Affix a label saying “Hot Pizza.”
8. Develop a pizza cheese additive that will color the cheese according to how hot it is (traffic-light colors could be used for temperature ranges).
9. Engineer pizza ingredients (cheese, ham, etc.) that cannot be heated beyond a certain temperature.
10. Develop a disposable heat-absorbing wrap/film that could be used to cover the pizza after it has been heated.
11. Develop a paper band that can be put on top of a pizza and that will change colors, similar to what is used to measure pH values of liquids.
12. Ban pizza consumption.

13. Develop consumer user-friendly temperature probes and educate consumer to measure pizza temperature prior to consumption.
14. Pizza burn crisis center with hotline.
15. To make children practice eating hot food at school lunch. We get a strong stimulus repeatedly, we can adjust ourselves to it. Likewise, if we practice eating hot food from childhood, we will be able to eat hot food more easily.
16. While you are eating pizza, asking someone to whip you and cause you pain in the hopes that it will get you to forget the pain in your tongue.
17. Add “how to prevent pizza burn” to school curriculum.
18. Be strong: pizza burn is nothing.
19. Sponsor a company to research and produce a cheese with a biothermal marker in it, so the pizza changes color as it cools.
20. Place pizza in strong plastic envelope and sit on it. Start counting each second. If you can reach 50 without burning yourself, it is okay to eat. If you have to stand up rapidly, then stop and get ready to repeat. Wait two minutes and repeat. This is known as “bottoming out” the pizza.
21. Obtain postcard with picture of President Obama shaking hands with President Putin. On the other side of this card in your own writing make a forgery of their signatures with a sentence giving you best wishes from them both. Go into pizza restaurant. Show the card to the manager and say: “If you serve me a pizza that burns my tongue; then I have to tell you as a consequence of the burn one of these two friends of mine will destroy your restaurant.”
22. Train an elephant to place its trunk through a window. Cook many pizzas at different temperatures and offer them to the elephant. Train the elephant to waggle its ears when the temperature is correct. Take the trained elephant to a pizza restaurant and park it outside near a window so that its trunk can reach your table. Only eat pizza when you see the elephant waggling its ears.
23. Give the delivery guy the wrong address.
24. Apply Orajel (or another numbing agent, e.g., Novocain) to tongue before eating. Assemble napkins or towels nearby to clean up the St. Bernard–like drool/mess that will inevitably result.
25. “Pizza burn” is an unheard-of phenomenon for a Chinese family from Guangdong.

8.10 SUMMARY AND LOOK FORWARD

Brainstorming is a simple, convenient and effective tool for promoting the kinds of divergent thinking risk managers need at different times in the risk management process. There are more variations of brainstorming techniques than you will ever need in a lifetime. The four sacrosanct elements of a good process are: quantity counts, no evaluation of ideas, unusual ideas are welcomed, and combining ideas to continue the process is desirable. Find a useful technique or two that combines these elements and use them. One good brainwriting technique and one good brainstorming technique should serve risk managers well.

Continuing our focus on risk management topics, the next chapter turns to economics. Someone is always going to care about costs, no matter what your other risk management objectives are. It is essential that every risk management professional understand a little bit about the economic realities of choice: we cannot do everything, and every choice costs us the opportunity to have done something differently. They also need to know a little something about how economic motivations influence the response to risk management decisions. These are the topics of the next chapter.

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9 Economics of Risk Management

9.1 INTRODUCTION

No matter what the risk management issue is, someone is always going to care about costs. Whether the problem falls in the realm of public health, public safety, profitability, or anything else, costs matter. This chapter* explains why costs, or opportunity costs as economists tend to think about them, should matter to everyone. Because costs matter, it is essential that all risk managers have some basic understanding of a few economic principles. These include scarcity, trade-offs, opportunity cost, marginal analysis, incentives, and rent seeking. The economic bases for interactions among people are considered along with a few principles of the economy as a whole. The chapter concludes by considering the difficult and subjective business of identifying and making trade-offs and the economic analysis techniques used to support those decisions.

9.2 ECONOMICS FOR RISK MANAGERS

Economics is the study of how society establishes the institutions and social norms that result in the allocation and distribution of its scarce resources. It includes individual behavior and such things as how people decide what and how much to buy, how to spend their time, how much to work, how much to save, and so on. It includes firms' behaviors, including what and how much to produce, as well as how to produce it. It helps to explain how firms will choose from the many ways they have to respond to a government regulation, compliance being only one of them. Economics includes how society, often through government, decides to divide its resources among national defense, public health, public safety, public works, consumer goods, protecting the environment, and other needs. Economics can help guide the choice in determining how much and what kinds of risk management are best for a firm or for society.

* I would like to gratefully acknowledge the many helpful comments and contributions of Dr. Richard Williams to this chapter. His knowledge of and experience in the world of public choice and regulatory economics are, if rivaled at all, rivaled by very few. The discussion of rent-seeking behavior and government failure are due to Richard, as is a significant portion of the first trade-off discussion. There is no part of this chapter that does not bear some part of his fingerprints.

RESOURCES

Resources are often grouped into categories such as land, labor, and capital. Land includes all natural, environmental, and agricultural resources. This includes everything that is in, on, under, and moving over the land as well as all that springs forth from it.

Labor includes all forms of human and animal work, intellect, and productivity. Capital resources are basically everything else. This includes all means of production and everything that has been produced for the benefit of society.

Resources are real things. Do not confuse them with financial resources. The two are similar only to the extent that financial resources are useful only insofar as they enable one to command real things.

Decision making is at the heart of economics. Decision making under uncertainty is at the heart of risk management. It stands to reason that the two disciplines are closely intertwined. Mankiw (2009) offers 10 economic principles for understanding how people make decisions, how they interact, and how economies as a whole function. They are:

1. People face trade-offs.
2. The cost of any action is measured in terms of forgone opportunities.
3. Rational people make decisions by comparing marginal costs and marginal benefits.
4. People respond to incentives.
5. Trade can be mutually beneficial.
6. Markets are usually a good way of coordinating trade.
7. Government can potentially improve market outcomes if there is a market failure or if the market outcome is inequitable.
8. Productivity is the ultimate source of living standards.
9. Money growth is the ultimate source of inflation.
10. Society faces a short-run trade-off between inflation and unemployment.

These principles provide effective touchstones for the topics presented in this chapter.

9.3 ECONOMICS AND DECISION MAKING

Individuals, businesses, government, and society at large all make decisions. Economics offers several insights into the aspects of decision making that risk managers cannot afford to ignore. Six of these aspects are offered here. They are scarcity, trade-offs, opportunity cost, marginal analysis, incentives, and rent seeking.

9.3.1 SCARCITY

Scarcity is a fundamental fact of life. Resources are limited in relation to society's wants and needs. We simply do not have enough resources to do everything we

want or need to do. This simple fact of life holds true for the individual, the firm, government, and society at every imaginable level.

9.3.2 TRADE-OFFS

Because of scarcity, we cannot do everything, so we have to make choices. By their nature, choices require that we do one thing and not do another. Why did we choose a baked potato instead of french fries? Why did we watch one television program and not another? We are not always able to articulate why we choose to do certain things. Most of our choices are context-specific, that is, they change depending upon the context in which they are made. The fact is, whether we can articulate why we do what we do or not, we always are choosing between at least two options, and choices require trade-offs.

It is important to distinguish between private choices, such as the examples just given, and public choices. When making private choices, we can resolve the trade-offs in any way we choose. Public choices are those made in the public sphere, and they often involve consequences for many people. The choice made by a risk manager may have personal consequences (e.g., a philosophical desire for a particular outcome, job promotion, or a desire to reward one's allies), but the choice also has consequences for those who benefit from and those who bear the costs of the choice. In some cases, such as local political issues, those who are impacted by the choices may affect the outcome directly through voting. In other cases, such as when the appointed head of a federal regulatory agency makes a decision, those affected have little control over their fate.

Whether acknowledged or not, public choices require trade-offs, often of multiple effects. For example, increased public health protection increases costs that must be paid for by consumers and may result in job losses in affected industry. A public choice to allow speed limits to increase (the benefit is reducing travel time) may increase the risk of death and injury. Some public trade-offs are obvious, such as paying more for increased security, health, or safety, but others are indirect and require study to understand.

An important recurring social trade-off is that of efficiency versus equity. Efficiency means society is getting the most from its scarce resources, that is, what is sometimes called "getting the biggest bang for the buck." Suppose there are two ways to prevent people from crashing at a local intersection and both have the same probability of reducing crashes. One is a stoplight that costs \$300 per year and another is to have a full-time police officer directing traffic for \$30,000 per year. It would be inefficient to hire the police officer. In fact, by buying the stoplight you could, if you wished, get 99 more stoplights that might save many more lives at the same cost as one police officer.

Equity refers to how resources are distributed, not how efficiently they are used. If in the previous example, a public decision maker decided that the police officer deserved the job to achieve some sort of social justice, then that would be a decision based on equity. When risk managers choose, for example, to protect a small minority of consumers who are at high risk (either highly sensitive or highly exposed), those decisions generally are more driven by equity than efficiency. One could argue that

money spent on the Transportation Security Agency's air travel security rather than on feeding the hungry, reducing highway deaths, or providing health care is an equity decision rather than an efficiency one. Most decisions in government involve elements of efficiency and equity, and they are often in opposition to one another. Those who are stewards of some public trust must always choose, that is, make trade-offs between efficiency and equity.

As long as there are choices to be made—and every decision problem has at least an action/no action choice—there will be trade-offs. Decision making is best served by making the nature of the trade-offs explicit. Benefit-cost analysis, an economic tool, has been developed to try to help decision makers identify the trade-offs with a common metric (dollars). It is one tool by which trade-offs can be addressed. We'll return to this topic later in the chapter. For now, it is sufficient to understand that most risk management decisions will entail trade-offs.

9.3.3 OPPORTUNITY COST

If you think of cost as the money price of obtaining something, think again. Economists wish to challenge that notion. The cost of something is what you must give up to get it. Cost is measured in real things sacrificed for a choice. Money, the most common measure of cost, is simply a shorthand means of communicating what economists call opportunity cost. When we choose one thing we have simultaneously forgone the opportunity to have chosen another. This is the essence of opportunity cost.

Any one risk management option (RMO) will cost us the opportunity to have chosen other RMOs and other real outcomes. Opportunity cost is one of the most important concepts to grasp because it is not well served by simple accounting measures. This is in part because of the differences between explicit and implicit costs.

OPPORTUNITY COST EXAMPLE

If you go to the vending machine and come back with a bag of M&M's and I ask what that cost you, you are likely to reply \$1, or whatever the money cost was.

But if you stood before the machine with your only dollar, weighing the choice of a Twix, candy with a cookie crunch, or M&M's, melts in your mouth not in your hands, then chose the M&M's, that choice cost you the opportunity to have a Twix. So, the economist's answer is: the M&M's cost you a Twix. It is a real thing foregone.

Others may have chosen a bag of chips, a peppermint, pretzels, and so on. It becomes unwieldy to list all the opportunities foregone by a single purchase with so many different people and preferences, so money prices serve a wonderfully efficient shorthand means of communication. When we say it costs \$1, that stands for everything real you could have done with that \$1.

Imagine the Rolling Stones on tour yet again. Face value on a ticket is \$1,000 and you have one for row three. As you walk into the arena you see an aging hippie in a ponytail and red Converse All-Stars holding a sign announcing he will pay \$3,000 for a seat in the first three rows. You smile and walk into the concert. What did it cost you?

Your explicit costs were \$1,000. Think of explicit costs as those costs you must pay from your income or savings. But there was also an implicit cost to your going to the concert. When you saw the sign, you had a choice: Sell your ticket for \$3,000 or see the concert. Had you sold the ticket, you could have reimbursed yourself \$1,000 for the explicit cost of your ticket and made a tidy \$2,000 profit. When you decided to keep your ticket, you were saying no to a \$2,000 gain. This \$2,000 is an implicit cost of your decision. Think of an implicit cost as an opportunity for gain that you declined. Opportunity cost is explicit cost plus implicit cost, in this case $\$1,000 + \$2,000$. The concert cost you \$3,000. Note that this example conveniently ignores other associated costs, some explicit (travel and hotels perhaps) and some implicit (the value of your time spent going to the concert) to keep the example simple.

It is very easy for a decision maker to take an incomplete view of costs. It is important for someone to carefully consider the opportunity costs of your risk management decisions.

There are several notions of opportunity costs that are important in the public sphere for risk choices. The first is that individuals make private choices to reduce their own risks all of the time. Buying a Mercedes rather than a Toyota Tercel may at least in part be because they are safer cars. Having regular medical and dental checkups reduces risks. Smoke detectors are an excellent investment in risk reduction. When government spends to reduce risk, one opportunity cost is that the people who pay taxes to support government programs have less money to make their own private expenditures to reduce risk.

The next notion is that there is an almost limitless menu of public risks that we ask government to address. Workplace safety, food safety, drug safety, airline safety, terrorism, crime, mental health, education, and literally every sphere of life is affected by public-sector decisions. If we think of risk as, for example, risk of death, it becomes a reasonably easy job to compare how much it costs to reduce various risks associated with death. We can compare the costs of reducing one death from cancer to the costs of reducing one death from a car accident, for instance. When we do, we discover that there is an extremely broad distribution of costs of lives saved. With limited resources, the opportunity cost of addressing one risk rather than another becomes a significant concern. Any risk manager who has been faced with the need to set risk management priorities—as is done routinely in food safety, health care, international trade, and many other areas of responsibility—knows this only too well.

Tengs et al. (1995), in a fascinating but now dated study, identified the cost per year of life saved for 500 different measures. The costs ranged from negligible, for such measures as smoking advice for pregnant women, compression stockings to prevent venous thromboembolism, and automatic seat belts in cars, to much higher amounts. [Table 9.1](#) shows some sample values selected from the appendix of Tengs' paper.

Imagine yourself as the risk management czar with the power to enact RMOs that can impose costs of up to \$100 billion on society. If your objective is to preserve life,

TABLE 9.1
Selected Lifesaving Interventions and Their Cost Effectiveness

Risk Reduction Measure	Cost per Year of Life Saved
Mandatory seat belt use and child restraint law	\$98
Flammability standard for upholstered furniture	\$300
Mandatory motorcycle helmet laws	\$2,000
Dual master cylinder braking system in cars	\$13,000
Ban asbestos in brake blocks	\$29,000
Kidney transplant from cadaver	\$29,000
Ban asbestos in specialty paper	\$80,000
Annual mammography for women age 40–49	\$190,000
Benzene emission control at pharmaceutical manufacturing plants	\$460,000
Annual cervical cancer screening for women age 20 and above	\$1,500,000
Ban asbestos in thread, yarn, etc.	\$34,000,000
Trichloroethylene standard of 2.7 (vs. 11) microgram/L in drinking water	\$34,000,000
Control of benzene equipment leaks	\$98,000,000
Sickle cell screening for non-Black low-risk newborns	\$34,000,000,000
Chloroform private well emission standard at 48 pulp mills	\$99,000,000,000

Source: Tengs, T.O. et al. 1995. *Risk Analysis* 15 (3): 369–390.

what measures will you enact? You could impose a chloroform private well emission standard at 48 pulp mills and save one year of life and be done with the task. Or you could begin by imposing a mandatory seat belt use and child restraint law that would only cost \$98 for every year of life saved. The National Highway Transportation Safety Administration estimates that seat belts save 11,000 lives annually. If, for convenience, we assume an average additional life expectancy of 35 years, that is 385,000 years of life saved at \$98 per year for a total cost of about \$38,000,000—a much better deal than the chloroform standard. This is not the intended use of Tengs' data so much as a convenient gimmick to enforce a point.

Note, also, the relative costs of the asbestos bans and benzene controls. These suggest that total bans on the use of substances may not always be the most efficient risk management strategies. Recall that your \$100 billion of costs imposed on society will also affect the ability of taxpaying citizens and industries to pay for private risk reduction decisions. The opportunity costs of RMOs often involve some risk-risk trade-offs somewhere else along the line. It is wise to consider them.

9.3.4 MARGINAL ANALYSIS

Rational people are systematic and purposeful in trying to do the best they can to achieve their objectives. In economics, this means we make decisions by weighing, if only qualitatively, the costs and benefits of our actions when we act rationally. Acting rationally is taken as a minimum requirement for risk managers. If they do not decide rationally, they should. Likewise, people affected by an RMO will respond

TABLE 9.2
Costs of Different Regulation Levels for a Pathogen

Regulation Level (ppm)	Total Social Cost	Marginal Cost [MC]
100	\$0.50	NA
90	\$1.25	\$0.08
80	\$3.00	\$0.18
70	\$5.00	\$0.20
60	\$7.25	\$0.23
50	\$10.00	\$0.28

to it in a way that is rational for them. If risk managers do not seriously consider the rational responses to their decisions, the desired risk management objectives may not be realized.

A rational person will consider marginal changes, that is, incremental adjustments, to an existing plan. Imagine we have a public health risk issue and we are trying to decide how much regulation is appropriate. There is a hazard associated with a food, and it can be reduced to varying extents at the costs shown in [Table 9.2](#). Note that there are two costs shown. Total cost indicates it would cost \$0.50 to reduce the pathogen to 100 ppm but \$10 to get it down to 50 ppm.

In addition, there is the cost of each additional increment of pathogen reduction via increasing regulation level. This is marginal cost (MC), the cost of one more unit of hazard reduction. Think of marginal cost as the change in cost required to produce one more unit of output; in this case, output is the regulation level or hazard reduction. It is defined as the change in total cost divided by the change in output. Going from 100 ppm to 90 ppm, costs change by \$0.75 while the hazard reduction changes by 10 ppm. Thus, $\$0.75/10$ yields the marginal cost of \$0.075, say \$0.08, for each additional part reduced. At some point, marginal cost tends to exhibit the increasing trend shown in [Table 9.2](#).

Hazard reduction is expected to have benefits for society, and these benefits are shown in [Table 9.3](#). Total benefits range from \$4 for a reduction to 100 ppm to \$10.75

TABLE 9.3
Benefits of Different Regulation Levels for a Pathogen

Regulation Level (ppm)	Total Social Benefit	Marginal Social Benefit
100	\$4.00	NA
90	\$7.00	\$0.30
80	\$9.00	\$0.20
70	\$10.00	\$0.10
60	\$10.50	\$0.05
50	\$10.75	\$0.03

for a reduction to 50 ppm. What we gain from each increment of hazard reduction is the difference in the total social benefit divided by the difference in the hazard reduction. This is called the marginal social benefit in the table. In going from 100 to 90 ppm, benefits rise from \$4 to \$7, a change of \$3. The hazard level also changes by 10 ppm, so $\$3/10 = \0.30 , as shown.

We see that marginal benefits (MB) are decreasing. This is a common pattern that results from the economic principle of diminishing marginal utility. It means that, usually, the more you have of something (including risk-reducing regulation), the less valuable additional units of that thing become.

Given these facts, the question for risk managers now becomes what is the most appropriate level of hazard reduction in this instance? Risk management decisions can be based on science and social values, so any answer is in fact possible. However, one of the social values that people will always care about, especially with public decision making, is economic efficiency. Economic efficiency relies on marginal analysis, and this is not intuitive for many risk managers and stakeholders.

Should society pay \$10 to reduce the hazard to 50 ppm? Its value to society is, after all, \$10.75. Would you trade \$10 for \$10.75? Most people would say yes. [Table 9.4](#) shows a net profit to society for every level of hazard reduction through regulation.

However, the answer changes rather dramatically when we use marginal analysis to choose the optimal level of hazard reduction. Note, for example, that net social benefits rise to a maximum of \$6 at a hazard level of 80 ppm, then decline to \$0.75 at 50 ppm. In a world of scarcity, where we cannot do everything, we do not want to waste resources. Choosing 50 ppm wastes resources, as the marginal analysis in [Table 9.5](#) shows.

[Table 9.5](#) reproduces all of the information from [Tables 9.2](#) through [9.4](#) and adds two new columns. Note that the table shows a positive level of net social benefits for every level of hazard reduction, as noted previously. Now look at the marginal cost and marginal benefits. If you held the marginal cost in your hand, would you trade that sum of money for the corresponding amount of marginal benefit? That is, in its essence, the choice the risk manager is making on society's behalf. Would you trade \$0.05 for \$0.40? Of course, you would. The net gain is \$0.35 for every additional ppm reduced, that is a good deal for you and it would be a good deal for society as

TABLE 9.4
Total Net Social Benefits for Different Regulation Levels for a Pathogen

Regulation Level (ppm)	Total Social Cost	Total Social Benefit	Net Social Benefit
100	\$0.50	\$4.00	\$3.50
90	\$1.25	\$7.00	\$5.75
80	\$3.00	\$9.00	\$6.00
70	\$5.00	\$10.00	\$5.00
60	\$7.25	\$10.50	\$3.25
50	\$10.00	\$10.75	\$0.75

TABLE 9.5
Marginal Analysis of Different Regulation Levels for a Pathogen

Regulation Level (ppm)	Total Social Cost	Total Social Benefit	Net Social Benefit	Marginal Cost [MC]	Marginal Social Benefit	Marginal Net Benefit	Do It?
100	\$0.50	\$4.00	\$3.50	\$0.05	\$0.40	\$0.35	Yes
90	\$1.25	\$7.00	\$5.75	\$0.08	\$0.30	\$0.23	Yes
80	\$3.00	\$9.00	\$6.00	\$0.18	\$0.20	\$0.03	Yes
70	\$5.00	\$10.00	\$5.00	\$0.20	\$0.10	−\$0.10	No
60	\$7.25	\$10.50	\$3.25	\$0.23	\$0.05	−\$0.18	No
50	\$10.00	\$10.75	\$0.75	\$0.28	\$0.03	−\$0.25	No

well. Would you spend \$0.08 for a \$0.30 gain? Yes. Would you incur marginal costs of \$0.18 for a chance to gain \$0.20? Sure. Would it be wise to spend \$0.20 to gain \$0.10? No. We would not make this deal knowingly. So, we would stop at 80 ppm because it is the last level of hazard reduction that paid for itself. Not coincidentally, this is also where net social benefits are maximized.

The rule for rational marginal behavior is to undertake any change for which $MB \geq MC$ and avoid any change where $MB < MC$. Applying this rule will also maximize total net benefits to society. Looking at marginal net benefits, we see they exceed zero for 80 ppm but become negative for any additional reduction. In a world where it is not possible to do everything, it is wise to avoid doing things that require costs in excess of their value to society. Risk managers should take care to request information in a marginal analytical framework so they can better see the trade-offs between benefits and costs.

9.3.5 INCENTIVES

People respond to incentives. Incentives are rewards or punishments that induce people to act in specific ways. When gasoline prices rise, people drive less and they buy more hybrids and fewer SUVs. Likewise, with risk management, people respond to incentives. It is important to understand both the intended and unintended incentives associated with a risk management option.

Consider a hypothetical contaminant in a food. Suppose a baseline study of 10 businesses shows that all 10 test for the contaminant, but five do not test adequately; that is, they use neither a sensitive enough method to detect the contaminant down to the lowest levels that matter nor do they test frequently enough to actually reduce risk. Imagine an RMO that requires mandatory testing for the contaminant at the level and frequency that the regulator believes is adequate, based on marginal analysis. Food-safety regulators may expect they have solved the problem by requiring testing to assure no more than 80 ppm.

This requirement has an incentive effect on businesses, but it may not be the expected one. Changes in requirements present people with choices that necessitate

changes in behavior. So, imagine that two of the firms not testing adequately decide to meet the requirements, one goes out of business, one chooses to stop testing altogether to lower costs and hopes not to be detected by inspectors, and another moves the company overseas where there are no testing requirements. For the last two companies, risks may have actually increased. The RMO provides everyone with a choice of how to respond. An RMO may present some with a reward and others with a punishment. Those already testing are rewarded by the increased cost of operation imposed on their competition by the RMO. Companies not already testing are punished by higher costs of operation. Responses to these incentives should be anticipated by risk managers.

It can be useful, at times, to incentivize an RMO to ensure faster and more complete implementation of the planned measures by those responsible for implementing the measures. Subsidies, rebates, tax breaks, coupons, and such can be effective financial incentives. Helping affected parties understand and then realize the benefits of the measures can also be helpful.

9.3.6 RENT SEEKING

Rent seeking is a special kind of incentive, worthy of its own discussion. It is easy to imagine that all choices made by public managers should be made with the best interests of people at heart, whether that means being more efficient or more equitable. In reality, it is not always or even often done this way. The study of “public choice” is dedicated to understanding how choices are actually made in the public arena, instead of the way we would like to think they are made.

Whenever government has the power to make choices for others, and some will benefit and some will lose, people are willing to expend resources to try to influence decisions in a way that benefits them. That behavior is called “rent seeking.” The term *benefit* is defined here to mean that they either gain financially from the decision or they seek to gain an outcome from the decision that matches their personal philosophy.

In the testing example considered above, consider that some firms gain from having their rivals spend more to increase testing. Such a requirement would be worth trying to influence in the hopes that the regulator decides in that way. If you are the firm that is not testing sufficiently, you might invest in lobbying to avoid it. Some, in the advocacy sphere, may spend to advocate for testing because they believe the product is unsafe.

Those who are both best organized and most committed tend to lobby for or against the regulation to realize the most gain from the decision. Those who bear the costs of the decision, usually widely distributed among consumers, generally will lose in this situation. Individual consumers have so little to gain or lose from the decision that such groups rarely unite to protect their collective (often large) interests. In many cases, there are politicians and bureaucrats who also may gain by rewarding rent seekers.

This system of rent seeking, rent avoidance, and political and bureaucratic rent distribution is well entrenched in the 150 regulatory agency systems of the United

States. It is just as important to understand why certain decisions get made and how we can avoid the worst excesses of this system as it is to study rational ways to address risks.

9.4 ECONOMIC BASIS FOR INTERACTIONS AMONG PEOPLE

9.4.1 TRADE

Trade includes both interstate commerce and international trade. A great deal of the recent rising interest in risk analysis can be traced to international trade issues. As used here, the term *trade* means that rather than being self-sufficient, people can specialize in their careers and firms can specialize in producing one good or service and exchange it for other goods. Individuals as well as countries benefit from specializing and then trading.

Trade provides for a greater variety of goods from which consumers can choose. It also frequently offers a better price abroad for goods that domestic firms produce. Conversely, we can often buy other goods more cheaply from abroad than can be produced at home. The mutual benefits of trade ensure that this will remain an important dimension for many risk management decisions.

SPS AGREEMENT

The Agreement on Sanitary and Phytosanitary Measures (SPS) grew out of the Uruguay round on multilateral trade negotiations from 1986–1994. The SPS Agreement recognizes the right of governments to protect the health of their people from hazards which may be introduced with imported food by imposing sanitary measures, even if this means trade restrictions. It obliges governments to base such sanitary measures on risk assessment to prevent disguised trade protection measures.

Sanitary measures need to be nondiscriminatory, not more trade-restrictive than necessary, and based on sufficient scientific evidence. In order to harmonize these measures as widely as possible governments should base their sanitary measures on international standards where they exist.

9.4.2 MARKETS

A market is a group of willing buyers and sellers. Thanks to international trade and technology, they no longer need to be in a single location. Markets are used to organize economic activity in most countries around the world. Planned economies, the primary alternative to market economies, have waned with the fall of Communism, and even nominally Communist countries today have mixed economies that rely on markets to varying extents. International trade is almost exclusively a market activity.

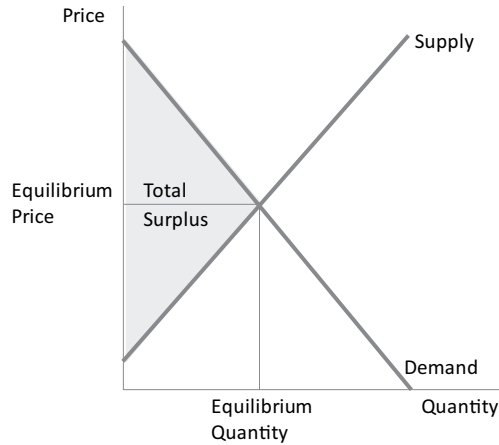


FIGURE 9.1 Market forces of supply and demand determine equilibrium price and quantity while maximizing total surplus to buyers and sellers.

Markets are used to decide what goods to produce, how to produce them, how much of each to produce, how much to charge for them, and who gets them. Market economies answer these questions through the decentralized decisions of many consumers and firms as they interact in markets.

Supply (willing producers and sellers) and demand (willing consumers and buyers) interact in a market and determine both prices and quantities of goods and services that change hands. Prices function to allocate society's scarce resources. Price simultaneously reflects the good's value to buyers and the supplier's cost of producing the good. Market-determined prices guide self-interested consumers and firms to make decisions that, in most cases, maximize society's economic well-being (see [Figure 9.1](#)).

Market operations sometimes transform risks. Risk management options can have unanticipated effects on markets and market prices. A desire to protect infants in airplanes might result in a requirement for parents to purchase a seat and use a safety restraint. The increased cost of family travel may cause more families to choose to drive, which could result in more infant deaths in highway accidents. Thus, an effort to reduce the risk of infant deaths could result in an increase in infant deaths due to consumer responses to market incentives.

Prices provide incentives to consumers and producers. Risk managers are well advised to consider the price/incentive effects of any RMO they are considering.

9.4.3 MARKET FAILURE

When markets work, they can work very well in allocating resources. Sometimes markets fail to allocate society's resources efficiently for a variety of reasons. When this happens, government intervention has the potential to alter and improve market outcomes.

Common causes of market failure include:

- Asymmetric information
- Market power
- Externalities
- Nature of certain goods

Asymmetric information occurs when one party knows more about a product than another. If exporters sell a product with melamine in it to give the impression of a higher protein content, this is asymmetric information. If a peanut product company continues to sell its products after they have tested positive for *Salmonella*, that is asymmetric information. Buyers, unaware of the facts about the quality of the product, may overestimate the value of that product and unwittingly pay a price that is greater than the true value of that product to them.

Asymmetric information can be a two-way street. Buyers with inside information can benefit if a large entertainment company buys land in a rural area with the intention of building an entertainment park or with the knowledge that there will be a zoning change. They may pay a price substantially under its true market value. Risk communication can be an effective tool for correcting certain asymmetries of information.

When a single buyer or seller can exert significant influence over prices or output, we can observe a failure by market power. Monopolies are the best example. Here a single firm can set the price for their good at any level they desire. Although monopolies provide the best-known example of market power, any imperfectly competitive situation can distort the market outcome. Market power enables a producer to charge more and produce less than the social optimum would dictate in a market.

Risk management options that reduce competition or help consolidate market power can contribute to market failures. On the other hand, government RMOs may be designed to reduce market power and to promote efficiency in markets as well. Just as RMOs can affect market operations, market operations can sometimes make effective RMOs.

An externality is an economic side effect, and it occurs when an economic activity (consumption or production) affects a bystander to that activity. These side effects are never fully reflected in the prices of goods. Externalities don't enter the cost or benefit decisions of either buyers or sellers; that is why they are called external. They can be harmful (negative externalities) or beneficial (positive externalities), but the harmful ones seem to attract more attention.

Pollution risks are the classic example of a negative externality. Food-borne illness in the United States was estimated to cost \$152 billion in health-related costs (Scharff 2010). These are serious public health externalities, as are the additional costs to industry from reputation externalities and recalls. It is easily argued that RMOs have the potential for significant positive externalities to the extent that they can reduce some of these effects. Addressing negative externalities has long been a primary motivation for government regulation of industry.

The final cause of market failure is related to the nature of the good itself. What firm, for example, can produce public health or public safety? There are some things that can only be consumed by everybody (relatively speaking) or nobody at all. These are called public goods, and they have distinct characteristics. They are:

- *Nonrival*: One person's consumption of them does not stop another person from consuming them, that is, the supply of the good is not reduced when a person consumes it.
- *Nonexcludable*: If one person can consume them, then anyone can consume them, that is, it is impossible to stop another person from consuming them.

A subset of these public goods is also nonrejectable. People can't choose not to consume them even if they want to. National defense, homeland security, and public health are examples of nonrejectable public goods. Risk management options can increase the supply of public goods.

Some risks threaten common goods. Nations that continue whaling provide such an example. Common goods are goods that are nonexcludable but are rival. Many environmental resources are common goods. Government regulations can sometimes effectively reduce the risk to common resources.

9.4.4 GOVERNMENT FAILURE

Market failure should always be compared to the possibility of government failure. Even when we can identify a market failure, we cannot guarantee that government intervention will improve on the situation. The previous section on rent seeking shows that governments, when influenced by special interests, can make decisions that are not "rational" in an economic sense.

If there is such a thing as a true public servant not beholden to any outside interests, there is still one problem that is not solvable. This was identified by Nobel Prize winner Friederich Hayek (1945) years ago in what he termed "the knowledge problem." Any modern economy is founded on a great sea of private know-how that is dispersed among many specialized participants. No one, not even a state agency, can amass all the knowledge that each participant "on the spot" inevitably acquires. This suggests that government is always making decisions under uncertainty and would be unable to be fully rational even if that was its intent.

9.5 PRINCIPLES OF THE ECONOMY AS A WHOLE

9.5.1 LIVING STANDARDS AND PRODUCTIVITY

There is a significant variation in standards of living across countries and over time. According to the Central Intelligence Agency's *World Factbook* (accessed January 4, 2018), the gross domestic product per capita for the richest nations in the world can be well over 100 times greater than for the poorest nations.

Economists agree that productivity, the amount of goods and services produced per unit of labor, is one of the most important determinants of a country's standard of living. Productivity depends on the equipment and technology available to workers

as well as their education and skills. Studies consistently show that other factors like labor unions and competition from abroad have far less impact on a country's living standard. The best risk managers will consider the potential effects of their RMOs on the productivity of their affected populations. In many cases, however, because of the way we organize our regulatory agencies, these kinds of considerations are not taken into account because of the single-minded nature of the statutory authority mind-set.

9.5.2 INFLATION AND UNEMPLOYMENT

Inflation is an increase in the general level of prices. Inflation is usually caused by excessive growth in the quantity of money. This causes the value of money to fall. Simplistically speaking, in the long run, the faster the government creates money, the greater is the inflation rate. In the shorter run, say two years or less, economic policies tend to push inflation and unemployment in opposite directions. For example, government spending tends to reduce unemployment and exacerbate inflation, while decreasing the money supply can reduce inflation and increase unemployment. The rare risk management issue large enough to affect the economy as a whole, needs to consider the potential effects of the RMOs on inflation and unemployment.

9.6 MAKING TRADE-OFFS

The concepts introduced here argue, we hope persuasively, for considering the economic effects of any risk management decision. At the same time, we recognize that not everyone will share this opinion, and other values may supersede economic considerations at times. So, we return one more time to the topic of trade-offs, this time to consider a few more notions that arise when making them. Additional discussions on trade-offs are found in [Chapter 3](#) under multicriteria decision analysis (Section 3.5.3.1).

In the broadest sense, a trade-off is giving up one thing to get another. Some choices entail trade-offs while others do not. Optimization choices, for example, do not always acknowledge trade-offs. An optimization choice is usually minimizing or maximizing some single objective. If we are maximizing net national economic development or minimizing deaths, the decision rule is simple.

That does not mean the choice is trivial; it simply means that decisions based on such choices do not use trade-off analysis or multicriteria decision-making models. There may be a great deal of analysis required to get the information upon which the choice will be based, but in such choice settings the solution is imbued in the model or the decision rule used. Once the decision model is chosen, there is no further choice to be made. The model makes the decision, and trade-offs may not be explicitly considered.

Not all decisions are so easy. Reservoir storage reallocation studies provide a good example of trade-offs. Will storage be allocated to hydropower or flood control? Storage filled with water to drink can't be left empty to hold potential floodwaters. An acre-foot of water can be used for withdrawal purposes (irrigation, water supply) or in-stream purposes (navigation, water quality, habitat). More of one usually means less of another.

Hadari (1988) offers a formal definition of a value trade-off that I have modified slightly here. A value trade-off exists if a risk manager must choose a course of action whose implementation involves at least two values, V_a and V_b , both held as positive values. Two conditions must hold. First, the alternatives available would each necessarily entail sacrificing, at least to some degree, either V_a for V_b or the opposite. To use more technical language, past some point, the values to be upheld are divergent. Second, no common unit of measurement applies to both V_a and V_b , that is, the values are incommensurable.

There is no formal value trade-off if these two elements do not hold. If there is no divergence, then we do not have to give up one value to gain another. If the values are commensurable, then in theory this decision could be made using optimization analysis. We need trade-off analysis because of conflicts among values and a lack of a common unit to measure relative gains and losses in implementing RMOs that reflect a variety of values.

Some trade-offs are explicit. One more acre-foot of irrigation water means one less acre-foot of water supply. When, for example, a given land or water resource has competing and mutually exclusive uses, the trade-off is an explicit one, and the terms of the trade-off may be fixed by the laws of our physical universe.

An acre of forest can be forestland or it can become an acre of mall parking. This is an explicit trade-off defined by this obvious one-to-one correspondence in outputs. Not all explicit trade-offs will be so easy to define. More agriculture in a watershed means more fertilizers and pesticides used on crops that can degrade drinking water quality. An increase/decrease in the use of pesticides and fertilizers means a decrease/increase in drinking water quality. The trade-off is explicit, and the laws of our physical universe fix the terms of the trade-off even though we may be unable to ascertain them in a precise manner.

In contrast to these explicit trade-offs stand subjective trade-offs. The terms of a subjective trade-off are fixed by the value systems and preferences of risk managers, decision makers, and the public. There is no explicit trade-off for jobs lost and illnesses prevented. That trade-off is subjective because its terms of trade are based on something other than the laws of the physical universe. Explicit trade-offs can sometimes be easier to quantify and measure than subjective trade-offs.

As mentioned previously, many risk management decisions involve trading off values. Consider, for example, two RMOs alike in all respects except that one has 100 acres of wooded urban recreation and the other uses those 100 acres to create wetlands inaccessible to the public. The trade-off is explicit. But weighing these two alternatives will still require a subjective trading off of the risk manager's values. In any true trade-off, someone must at some point attach subjective weights to the values being traded off.

A good trade-off analysis is transparent, and a transparent trade-off analysis makes the subjective nature of a trade-off of values as explicit as possible. This usually happens by specifying the weights used to make the trade-offs.

Costs aside for the moment, if there are no value trade-offs, then there is rarely a problem selecting the best risk management measure. Without trade-offs we are simply identifying the optimum plan. Only when we have to give up something to get

something incommensurable do we face a trade-off in the decision-making process. The optimization paradigm does not often work for risk management decisions. It almost invariably involves analysis that must take multiple criteria into account. One reason for this is that someone is always going to care about costs, and more risk reduction invariably means more cost.

A FEW RESOURCES

The topics in this chapter are treated in a very superficial manner. For additional information about the techniques in this section consult the following:

Cost Effectiveness Analysis Methods and Applications, 2nd ed. Henry Levin and Patrick McEwan, Sage Publications, Thousand Oaks, 2000 ISBN 0-7619-1934-1.

Cost-Benefit Analysis Concepts and Practice, 2nd ed. Anthony E. Boardman, David H. Greenberg, Aidan R. Vining, and David L. Weimer, Prentice Hall, Upper Saddle River, 2001, ISBN 0-13-087178-8.

Risk-Benefit Analysis. Richard Wilson and Edmund A. C. Couch, Harvard University Press, 2001, ISBN 0-674-00529-5.

Regional Economic Development: Analysis and Planning Strategy. Robert J. Stimson, Roger R. Stough, and Brian H. Roberts, Springer, Berlin, 2006 ISBN 3-540-34826-3.

9.7 ECONOMIC ANALYSIS

Economics is the study of resource allocation. While we can rely on markets to produce the “right” number of shoes, pens, and potato chips, markets may fail to capture the value of reductions in risks being managed by the public sector. In fact, many risks are allocated perfectly well by the market, although not everyone is comfortable with the outcome. Two examples might be smoking and obesity. The risks of each of these are widely understood so that, in a sense, the market works. There are, however, many risks that society has chosen to allow government to manage, instead of leaving it to people in their own private choices. They are allocated by risk managers and decision makers higher up in the decision-making pyramid.

Risk management decisions will always affect the allocation of resources; as a result, economic analysis is always potentially relevant to risk managers. In a world of scarce resources, economists maintain that only RMOs that result in positive net benefits are economically efficient. If risk managers enact measures with negative net benefits, they must do so on some basis other than economic efficiency.

Economists have many methods for conducting their analyses. Five that are most germane to evaluating risk management options and aiding risk management decisions are introduced here. The introductions are brief and sparse on details. The purpose of this chapter is to raise awareness of the availability of these techniques rather than to explain their usage.

9.7.1 COST-EFFECTIVENESS ANALYSIS

Cost-effectiveness analysis is concerned with achieving a fixed objective with the least expenditure of resources. In a risk management context, it might mean finding the least costly way to obtain a given level of risk reduction. For example, what is the least expensive way of cutting the risk in half? Alternatively, it may be looking for the RMO that provides the greatest risk reduction for a given expenditure.

Cost effectiveness relies on a measurable output like the number of illnesses reduced, days without accidents, habitat units created, increased tons of commerce, loans repaid, quality-adjusted life years (QALY), and the like. It also requires estimates of the costs of obtaining different levels of output. Cost-effectiveness analysis is most useful when the outcomes of an RMO cannot be readily or reliably monetized but can be quantified.

9.7.2 INCREMENTAL COST ANALYSIS

When risk managers are not considering a fixed level of risk reduction or a fixed expenditure on risk reduction as they do with cost effectiveness, incremental cost analysis is an effective technique. Incremental cost is the cost of a little more (i.e., an increment) of an output. When the increment is one additional unit of output or an arbitrarily small increment of output, incremental cost is sometimes called marginal cost. It can be used to compare different resource allocation options in like terms. The health-care profession has used cost effectiveness and incremental cost analysis to guide health-care budget allocation decisions.

Consider the risk of children being poisoned by eating vitamin pills mistaken for candy. Imagine the following independently implementable risk management measures have the costs and impacts shown in [Table 9.6](#). The incremental cost is defined as the change in total cost divided by the change in output. It is a synonym for marginal cost and is often the preferred term for changes in output larger than a unit. In this example the change in output is poisonings prevented. The incremental costs show that redesigning the container is the best buy, that is, it has the lowest incremental cost of poisonings prevented for \$15 million, followed by individually bubble wrapping each pill at a cost of \$30 million, for a cumulative RMO cost of \$45 million.

TABLE 9.6
Incremental Cost of Poison-Prevention Options

Risk Management Measure	Additional Cost	Poisonings Prevented	Incremental Cost of Poisonings Prevented
Labeling	\$10 million	250	\$40,000
Bubble wrap	\$30 million	1,100	\$27,300
Redesigned container	\$15 million	650	\$23,100
Education	\$20 million	100	\$200,000

When incremental costs take an order-of-magnitude jump, as they do for the education option, this break point often signals when enough has been spent. The analysis here helps risk managers allocate a limited budget on risk management measures. Incremental cost analysis helps risk managers obtain the biggest bang for the buck. Or it may suggest that it is reasonably cost effective to prevent 2,000 poisonings at a cost of \$55 million, but it is not worth spending an extra \$20 million for only 100 more reductions. That money may best be spent elsewhere.

9.7.3 BENEFIT-COST ANALYSIS

When risk managers seek the option that will do the most good given the choices available, benefit-cost analysis can be a useful tool. Benefit-cost analysis (BCA), also called cost-benefit analysis, analyzes the advantages and drawbacks of a risk management option. All the advantages and drawbacks are estimated in monetary terms. If the advantages (benefits) measured in, say, dollars exceed the drawbacks (costs) in dollars, the option is said to be economically efficient. This means its value to society exceeds its costs to society. The most desirable RMO from a BCA perspective is the one with maximum positive net benefits, and this is not necessarily the option with the highest benefit-cost ratio.

BCA

“Benefit-cost analysis is simply rational decision-making. People use it every day, and it is older than written history. Our natural grasp of costs and benefits is sometimes inadequate, however, when the alternatives are complex or the data uncertain. Then we need formal techniques to keep our thinking clear, systematic, and rational. These techniques constitute a model for doing benefit-cost analysis. They include a variety of methods:

- Identifying alternatives
- Defining alternatives in a way that allows fair comparison
- Adjusting for occurrence of costs and benefits at different times
- Calculating dollar values for things that are not usually expressed in dollars
- Coping with uncertainty in the data
- Summing up a complex pattern of costs and benefits to guide decision-making

It is important to keep in mind that techniques are only tools. They are not the essence. The essence is the clarity of the analyst’s understanding of the options.”

Source: Treasury Board of Canada Secretariat (1999) Benefit-Cost Analysis Guide.

9.7.4 RISK-BENEFIT ANALYSIS

We all accept risks to realize the benefits associated with the risky behavior. Risk-benefit analysis is another comparison method available to risk managers. It compares the risks of a situation to its related benefits. A tolerable level of risk may be judged to be warranted by the fact that substantial benefits accrue in relation to the risk. A risk-benefit analysis is to some extent the reverse image of cost effectiveness. In cost-effectiveness we are unable to express the advantages in monetized terms, whereas the costs of risk management are more easily estimated. In risk-benefit analysis the risks (costs) remain quantified in risk-related terms while the benefits that accompany that risk are often monetized. Another application of risk-benefit analysis is found in pharmaceuticals, where statistically rigorous methods are used to demonstrate the level of risk patients and other decision makers are willing to accept to achieve the benefits provided by a new drug or health-care product.

Institutional review boards—bodies that review research proposals for organizations—have developed their own jargon and guidance on risk-benefit analysis. Risks to research subjects posed by participation in research should be justified by the anticipated benefits to the subjects or society. This requirement is clearly stated in all codes of research ethics, and it is central to U.S. federal regulations. The risks to which research subjects may be exposed have been classified as physical, psychological, social, and economic (Levine 1986).

9.7.5 ECONOMIC IMPACT ANALYSIS

Economic impact analysis (EIA) studies how the direct benefits and costs of an RMO affect the local, regional, or national economy. The economic impacts of RMOs usually include effects on jobs, incomes, prices, taxes, and possibly measures of economic welfare like consumer and producer surplus or QALYs. Thus, economic impact analysis is intended to measure these types of economic effects associated either with the status quo or with particular RMOs that may be implemented. BCA measures direct benefits and costs of an RMO. It typically does not convert these direct effects into their indirect effects on the economy, such as changes in employment, wages, business sales, or land use. This is the role of EIA.

The most common forms of economic impact analysis trace spending through an economy and measure the cumulative effects of that spending in the impact region. The impacts forecast the number of jobs created or lost by a risky event or an RMO. Many economic impact models also predict impacts on personal income, business production, sales, profits, and tax collections. It is not unusual for an economic impact analysis to show impacts on hundreds of different sectors of a region's economy.

9.8 SUMMARY AND LOOK FORWARD

Resources, that is, real things, are always scarce, and so we can't do everything. We have to make choices. Choices cost us the opportunity to do other things, so they entail trade-offs. These trade-offs are best examined at the margin, that is, marginal analysis. Risk managers are always well advised to consider the incentive effects of

their decisions, especially when the response to a decision is essential to the success of a risk management strategy.

We are ready to turn now from the risk management task to risk assessment. This is the evidence-based analytical process that is designed to reduce uncertainty to the greatest extent possible while providing risk managers with the information they need to achieve their objectives and solve problems.

Risk assessment can be qualitative or quantitative. The number of tools and methodologies employed in risk assessment have grown rapidly with the spread of risk analysis science. The next chapter provides a look inside the risk assessor's toolbox as it summarizes several dozen qualitative and quantitative risk assessment tools.

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10 Risk Assessor's Toolbox

10.1 INTRODUCTION

This chapter provides an introduction to a wide variety of qualitative, semiquantitative, and quantitative risk assessment tools and techniques. It will not make you proficient in the use of any of them but it may make you aware that “there is a tool for that.” Risk assessment provides the scientific and other evidence required to support risk management decision making under conditions of uncertainty. It is often divided into two broad types: qualitative and quantitative.

Qualitative risk assessment is distinguished primarily by its lack of reliance on numerical expressions of risk. That means that qualitative risk assessment depends on risk descriptions, narratives, and relative values often obtained by ranking or separating risks into descriptive categories like high, medium, low, and no risk. When the relative values are numeric but nominal or ordinal in character, such as when index numbers are used, the risk estimate is said to be semiquantitative, but they remain more qualitative than quantitative in character. Quantitative risk assessment relies on numerical expressions of risk. The toolbox presented in this chapter has numerous examples of tools for each of these types of assessment.

Risk was defined as the product of consequence and probability in [Chapter 1](#). A complete assessment of a risk must describe and explain these two factors using the best available evidence. An experienced risk assessor knows you do not always need a complete risk assessment. In fact, if you can establish that there is no hazard, no consequences, or no likelihood, you can disprove the existence of a risk and that may be the most efficient way to proceed for many circumstances.

In this toolbox you will find tools intended to be used to complete a risk assessment and for narrower purposes as well. Some were designed for hazard identification, others for consequence assessment, and some for likelihood assessment. Each tool is introduced with a set of checkboxes: “Useful for: Hazard identification Consequence assessment Likelihood assessment Risk characterization Uncertainty characterization Risk management options Other.” Take the ratings you see with a grain of salt as they are rather subjective in many instances. Consider these ratings a first attempt at letting you know what parts of risk assessment they may help you with.

A tool is a device that enables you to do something, for example, a microscope or a computer program. A technique is a process or procedure that you follow. A method is a technique, usually differentiated by being a settled kind of procedure, usually according to a definite, established, logical, or systematic plan. A methodology is sometimes referred to as the ideology behind a method. You may find examples of each in this toolbox. For simplicity, all the items in this chapter are referred to as tools.

The first four checkboxes correspond fairly closely to the four generic steps of a risk assessment. “Risk management options” is provided for those tools that are useful in identifying or assessing the efficacy of RMOs. Uncertainty characterization is sometimes a stand-alone function but it is more often aligned with one or more of the other uses. The “other” category is provided to cover the many analytical aspects related to risk assessment that do not fall conveniently into a named category.

The chapter presents the tools in alphabetical order. Regardless of the tool chosen, there are a few tasks that are necessary to prepare for any kind of risk assessment work. These are the basic risk management tasks that prompt a risk assessment:

- Identify the problem
- Identify the objectives
- Identify the questions to be answered

With this necessary preparation in mind, let us begin to look over the tools available to answer those questions for the risk manager.

10.2 BRAINSTORMING

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.2.1 OVERVIEW OF THE TECHNIQUE

Brainstorming is a proven effective methodology for generating ideas. It is especially useful for generating unusual ideas. A common goal of brainstorming is to generate the greatest number of ideas in the least amount of time possible. Some brainstorming techniques include evaluation of ideas; others do not. Good brainstorming uses a particular technique and structure that ensures the participants’ imaginations are triggered by their own thoughts as well as the thoughts and comments of others. A great many such techniques are described in the literature and the worldwide web. Careful preparation and effective facilitation are two important elements in a successful brainstorming process. Brainstorming is the topic of [Chapter 8](#).

10.2.2 HOW THE TECHNIQUE IS USED

Brainstorming can be used alone or in conjunction with other risk assessment methods. You can brainstorm hazards, types of consequences, or sequences of events that enable hazards to produce consequences. Its purpose is to encourage imaginative thinking at any stage of a risk management activity. It can be used for scoping activities (e.g., to identify risks and stakeholders). It can also be used at a detailed level for particular issues (e.g., to identify means of keeping specific aquatic nuisance species out of specific waterways). Because it relies so heavily on imagination, brainstorming can

be particularly useful to identify the risks of new technology or novel solutions to new and old problems.

10.2.3 INPUTS

The inputs for successful brainstorming include:

- Well-defined problem
- Team of people with knowledge of the problem
- Brainstorming technique
- Facilitator
- Means to both record and disseminate the results of the process

10.2.4 PROCESS

The process itself can be formal or informal. Formal brainstorming is more structured. Facilitators prepare in advance and participants may be prepared as well. The session has a defined purpose, structure, and outcome. Informal brainstorming is less structured. It may be represented by the “let us go around the table and see what everybody thinks” method we have all experienced.

10.2.5 OUTPUTS

The outputs depend on the purpose of the brainstorming session but you can expect a list of ideas. Most of the time the ideas will not be evaluated, although some brainstorming techniques provide for some degree of evaluation of the ideas. Most purists would argue that evaluation is a process separate from brainstorming.

10.2.6 STRENGTHS AND WEAKNESSES

Strengths:

- Encourages imagination
- Identifies new risks and novel solutions
- Involves key stakeholders and hence aids communication overall
- Relatively quick and easy to set up

Weaknesses:

- Failing to get the right mix of skills and knowledge in the group
- Group domination by one or more strong personalities or bosses
- Free-riding by group members
- Social phenomena like “groupthink” or “groupshift”
- Difficulty verifying that the effort is comprehensive

There are techniques designed to overcome these weaknesses.

10.2.7 EXAMPLES OF USE

Brainstorming may be useful for identifying hazards, risks, stakeholders, decision criteria, and risk management options. For a more complete discussion of brainstorming see Aiken et al. (1997), Isaksen (1998), Osborn (1963), and Yoe (2012), or simply do a web search on brainstorming. The Mind Tools web page provides a good introduction to brainstorming at <https://www.mindtools.com/brainstm.html> (accessed May 4, 2018).

10.3 BAYESIAN STATISTICS AND BAYES NETS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.3.1 OVERVIEW OF THE TECHNIQUE

The premise of Bayesian statistics, attributed to Thomas Bayes, is that any already known information can be combined with subsequent information to establish an overall probability. The simplest expression of the Bayes Theorem is:

$$P(A|B) = \frac{[P(A)P(B|A)]}{P(B)}$$

Classical statistics assumes that all distribution parameters are constants. Bayesian statistics views them as random variables. Probability, in the Bayesian sense, is easier to understand if it is considered as a person's degree of belief in a certain event, it is a probability of the mind rather than a probability of the object. The Bayesian approach is based on this subjective interpretation of probability. It has proven useful for decision thinking and the development of Bayesian Nets, also called Belief Nets, Belief Networks, or Bayesian Networks.

These nets use graphical models to represent probabilistic structures. The network comprises nodes that represent a random variable and arrows that link a parent node to a child node to show how variables influence one another. A simple example of a network showing the likelihood of being a victim of crime is depicted in [Figure 10.1](#).

It says the variable being in a Bad Neighborhood (BN) influences variables Victim of Crime (VOC) and Not Paying Attention (NPA) directly. Variable Alone (A) influences variable Not Paying Attention directly. Variable Victim of Crime is directly influenced by Bad Neighborhood and Not Paying Attention and indirectly by Alone and Bad Neighborhood through their influence on Not Paying Attention. We will return to this network shortly.

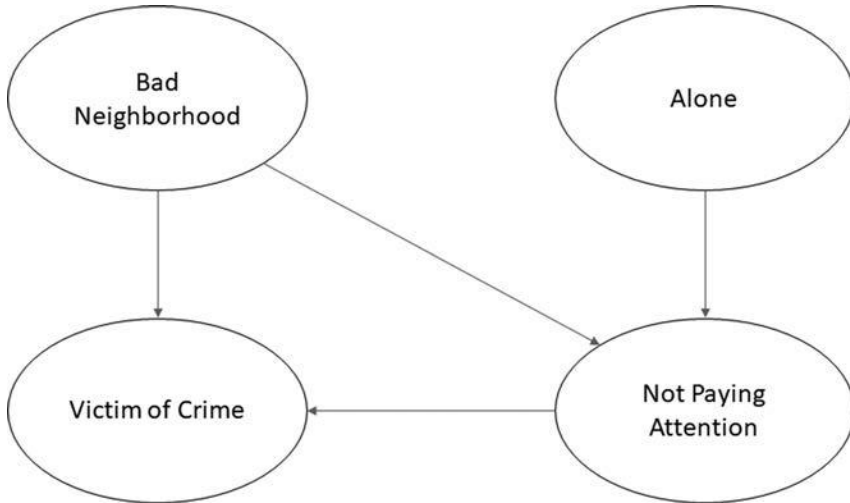


FIGURE 10.1 A simple Bayes Network.

10.3.2 HOW THE TECHNIQUE IS USED

Intuitive appeal and user-friendly software, like Netica and AgenaRisk, have resulted in widespread use of Bayes' theory and nets in recent years. They are useful in any application where analysts must find out about unknown variables using structural relationships and data. This could be especially useful for estimating the probability of events identified in the sequence of events necessary to result in the identified consequences.

10.3.3 INPUTS

The inputs for a Bayes Net include:

- The definition of system variables and causal links between the variables
- Specified conditional and prior probabilities
- Evidence to be added to the net
- Updated beliefs

10.3.4 PROCESS

Bayes Nets can best be demonstrated with an example. Consider the Bayes Net of [Figure 10.1](#) once more. Let the prior probabilities be as defined in [Table 10.1](#). BN+ means it is a bad neighborhood, BN- means it is not, A+ means the person is alone, A- means they are not. In a similar way NPA+, NPA-, VOC+, and VOC-, not shown, are defined.

Let the two events, A and BN, be defined by a yes/no condition. These are both independent events, that is, their probabilities do not depend on any other event in

TABLE 10.1**Prior Probabilities of Nodes Bad Neighborhood and Alone**

P (BN+)	P (BN-)	P (A+)	P (A-)
0.9	0.1	0.6	0.4

TABLE 10.2**Conditional Probabilities for Node Not Paying Attention with Node Alone and Node Bad Neighborhood Defined**

A	BN	P (NPA+)	P (NPA-)
Y	Y	0.3	0.7
Y	N	0.5	0.5
N	Y	0.6	0.4
N	N	0.7	0.3

TABLE 10.3**Conditional Probabilities for Node Victim of Crime with Node Bad Neighborhood and Node Not Paying Attention Defined**

BN	NPA	P (VOC+)	P (VOC-)
Y	Y	0.35	0.65
Y	N	0.2	0.8
N	Y	0.1	0.9
N	N	0.05	0.95

the net. The Not Paying Attention node has values that depend on both events BN and A. [Table 10.2](#) shows the conditional prior probability for node NPA.

The Victim of Crime node depends on nodes BN and NPA. Its conditional prior probabilities are given in [Table 10.3](#).

Given these prior probabilities, the overall $P(\text{VOC}+)$ is 24.26% and $P(\text{VOC}-)$ is 75.54% as shown in [Figure 10.2A](#). With this network, you can select as many values for the nodes as you like. [Figure 10.2B](#) shows all three input nodes as true, yielding the values of [Table 10.3](#) for the Yes/Yes condition. This network also enables you to calculate posterior probabilities as well. For example, the *a priori* probability of being in a bad neighborhood is 90% per [Table 10.2](#), but the posterior probability of being in a bad neighborhood, given you are not a victim of crime, is 87.8% ([Figure 10.2C](#)). The posterior probability of being in a bad neighborhood, given you were a victim of a crime, is 96.77% ([Figure 10.2D](#)). In a similar fashion, a wide range of posterior probabilities can be estimated using the power of the

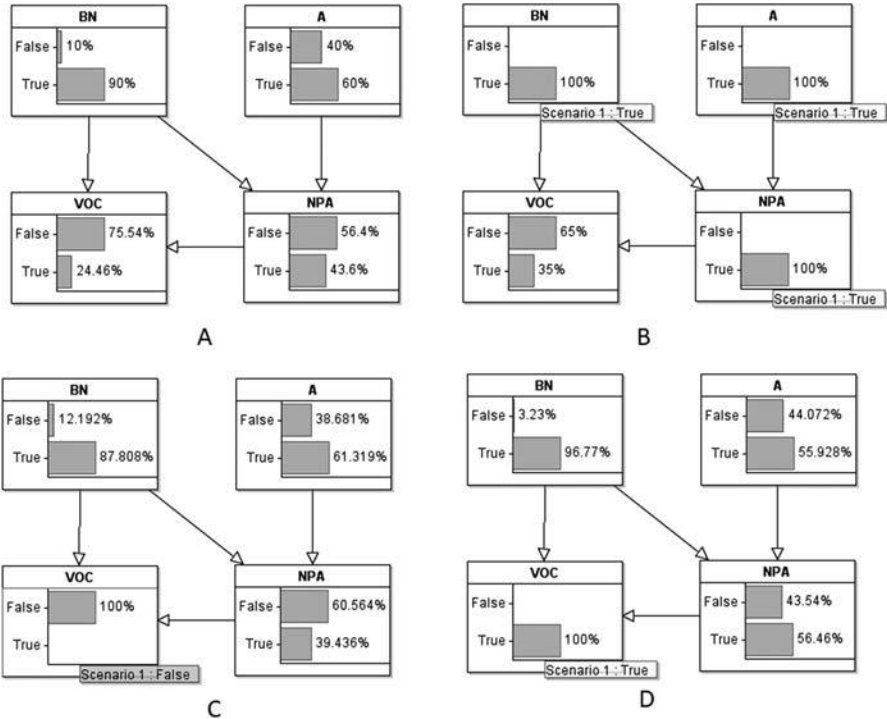


FIGURE 10.2 Four scenarios for the Bayes Net example.

network and Bayes Theorem. The probabilities for this example were calculated using AgenaRisk.

10.3.5 OUTPUTS

The outputs of Bayes Nets are derived posterior distributions and a graphical model that explains the relationships among variables. The example demonstrates how the Bayesian approach can use information, for example, that $VOC = N$, to update probability estimates based on a degree of belief.

10.3.6 STRENGTHS AND WEAKNESSES

Strengths:

- Knowledge on the priors and Bayes rule are all that is required
- Subjective beliefs can be used in a problem

Weaknesses:

- Inferential statements are often difficult for people to understand
- Knowledge of priors is essential

10.3.7 EXAMPLES OF USE

Bayes Nets are widely used for medical diagnosis, image modeling, genetics, speech recognition, economics, space exploration, and in the powerful web search engines used today (IEC, 2008). The U.S. Army Corps of Engineers makes extensive use of Bayes Nets in its dam and level safety programs. The Netica Tutorial provides an excellent introduction to Bayes Networks at https://www.norsys.com/tutorials/netica/nt_toc_A.htm (accessed May 4, 2018).

10.4 BOW TIE ANALYSIS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.4.1 OVERVIEW OF THE TECHNIQUE

A “bow tie” is a diagram that helps you visualize the risk you are dealing with in one simple picture. Sometimes called bow tie analysis (BTA), this simple diagram helps conceptualize the interaction of hazards, causes, controls, and consequences of a risk. Although it reflects elements of both event tree and fault tree logic, it differs by its focus on the control barriers between the causes and the risk events and recovery barriers between the risk events and its consequences. [Figure 10.3](#) provides an example of a generic bow tie diagram.

10.4.2 HOW THE TECHNIQUE IS USED

The bow tie analysis is useful when the decision problem does not require more complex methods and when there are clear independent pathways leading to failure. It is usually easier to understand than fault and event trees and is therefore a more useful communication tool.

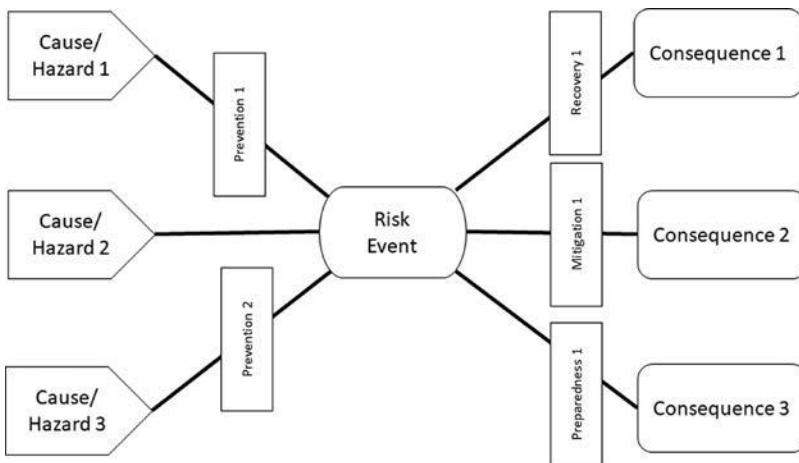


FIGURE 10.3 A generic bow tie diagram.

10.4.3 INPUTS

Inputs to a bow tie analysis include:

- A clearly identified risk
- Causes and consequences of the risk
- Factors that may prevent or mitigate the risk and its consequences
- Factors that may stimulate or promote desirable consequences

10.4.4 PROCESS

The process begins by identifying a specific risk or event that becomes the knot in the bow tie. Causes that can lead to consequences are listed on the left and connected to the knot via lines that form the left side of the bow tie. Escalation factors (not shown in the figure) can be added between the lines on the left when they can be identified. They feed into one or more of the existing cause/hazard lines.

Barriers that can prevent a cause from leading to the sequence of events that results in unwanted consequences can be shown as vertical bars across the lines. Bars or barriers on the left side of the bow tie generally prevent the risk from occurring. The control barrier is placed on the line it disrupts. If there are barriers to escalation, they can also be shown on the escalation lines if they are used. When the risk is a potential gain, the bars represent stimulation measures on the left side of the diagram.

The right side of the bow tie shows the potential consequences that can result from the risk event. Although the conceptual figure is symmetrical, an actual bow tie need not be. The consequences are also connected to the risk by lines. Recovery barriers for the consequence are shown as bars across the radial lines that represent preparedness, mitigation, and recovery options that can prevent or reduce specific consequences. When the consequences are positive the bars reflect promotion options that support the generation of positive consequences.

The bow tie diagram may be quantified to some extent when the pathways are independent and the likelihood of a particular consequence or outcome is known, so long as the effectiveness of a control can be estimated. Generally, quantification is more appropriate with event and fault trees.

10.4.5 OUTPUTS

A simple diagram is the output of a bow tie analysis. It shows the main failure pathways and the risk management measures in place to prevent or mitigate the undesired consequences or to stimulate and promote desired consequences.

10.4.6 STRENGTHS AND WEAKNESSES

Strengths:

- Simple to understand
- Presents a clear picture of the problem

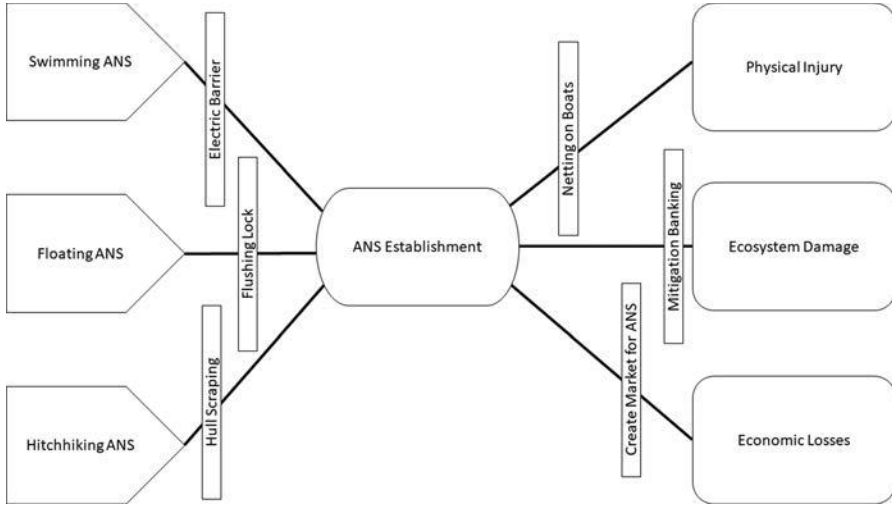


FIGURE 10.4 BTA diagram for aquatic nuisance species.

- Focuses attention on measures that are supposed to be or can be in place to prevent and mitigate risks
- Can be used for desirable consequences
- Does not require a high level of expertise to use

Weaknesses:

- Limited by its simplicity
- Does not address situations where multiple causes must occur simultaneously
- Could oversimplify complex situations, especially when the model is quantified

10.4.7 EXAMPLES OF USE

Figure 10.4 demonstrates the potential use of BTA by replacing the generic figure with a simple example for the risk of establishment of aquatic nuisance species in a watershed. It shows the main failure pathways and the risk management measures in place or that can be put in place to prevent or mitigate the undesired consequences or to stimulate and promote desired consequences. An informative discussion of the bow tie method can be found at https://www.cgerisk.com/knowledgebase/The_bowtie_method (accessed May 4, 2018).

10.5 CAUSE-AND-EFFECT ANALYSIS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

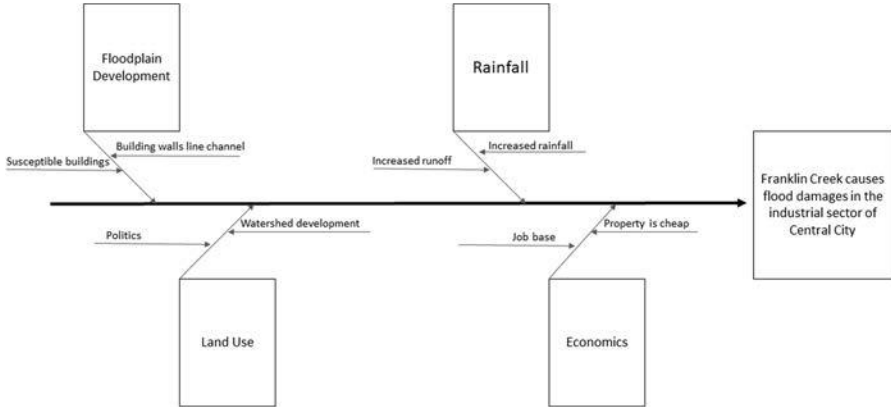


FIGURE 10.5 Simplified example of a cause-and-effect diagram.

10.5.1 OVERVIEW OF THE TECHNIQUE

Cause-and-effect analysis helps the assessor to think through the causes of a risk. This structured method pushes the team to consider all the possible causes of the risk, not just the obvious ones. Figure 10.5 provides a sample cause-and-effect diagram, also called a fishbone or Ishikawa diagram. The problem, shown on the right, is first explained by potential hazards or contributory factors grouped into broad categories and shown as squares in the figure. Factors contributing to each of these broad categories are identified on the horizontal lines (fishbones), and another level of contributory factors can be identified on slanted lines that can be added to the horizontal lines (not shown in the figure). A completed fishbone diagram details a number of testable hypotheses. The diagram can point to potential causes but only evidence and empirical testing of these hypotheses can determine real causes.

The completed diagram provides a visual display of the causes of a specific consequence. The effect displayed can be a problem (negative) or opportunity (positive). Cause-and-effect analysis enables analysts to consider a broad range of both causes and scenarios that lead to them. The diagram is generated by a team of experts. Once completed it often helps support development of a consensus view of the most likely causes, which can then be tested empirically or evaluated with available data.

10.5.2 HOW THE TECHNIQUE IS USED

A fishbone diagram may be most useful at the beginning of a risk assessment when the team is trying to identify complex risks and articulate problems and opportunities. It helps the team think more broadly and comprehensively about possible causes. Once completed, it can help guide the collection of data, especially if the analysis will involve formal hypothesis testing. Cause-and-effect analysis can be used as part of a root-cause analysis.

10.5.3 INPUTS

The critical inputs include:

- Expertise and experience of the team
- Good understanding of the effect (problem, opportunity) that is being explained
- Ability to differentiate causes from effects

10.5.4 PROCESS

The basic steps in performing a cause-and-effect analysis consist of:

- Identify the effect
- Work out the major factors involved (the boxes in the figure)
- Identify possible causes and sub-causes (the “fishbone” lines of the figure)
- Analyze your diagram

The major factors or main causes of an effect might include people, equipment, environmental factors, processes, events, situations, and the like. The next task is to fill in the possible causes for each major factor with branches and subbranches (the fishbones) to further describe the cause. It can help to keep asking “why?” or “what caused that?” to understand the causes and develop the diagram.

At this point the diagram should show all the possible causes of your effect. When the problem lends itself to further investigation, the team can establish formal hypotheses, set up investigations, carry out surveys, conduct analyses, and so on, to test the accuracy of the identification of the causes.

This is usually a qualitative assessment. To quantify it, analysts sometimes assume the probability of the problem or opportunity occurring is one and assign probabilities to the major factors, which can subsequently be broken down to the causes and subcauses based on expert opinion and the degree of belief about their relevance. This is very difficult to do in a valid way because the contributing factors often interact in ways that are difficult to account for in subjective probability estimates.

10.5.5 OUTPUTS

The primary output is the fishbone diagram that shows possible and likely causes. Such a diagram should be verified and tested empirically before risk management recommendations are made.

10.5.6 STRENGTHS AND WEAKNESSES

Strengths:

- Structured team approach to identify and consider all hypotheses
- Outputs are easy to read and understand
- Technique can guide data collection and analysis

Weaknesses:

- Not a complete risk assessment
- Not a true analysis, but rather a brainstorming tool used at the beginning of an assessment
- Separating factors and causes may mask important interactions among the elements of the diagram

10.5.7 EXAMPLES OF USE

This technique is well used at the outset of an investigation or when the cause-and-effect relationships in a risk situation are complex. It is a valuable tool to use when defining the decision context. Mind Tools offers an effective overview of cause-and-effect analysis https://www.mindtools.com/pages/article/newTMC_03.htm (accessed July 13, 2018).

10.6 CAUSE-CONSEQUENCE ANALYSIS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.6.1 OVERVIEW OF THE TECHNIQUE

Cause-consequence analysis (CCA) is an analytical technique used to gain a better understanding of failures by identifying causes and their sequences of events that lead to consequences. CCA can be used to analyze consequence chains individually or as part of a larger risk assessment. The CCA technique was invented by RISO Laboratories in Denmark to conduct a risk analysis of nuclear power stations. CCA combines cause analysis, described by fault trees, and consequence analysis, described by event trees. CCA has the ability of fault trees to show the different ways factors can combine to cause a risky event and the ability of event trees to show the many possible outcomes. By combining deductive and inductive analysis, CCA can help illustrate chains of events that can result in multiple undesirable consequences. When probabilities can be estimated for the various events in a CCA diagram, the probabilities of the various consequences can also be calculated. The technique has been adapted by other industries to estimate the safety of protective systems. It has subsequently been extended to the assessment of risks in other systems as well.

10.6.2 HOW THE TECHNIQUE IS USED

CCA has been used primarily as a reliability tool for safety critical systems to provide a more thorough understanding of system failures. It enhances the failure logic of fault trees by supporting the analysis of time sequential failures. Time delays can also be incorporated into the consequence analysis, a refinement over event trees.

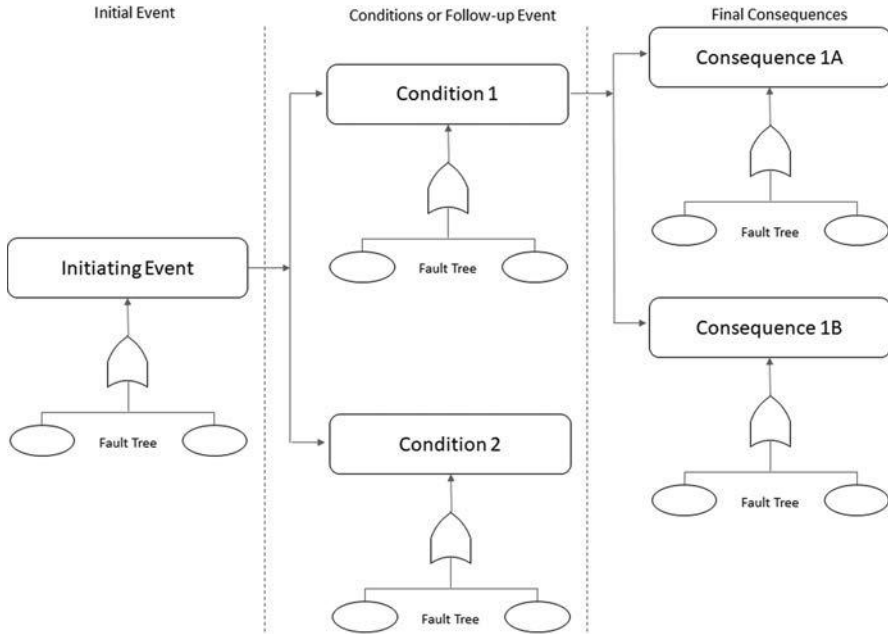


FIGURE 10.6 Simplified cause consequence analysis diagram.

The method can be used to examine the various paths a system could take following a critical event that depends on the behavior of particular subsystems. For example, the deployment of critical personnel or the performance of emergency response systems can be modeled. If these elements are quantified, the model can then yield estimates of the probabilities of different potential consequences following the critical event.

A simplified sample CCA diagram is shown in [Figure 10.6](#). Details are omitted to simplify the exposition. The figure shows an initiating event that has a fault tree cause (details of the fault tree analysis are suggested rather than shown). The event may or may not lead to Condition 1, which itself may have contributing factors explained by a fault tree. If the event fails to lead to the condition of interest another condition will be obtained. In the example, the subsequent consequences of Condition 2 are not developed. Even absent specific detail, the potential richness and complexity of CCA is evident. Any number of conditional branches can proceed from the initiating events. The chain of conditions along any pathway can vary in length before consequences are realized. Fault trees are shown at each event tree branch to illustrate the possibilities; they are not requirements of CCA.

CCA diagrams can be complex, so they tend to be used when the magnitude of the potential consequence of failure justifies this intensive effort. The method can be used to examine the various paths a system could take following a critical initiating event that depends on the behavior of particular subsystems or conditions, each of which may depend on other subsystems.

10.6.3 INPUTS

The primary inputs to this technique include:

- An understanding of the system being modeled
- The events that threaten its function
- Its failure modes
- Failure scenarios
- Working knowledge of event trees and fault trees

10.6.4 PROCESS

Cause-consequence analysis requires the assessment team to recognize:

- Cause-consequence chains
- The primary event that initiates the chain
- The follow-up events or conditions between the primary event and final consequences
- Final consequences that result from different sequences of conditions
- The causes of primary events and conditions

Although usually a qualitative effort, the team may quantify the model with realization probabilities for the causes of primary and follow-up events. The qualitative value of this technique rests in the utility of the visual and logical description of the consequence chain evolving from the initiating event and the cause-consequence relations (causalities) among events. A CCA diagram shows how a system can fail as well as the consequences of the failure. The probability of occurrence of each potential consequence can be estimated based on an analysis of the probabilities of particular conditions that can follow the initiating event. The diagrams are often useful for identifying requirements for safety features in a system.

Ericson (2005) describes the tasks comprising the CCA process as follows:

1. Define the system
2. Identify the accident scenarios
3. Identify the initiating events
4. Identify the intermediate events
5. Build the CCA diagram
6. Obtain the failure event probabilities
7. Identify the outcome risk
8. Evaluate the outcome risk
9. Recommend corrective action
10. Hazard tracking
11. Document CCA

10.6.5 OUTPUTS

The primary output is the diagram. A CCA diagram shows both how a system can fail as well as the consequences of the failure. The probability of occurrence of each potential consequence can be estimated based on an analysis of the probabilities of particular conditions that can follow the initiating event.

10.6.6 STRENGTHS AND WEAKNESSES

Strengths:

- Able to display potential scenarios following an initiating event
- Can account for timing, dependence, and domino effects that are cumbersome to handle in verbal descriptions and other models
- Provides a more comprehensive view of a system
- Can show events that develop over time

Weaknesses:

- Diagrams can be complex
- Quantification of dependent probabilities can be challenging

10.6.7 EXAMPLES OF USE

CCA is most useful in industries where system safety is a primary concern. The technique was developed for nuclear power stations and has been applied throughout the energy industry, especially for pipelines.

10.7 CHECKLISTS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.7.1 OVERVIEW OF THE TECHNIQUE

Checklists are useful tools. They aid task accomplishment by compensating for potential limits of human memory, attention, and imagination. They can also help to ensure consistency and completeness in carrying out a task. The most basic lists are to-do lists; preflight checklists are an example. Processes may be described by a list of steps to take; industry process descriptions are examples. Comprehensive enumerations are also checklists; ornithological checklists of common and scientific names of birds are an example. Lists of hazards, risks, failure modes, or risk management measures are sometimes developed during a risk assessment. The lists are usually based on experience or the work of others in similar situations. They can be very helpful to those working in related areas. Checklists or protocols can be used at any stage of a project lifecycle.

PARTIAL CHECKLIST OF AQUATIC NUISANCE SPECIES

Gymnocephalus cernuus Eurasian ruffe
Hypophthalmichthys molitrix silver carp
Hypophthalmichthys nobilis bighead carp
Ictalurus furcatus blue cat
Lepisosteus platostomus shortnose gar
Lepomis auritus redbreast sun
Lepomis microlophus redear sun
Menidia beryllina inland silverside
Misgurnus anguillicaudatus Oriental weather
Morone americana white perch
Morone saxatilis striped bass
Mylopharyngodon piceus black carp
Neogobius melanostomus round goby
Notropis buchmanani ghost shiner
Noturus insignis margined madtom

10.7.2 HOW THE TECHNIQUE IS USED

Checklists can be used to help people follow carefully structured tasks or to help assure that a topic is exhaustively considered, for example, a list of pathogens associated with poultry in Southeast Asia. Although a checklist can be used as a stand-alone technique, it is often used to check that everything has been covered when a more imaginative technique, such as brainstorming, has been applied. They can also be used in conjunction with a number of other qualitative tools and techniques that rely on comprehensive identification of a list of elements.

10.7.3 INPUTS

The inputs to a checklist include:

- Identifying the scope of the decision problem
- Procuring or preparing a checklist that is adequate to the purpose
- Identifying the expert or team to use the checklist
- Stepping through each aspect of the decision problem to decide whether items on the checklist are present or applicable

10.7.4 OUTPUTS

The outputs of this process depend on the nature of the decision problem. Normally a checklist will produce a subset of items that are considered relevant to consider for the situation at hand. Thus, a checklist might be used to produce a list of potential hazards, failure modes, or relevant risk management measures.

10.7.5 STRENGTHS AND WEAKNESSES

Strengths (IEC, 2008):

- May be used by nonexperts
- Well-designed lists combine wide-ranging expertise into an easy-to-use technique
- Fast and helpful when done well
- Help ensure common elements are not overlooked
- Compiling and publishing lists related to risk identification and risk management is an activity that yields high value to others

Weaknesses:

- Can inhibit imagination in unique situations, for example, the identification of risks
- Address the “known knowns” and may neglect the “known unknowns” or the “unknown unknowns”
- Can encourage “check it off” types of behavior
- Tend to be based on what has been seen or done before

10.7.6 EXAMPLES OF USE

Checklists are used extensively in the health-care field. The Great Lakes and Mississippi River Interbasin Study (GLMRIS, 2014) was faced with identifying aquatic nuisance species of concern. After reviewing about 625 publications and reports as well as other sources and personal communications, they identified a total of 253 alien aquatic species. Their work now represents a potentially useful checklist for others dealing with potential introduction of nonindigenous species into waterways.

Lists of risk management measures have been prepared to aid the formulation of risk management options. An example of one such list of nonstructural flood risk management measures is found at <http://www.nwd-mr.usace.army.mil/rcc/MRFTF/docs/USACE-NFPC%20Nonstructural%20Measures%20Definitions.pdf> (accessed March 23, 2018).

10.8 COST-BENEFIT ANALYSIS

Useful for: Hazard identification Consequence assessment
 Likelihood assessment Risk characterization Uncertainty characterization
 Risk management options Other

10.8.1 OVERVIEW OF THE TECHNIQUE

There is a long history of using cost-benefit analysis (CBA) to assist decision making. CBA estimates the total equivalent money value of the benefits and costs of a project or action, expressed in a common price level and time value, to establish whether they are efficient from an economic perspective. These projects

may be dams, highways, training programs, health-care systems, or specific risk management options under consideration to reduce an unacceptable level of risk. Benefits are often divided by costs to produce a benefit-cost ratio where a $BCR \geq 1$ indicates a desirable project or costs may be subtracted from benefits, where positive net benefits indicate a desirable project. Maximum net benefits have been used to identify the most efficient means of solving a problem from among a set of alternative solutions.

The idea of CBA is usually attributed to an 1848 article by Jules Dupuit, a French engineer and economist. The practical application of CBA was greatly advanced in the United States as a result of the Flood Control Act of 1936 which required the U.S. Army Corps of Engineers to carry out projects for the improvement of the waterway system when the total benefits of a project to whomsoever they accrue exceed the costs of that project. Cost-benefit analysis has been widely adopted internationally by government agencies at all levels of government

10.8.2 HOW THE TECHNIQUE IS USED

The viewpoint of the entity undertaking a CBA will dictate the nature of the benefits and costs to be identified and assessed for decision making. For example, are the relevant effects global, national, regional, or proprietary in impact and scope? Usually, defined benefits include both direct and indirect benefits and costs associated with a risk management action. Direct benefits are those that flow directly from the risk management action; for example, flood damage reductions are the direct benefits of a levee. Indirect benefits are coincidental to the risk management action. Examples might include the peace of mind that comes with flood damage reductions and the regional economic activity that is spurred by construction of a levee. Direct costs are those associated with the risk treatment and its implementation, that is, the costs of building the levee. Indirect costs are those associated with the accrual of indirect benefits. Monetizing the relevant direct and indirect benefits and costs of a project or action can be more or less challenging, depending on the viewpoint taken and the nature of the benefits and costs.

10.8.3 INPUTS

The essential inputs for a cost-benefit analysis include:

- A clear description of the risk issue
- The risk management options under consideration
- Identification of the benefits and costs associated with each option
- Estimates of these direct and indirect benefits and costs
- Proper handling of price levels and the time value of monetary values

10.8.4 PROCESS

CBA analysis is a well-developed technique and numerous books have been written to describe the process. A simplified summary of the process would consist of the

following steps. First, identify the costs and benefits associated with the project or action from an appropriate viewpoint. It is important to consider the benefits and costs over the lifetime of the project because the streams of benefits and costs may well vary over time.

Second, quantify the benefits and costs. Benefits for some projects might be measured in deaths and illnesses prevented, so the analysis begins by first quantifying the effects in their natural quantities. Costs could be measured in terms of specific changes to a production process or real resources required to reduce a risk. Relevant costs and benefits can occur in different forms over the period of analysis for the CBA.

Third, calculate or assign a monetary value to the benefits and costs. This is where compounding and discounting monetary flows in a fixed price level becomes an important consideration. There is considerable controversy surrounding the monetization of some categories of benefits and costs. Determining the value of a statistical life is one such example; the choice of a discount rate is another. Calculations of streams of benefits that vary over time must be carefully undertaken.

Finally, benefits and costs must be compared to determine the desired course of action. Benefits are generally expected to exceed costs for an implementable project or action. In some instances, the BCR or net benefit estimate may simply be one of several decision criteria under consideration. At times the decision criterion of CBA may be the internal rate of return or a payback period.

10.8.5 OUTPUTS

The output of a CBA is an estimate of the net benefits, benefit-cost ratio, or some other monetary metric associated with the risk management options under consideration.

10.8.6 STRENGTHS AND WEAKNESSES

Strengths:

- Provides a powerful tool for evaluating risk management options when all benefits and costs can be reliably monetized
- Enables analysts to identify the most efficient economic solution from among a set of options

Weaknesses:

- Controversy about the reliability and appropriateness of reducing some risk management effects to dollar terms
- Technical issues may remain to be resolved, for example the choice of an appropriate discount rate

10.9 EXAMPLES OF USE

In the United States, Executive Order 12866, Regulatory Planning and Review, calls for a CBA to be prepared for any “significant” proposed regulation. As noted earlier,

the U.S. Army Corps of Engineers has been required to conduct CBA for water resource projects since 1936. CBA is used internationally and is a common practice throughout private industry.

10.10 DELPHI TECHNIQUES

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.10.1 OVERVIEW OF THE TECHNIQUE

The Delphi technique, developed by RAND in the 1950s, is an expert survey conducted in two or more rounds. It is designed to obtain a consensus of opinion from a group of experts. The most unique aspect of the Delphi technique is that it allows experts to express their opinions individually and anonymously while providing them with the views of other experts as the process progresses. Iterated rounds of input are used to focus the expert opinions and discussion until, ideally, a consensus among the experts is achieved.

10.10.2 HOW THE TECHNIQUE IS USED

The Delphi technique is an effective way to address uncertainty. Experts may be asked to rank options or to fill in gaps in critical knowledge uncertainty. It can be applied at any stage of the risk management process and at any stage in a project's lifecycle. It is most valuable when a consensus of experts' views is required. It is sometimes called a forecasting technique because it has, historically, been used for that purpose. It is most useful for problems plagued by uncertainty, especially knowledge uncertainty; otherwise, analytical solutions are more efficient. The experts in a Delphi process can only provide estimates of uncertain aspects of a decision process.

10.10.3 INPUTS

The essential inputs for a Delphi technique include:

- Decision problem for which consensus is required
- Facilitating team
- Group of experts that do not normally interact with one another

10.10.4 PROCESS

The first step, once the purpose of the process is clearly identified, is to form a small team to facilitate and monitor the process. This team identifies and secures the participation of a group of experts. Initial phases sometimes allow experts to add pertinent information to the knowledge base and define relative terms to be used, such as "importance," "high risk," "unlikely," and similar words and

phrases. The process is a combination of polling and conference, where much of the responsibility for communication is shifted from the members of the large group to the members of the facilitating team. The team develops and pretests the round one questionnaire, which is designed to elicit information relevant to the decision problem. The questionnaire then is sent to the expert group members individually. Information from this first round of responses is analyzed and summarized by the team. The summary is usually provided to the expert group without attributions. The group members are usually given one opportunity to revise their original responses based on this initial round of review of the original responses. The facilitators prepare a second questionnaire for the expert group. Experts respond to the second questionnaire and the process is repeated until consensus is reached.

10.10.5 OUTPUTS

The desired output of this process is the expert group's convergence toward consensus on the decision problem.

10.10.6 STRENGTHS AND WEAKNESSES

Strengths (IEC, 2008):

- Easier to get the needed experts as experts do not need to actually assemble in one place at one time
- Anonymity helps to assure that any unpopular opinions will be more likely to be expressed
- There is no group dominance; all views have equal weight
- The process achieves ownership of outcomes

Weaknesses:

- Process is very labor intensive and time consuming for the facilitating team
- Experts must be able to express themselves clearly in writing

The Delphi technique is one of the more common techniques for eliciting expert opinion. It may be most valuable for reducing knowledge uncertainty about matters of subjective judgment or interpretation.

10.10.7 EXAMPLES OF USE

One common example is classifying the condition of a structure or structural component based on limited physical evidence. A second common example is forecasting the efficacy of a risk management option "with condition." For additional information see *The Delphi Method, Techniques and Applications*, edited by Harold A. Linstone and Murray Turoff, New Jersey Institute of Technology, 2002 <https://web.njit.edu/~turoff/pubs/delphibook/delphibook.pdf> (accessed July 13, 2018). A nice online summary can be found at Practical Assessment, Research & Evaluation,

Vol 12, No 10 2 Hsu & Sandford, Delphi Technique <http://pareonline.net/pdf/v12n10.pdf> (accessed July 13, 2018).

10.11 DOSE-RESPONSE CURVE

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.11.1 OVERVIEW OF THE TECHNIQUE

A dose-response curve is the primary model used to characterize the adverse human health effects of chemicals, toxins, and microbes in the environment. The curve shows the relationship between the dose (magnitude and frequency) of a stressor (e.g., concentration of a toxin, number of microorganisms, intensity of radiation) to the response of the receptor organism (often a human) under study. A chemical dose may be measured in mg per kg of bodyweight daily for a lifetime. A microbial dose may be the number of organisms consumed or absorbed in an eating occasion. The response is generally some measure of an adverse health effect. It may be the probability of an illness, cancer, or death; the number of excess tumors produced by such a dose in a population; blood pressure increases; organ atrophy; or any other of a large number of adverse effects.

10.11.2 HOW THE TECHNIQUE IS USED

Dose-response relationships are used in consequence assessments to characterize the harm that can result from exposure (likelihood assessment) to the hazardous dose. Curves are fit to a series of data points or to a specific model form. Doses are typically shown on the x-axis and responses on the y-axis. [Figure 10.7](#) shows a stylized dose-response curve.

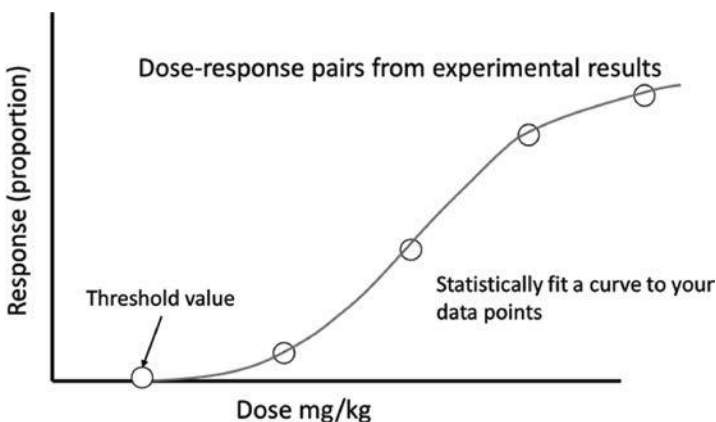


FIGURE 10.7 Stylized dose-response curve.

10.11.3 INPUTS

A dose-response curve requires the following inputs:

- Clearly identified hazard
- Defined dose
- Defined adverse effect (response)
- Data
- Specification or derivation of a mathematical model to fit the data

10.11.4 PROCESS

The data must come from valid scientific experiments or epidemiological studies that produce dose-response data points. These points are collected from the available data and a curve is fit to the points. The first point that produces an adverse effect is called the threshold dose. If zero is assumed to be the only nonresponse point, this is a no-threshold model. Doses below the threshold are assumed to have no adverse effects.

10.11.5 OUTPUTS

The dose-response curve is the output. It is usually part of a risk assessment. It helps answer the “what can go wrong?” question. It is still necessary to describe how the receptor organism may become exposed to the hazard and at what dose. A dose-response and exposure assessment are usually sufficient to develop a risk estimate for this class of hazards.

10.11.6 STRENGTHS AND WEAKNESSES

Strengths:

- Widely-accepted technique with well-known data requirements
- Successfully used in decision making for many years

Weaknesses:

- Lack of data in the low dose ranges, hence an inability to establish a threshold that has led to the widespread use of no-threshold models
- Available data are frequently for a species other than the receptor species, leading to extrapolation issues, for example, many human dose-response curves are based on animal feeding data

10.11.7 EXAMPLES OF USE

Dose-response relationships are widely used in chemical risk assessments and other situations where toxic contaminants have been introduced to food or the natural environment. Dose-response curves have also been used to estimate the beneficial effects of medicines. Over the last couple of decades, the use of dose-response curves

has been extended to microbiological risks, especially in the food safety community of practice. A good introduction can be found in [Chapter 8](#), “Conducting the Dose-Response Assessment” of *Quantitative Microbial Risk Assessment* by Charles N. Haas, Joan B. Rose, and Charles P. Gerba, John Wiley and Sons 1999. The concept is rather flexible, and clever adaptation of dose-response curves have been made. For example, depth-damage functions routinely used in flood risk management studies are themselves dose-response curves where water is the dose and damages are the response.

10.12 ECOLOGICAL RISK ASSESSMENT

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.12.1 OVERVIEW OF THE TECHNIQUE

Ecological risk assessment (ERA) is a process that was developed in the United States by the Environmental Protection Agency (EPA, 1998) to address risks to ecosystems, plants, animals, and humans as a result of exposure to a range of environmental hazards, including chemicals, anthropogenic activity, microorganisms, and the like. The basic approach begins with the hazard or source of harm and the pathways by which the hazard can affect a susceptible target population. It culminates in an estimate of the likelihood and consequences of that harm. The term “ecological risk assessment” tends to be reserved by the EPA for assessing the risks of pesticides in the environment. The use of ecological risk assessment models has evolved, however, and they are now valuable for consideration of broader scope environmental and ecological risks.

10.12.2 HOW THE TECHNIQUE IS USED

Early risk assessment models were geared toward the estimation of cancer risks in humans. As risk assessment progressed, the need to address a wider array of risk assessment endpoints became evident and the ERA model was initially developed. This was one of the first assessment models to rely heavily on pathway analysis. Pathway analysis explores the different routes by which a target endpoint might be exposed to a source of risk. Pathway analysis has since been adapted and used in many different risk applications. It has proven especially useful for identifying risk management options to reduce unacceptable risk.

10.12.3 INPUTS

ERA inputs (EPA, 1998) include:

- Overall purpose and general scope of the risk assessment
- Products needed by management for risk decision making
- Approaches, including a review of the risk dimensions and technical elements that may be evaluated in the assessment

- Relationships among potential assessment end points and risk management options
- Analysis plan and a conceptual mode
- Resources (e.g., data or models) required or available
- Identity of those involved and their roles (for example, technical, legal, or stakeholder advisors)
- Schedule to be followed (including provision for timely and adequate internal and independent external peer reviews)

10.12.4 PROCESS

The ERA process is summarized in Figure 10.8. The main steps of the process are problem formulation, analysis, and risk characterization. Data are collected and analyzed throughout the process. Critical tasks in the process include selecting the data that will be used and determining its strengths and weaknesses, an analysis of stressors and their distribution in the environment, and potential and actual exposure to the stressors.

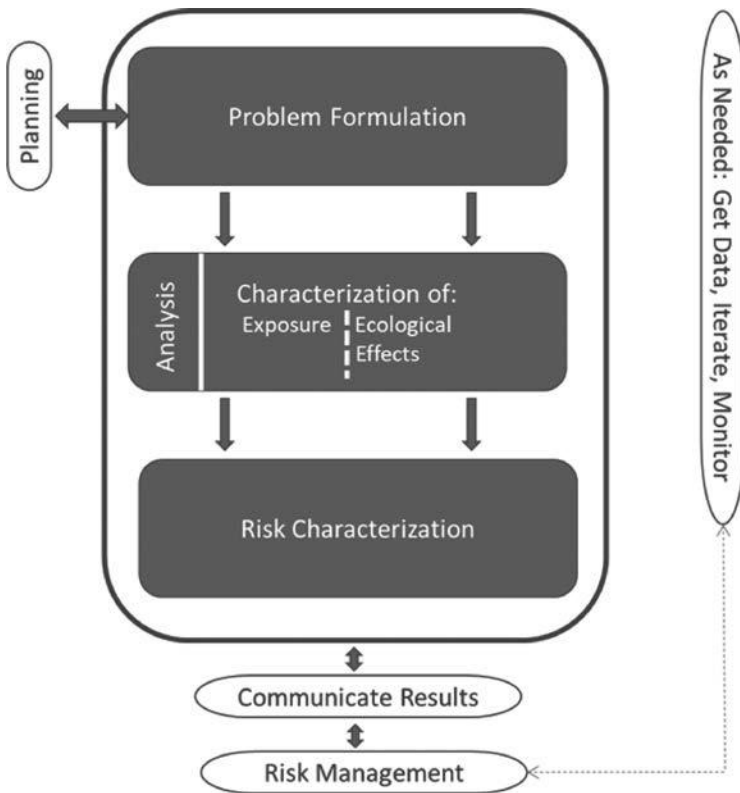


FIGURE 10.8 EPA's ecological risk assessment model.

10.12.5 OUTPUTS

Stressor-response relationships, exposure and effects profiles, and a risk characterization are the primary outputs of the process.

10.12.6 STRENGTHS AND WEAKNESSES

Strengths:

- Detailed understanding and presentation of the nature of the problem and the factors that contribute to environmental risk(s)
- Pathway analysis can identify critical points in the chain of risk events that show how and where it may be possible to improve risk controls or introduce new ones

Weaknesses:

- Relatively extensive data requirements
- Without extensive data, ERA can have a high level of uncertainty associated with it

10.12.7 EXAMPLES OF USE

The U.S. EPA is a primary user of this risk assessment technique. A wide variety of ecological risk assessments are available from their web site. "A Framework for Ecological Risk Assessment" is available at <https://www.epa.gov/risk/framework-ecological-risk-assessment> (accessed July 13, 2018). The EPA web site for Ecological Risk Assessment <https://www.epa.gov/risk/ecological-risk-assessment> (accessed July 13, 2018) provides access to a wealth of related resources.

10.13 EVENT TREE

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.13.1 OVERVIEW OF THE TECHNIQUE

An event tree is a qualitative or quantitative analytical technique for modeling a system, a pathway, or a sequence of events. It uses forward logic and begins with an initiating event and proceeds to the many different outcomes possible with that event. It is constructed of a sequence of nodes and branches that describe the unfolding possible outcomes of an initiating event. Each unique pathway through the tree describes a unique sequence of events that could result from the initiating event. It is believed to have been introduced during the WASH-1400 nuclear power plant safety study of the 1970s (Ericson 2005). A simple example of an event tree is shown in [Figure 10.9](#).

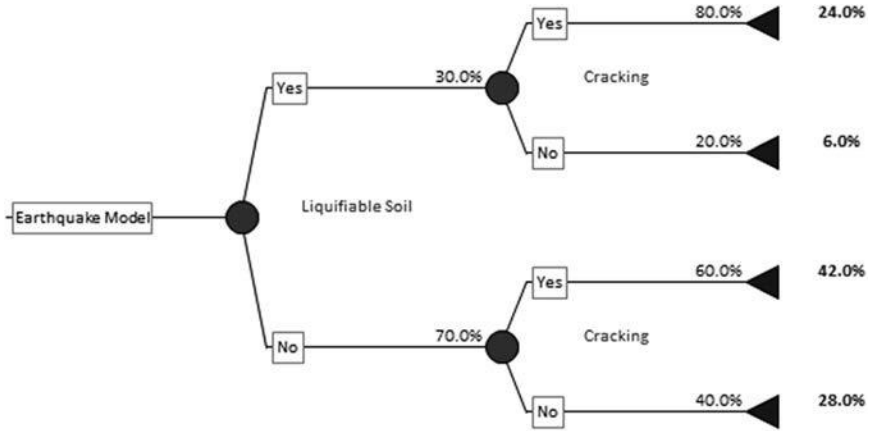


FIGURE 10.9 Simple event tree of a hypothetical earthquake effect on a concrete monolith.

DECISION TREE

A decision tree may begin with a decision or a chance event. A single stage decision tree requires one decision then the tree defines how that decision can play out. Multi-stage decision trees are a mixed pattern of chance and decision events. A decision tree enables managers to examine how different decisions made at various points in the model could turn out.

A decision tree model is a predictive tool that shows the ultimate consequences of the various decision choices. Each consequence is represented by a pathway through the tree. A decision that puts one on the path that leads to the most desired value or outcome (e.g., highest benefit, lowest probability of adverse outcome) is the decision that is typically chosen.

A distinguishing characteristic of the event tree is that all the events or nodes are assumed to be determined by chance. There are no decisions to be made along any of the pathways. When decision nodes are added to an event tree it is more appropriate to call the technique a decision tree (see box). Event trees that only assess the frequency of the various possible outcomes are sometimes called probability trees.

The event tree is an inductive logic technique that answers the basic question “what happens if ...?” by fanning out like a tree (IEC 2009). An event tree is useful for identifying both aggravating and mitigating events that might follow the initiating event.

10.13.2 HOW THE TECHNIQUE IS USED

Event trees can be used at any stage in the lifecycle of a project or process. They have value as a qualitative tool because the process of developing a tree aids the understanding of a risk situation by identifying the potential scenarios and sequences

of events that can lead to more or less desirable outcomes. Quantifying the tree with probability and consequence information enables the risk assessor to characterize the risk numerically. A quantitative model can be very useful in evaluating the efficacy of different risk control strategies. The trees are often used to model failure modes where there are multiple safeguards and/or multiple modes of failure.

10.13.3 INPUTS

An event tree model requires:

- Explicit understanding of the process that is being modeled
- A clearly and concisely defined initiating event
- Sequences of follow-on events
- Outcomes or endpoints must be known
- Sufficient data to numerically describe the function and failure of the system under consideration
- Knowledge of the properties of probabilities

10.13.4 PROCESS

An event tree begins with an initiating event. Events are represented by nodes. Chance events are represented by circles, decisions by squares, and endpoints by triangles. The initiating event may be a natural event, an infrastructure failure, an operator error, or any other causal event. A chance event will have more than one potential outcome. A branch leads to each potential outcome of the event from the preceding node. The outcome of an event may become the next event in an unfolding development of a pathway from the initiating event to the model's endpoint. Events between the initiating event and the endpoint may aggravate or mitigate the eventual outcome. The model proceeds from left to right. This node-branch sequence continues until an endpoint is reached. An endpoint represents the point at which the sequence of events from the initiating event is concluded for the purposes of the decision problem at hand.

“TREE TIME”

Nodes represent points in logical time. The position of a decision node marks the time in a sequence of events when the decision maker makes a decision. A chance node shows the “logical” time when the result of an uncertain event becomes known. An endpoint denotes the time when a process is ended or a problem is resolved.

Time (logic) flows from left to right. Branches leading into a node have already occurred. Branches leading out of or following a node have not occurred yet.

When a chronologic order exists, it should be reflected in the model. When the order is driven by the modeler's logic there is more flexibility and art in how events are sequenced. However, once the model is constructed a logical tree time is established.

In quantitative event trees, probabilities are estimated for each branch emerging from a node. These probabilities are usually listed above the branch. If consequences are quantified (dollars, lives lost, people affected, and so on) these are listed below the branch. Each probability is a conditional probability predicated on the nodes and branches that preceded it. Consider [Figure 10.9](#) again. Each path through the tree represents the likelihood that all of the events in that path will occur. There is often art involved in defining the sequence of events on the paths. These sequences enable assessors to calculate the probability of the identified outcomes by the product of the individual conditional probabilities and the frequency of the initiating event.

Ericson (2005) describes the tasks comprising the event tree process as follows:

1. Define the system
2. Identify the accident scenarios
3. Identify the initiating events
4. Identify the pivotal events
5. Build the event tree diagram
6. Obtain the failure event probabilities
7. Identify the outcome risk
8. Evaluate the outcome risk
9. Recommend corrective action
10. Document the event tree

10.13.5 OUTPUTS

A good event tree model provides a qualitative description of a potential risk. It fleshes out problems and their consequences as different combinations of events are shown to produce variations of the problem and a range of outcomes that can result from an initiating event. [Figure 10.9](#), for example, suggests four different ways damage to a concrete structure may occur as a result of an earthquake. Quantitative estimates of event consequences and their likelihoods can be obtained when the tree model is quantified. The best models can help assessors understand the relative importance of different sequences of events and failure modes. The efficacy of different risk management options can often be tested and quantified by changing critical model inputs to reflect the operation of the risk management options. Event trees can be used to examine part of a risk, for example, the likelihood assessment and its outputs may become inputs to other risk assessment models. Event trees provide an effective visual map of risks.

10.13.6 STRENGTHS AND WEAKNESSES

Strengths:

- Able to display potential scenarios following an initiating event
- Visually displays cause and effect relationships
- Can account for timing, dependence, and domino effects that are cumbersome to handle in verbal descriptions and other models

- Flexible and versatile tool
- Relatively easy to learn, do, and follow

Weaknesses:

- Require analysts to be able to identify all relevant initiating events
- May require a separate model for each initiating event
- Difficult to represent delayed or partial success or recovery events when nodes are constructed with dichotomous branches
- Any path is conditional on the events that occurred at previous branch points along the path
- Models can quickly grow very large

10.13.7 EXAMPLES OF USE

Event trees are one of the most widely applied risk assessment techniques. They are especially useful for modeling system failures.

10.14 EVIDENCE MAPS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.14.1 OVERVIEW OF THE TECHNIQUE

Summarizing scientific evidence about a potential hazard is a fundamental task in risk assessment. In an increasing number of instances, the existing data may be incomplete, inconsistent, or even contradictory on some significant matters of uncertainty. Evidence maps have been proposed by Schütz et al. (2008) as a tool for summarizing the scientific data about a potential hazard. The method has been used primarily in situations when the evidence is unclear on the existence of a hazard. For example: What is the likelihood and magnitude of sea level change this century? Do mobile phones cause cancer? The notion can be readily extended to opportunity risks. Will autonomous vehicles result in more jobs and fewer accidents? Evidence maps summarize the information available on these uncertain issues in an easily accessible form.

10.14.2 HOW THE TECHNIQUE IS USED

Summarizing scientific evidence is a fundamental purpose of risk assessment. Evidence maps are useful when the data are incomplete, inconsistent, or even contradictory on significant matters of uncertainty. Evidence maps are useful in these situations because they enable assessors to summarize what is known about suspected hazards, what is uncertain, and why. The maps have been used most predominantly in situations where the suspected existence of a hazard has not yet been proven. However, the technique can be readily adapted to other uncertain situations.

10.14.3 INPUTS

The essential inputs for an evidence map process are:

- A well-defined decision problem, usually a suspected hazard
- The evidence basis., that is, the number and quality of relevant scientific studies
- Logic and probability theory
- A panel of experts to review the evidence
- The pro- and con-arguments for the existence of a hazard with supporting and attenuating arguments
- The conclusions about the existence of a hazard with remaining uncertainties identified

10.14.4 PROCESS

Figure 10.10 shows the template for an evidence map. Sponsors of the evidence map assemble the relevant studies from the available literature that are suitable for a risk evaluation with input from the expert panel. The experts then extract the arguments for a hazard or risk (pro-argument) and the arguments against a hazard or risk (con-argument). They carefully document evidence that attenuates or supports these arguments and then draw some tentative conclusions about the hazard or risk while carefully noting the uncertainties that still attend the issue.

10.14.5 OUTPUTS

The process output is a map of the pro- and con-arguments along with the remaining uncertainties. The summaries are entered into a single-page template like that shown in the figure. The map and its accompanying documentation summarize what is and is not known about a hazard, risk, or other topic being mapped.

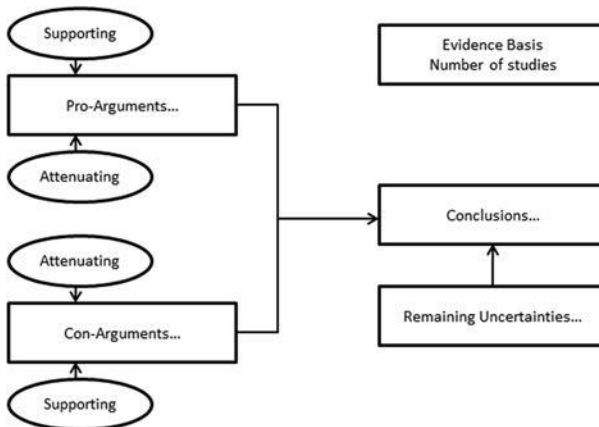


FIGURE 10.10 Template of the Schütz, Wiedemann, and Spangenberg evidence map.

10.14.6 STRENGTHS AND WEAKNESSES

Strengths:

- Summarizes the current state of the scientific evidence
- Provides an unbiased summary of what is and is not known about the issue
- Presents evidence-based arguments for all sides of an issue and notes evidence that either attenuates an argument or supports it
- Well-suited to situations where contradictory views on an issue exist

Weaknesses:

- Cannot be applied unless a reasonable evidence base exists
- May not definitively resolve an issue

10.14.7 EXAMPLES OF USE

For more information on evidence maps, see Schütz et al. (2008). The U.S. Food and Drug Administration's Center for Veterinary Medicine has used a version of the evidence map to evaluate applications for new veterinary drugs.

10.15 EXPERT ELICITATION

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.15.1 OVERVIEW OF THE TECHNIQUE

Risk managers are frequently required to make important decisions in the presence of uncertainty, and risk analysis seeks to increase understanding of the implications of uncertainty for decision making. Expert elicitation is a useful technique for characterizing uncertainty. It is a systematic process of formalizing, and usually quantifying, often in probabilistic terms, expert judgments about uncertain quantities. It has been used to elicit qualitative judgments about matters of uncertain facts as well as to integrate empirical data with scientific judgment and identify a range of possible outcomes and likelihoods. Thus, it can be applied as a qualitative or quantitative technique. Documenting the underlying thought processes of experts is the essence of the process. Expert elicitation is the subject of [Chapter 14](#); see it for a detailed treatment of this technique.

10.15.2 HOW THE TECHNIQUE IS USED

Many of the complex problems risk managers face are characterized by a lack of direct empirical evidence for some aspect(s) of the problem. Most of these situations require judgment to help bridge the gaps in data, knowledge, or theory. Expert elicitation is used to make subjective judgments as objectively as possible. It is defined, here, more narrowly than expert judgment. It is a method limited to characterizing the science (state of knowledge) in a decision problem. Expert judgment, as defined here, refers

to characterizing the decision-relevant values and preferences that lead up to decision making. Thus, estimating a parameter for a model is a matter of expert elicitation, while trading off economic development effects for ecosystem restoration effects is an expert judgment. Elicitations may be group or individual efforts. Elicitations cannot create information or knowledge. At their best they characterize the uncertainty around a value.

10.15.3 INPUTS

The inputs for an expert elicitation process include:

- Sponsor for the elicitation that includes domain experts and an elicitation facilitator
- Problem definition to include identification, selection, and development of technical issues to be resolved
- Formal elicitation protocol
- Experts
- Identification, summary, and sharing of the relevant body of evidence with experts
- Formal elicitation to encode the experts' judgments
- Presentation and/or aggregation of results

10.15.4 PROCESS

The elicitation process begins with problem definition and identification of technical issues by the sponsor in need of the elicited information. The elicitation process is facilitated according to the chosen protocol. A protocol provides for the elicitation of opinions, their analysis and aggregation, the revision of those opinions, and the development of a consensus when one is needed. Experts need to be identified and the relevant evidence should be shared. The experts define the scope of the problem, clarify terminology, and clarify all contextual matters that will influence their ability to render judgment. Significant elicitations may include the calibration of experts. The best processes may include a peer review. Formal elicitation is one of the last steps in the process.

10.15.5 OUTPUTS

The output of the process includes characterization of the uncertain values that were the focus of the exercise expressed qualitatively or quantitatively (typically probabilistically). The expert opinions may stand individually or they can be aggregated into a composite expert using weighted or unweighted methods.

10.15.6 STRENGTHS AND WEAKNESSES

Strengths:

- Can provide carefully considered and fully described views of highly respected experts affiliated with diverse institutions and perspectives when such cross-institutional viewpoints may be preferable to relying on the views of an in-house expert

- Can bound uncertainty and provide estimates of critical missing data and information
- Useful for addressing emerging science challenges and scientific controversies including such technical issues as model selection or use and data selection or use
- Deliberation by a group of experts can help render complex problems tractable

Weaknesses:

- Difficult to find informed experts
- Experts are not always well calibrated
- Problems can arise in combining expert judgments when a composite estimate is desired
- Potential for biased and imprecise estimates
- Because expert elicitations are based on subjective judgment, there is a concern that they may be considered arbitrary

10.15.7 EXAMPLES OF USE

For examples of use, Goossens et al. (2008) provide a comprehensive summary of the experience of Delft University in a wide variety of applications of the elicitation technique.

10.16 FAILURE MODES AND EFFECTS ANALYSIS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.16.1 OVERVIEW OF THE TECHNIQUE

Failure Modes and Effects Analysis (FMEA) enables analysts to assess the relative impact of different failures, in order to identify the parts of the process that are most in need of change (<http://www.ihl.org/resources/Pages/Tools/FailureModesandEffectsAnalysisTool.aspx> [accessed July 13, 2018]). It is a step-by-step approach for identifying the possible ways infrastructure, a process, product, or service can fail in order to identify design changes to prevent these failure modes. Developed by the U.S. military (originally described in MIL-P-1629 now MIL-STD-1629A), FMEA is a technique that can be used to answer the “what can go wrong?” and “how it can happen?” questions of risk assessment. When expanded to failure modes, effects, and criticality analysis (FMECA) it can also be used to answer the questions “what are the consequences?” and “what is their likelihood?” The method is sometimes said to consist of a Failure Modes and Effects Analysis that can be followed by a criticality analysis. Both techniques identify the ways components or systems can fail to measure up to design levels of performance. These techniques identify (IEC, 2008):

- All potential failure modes of the various parts of a system
- The effects these failures may have on the system
- The causes of failure
- How to avoid the failures and/or mitigate the effects of the failure on the system

10.16.2 HOW THE TECHNIQUE IS USED

These techniques try to predict failures before they occur, unlike root-cause analysis, which is a forensic technique. FMECA extends a FMEA by ranking each fault mode by its combined likelihood of occurrence and the severity of its consequences, usually qualitatively or semiquantitatively.

These techniques can be applied during the design, construction, or operation of a system. They have been used to help select design alternatives with high reliability/dependability and to ensure that all failure modes and their effects on operational success have been considered. They are also useful for developing lists of potential failures as well as the severity of their effects. Both techniques have been used to improve testing and maintenance as well as providing a basis for quantitative reliability and availability analysis. They have been used for component faults in physical systems and also to identify human failure modes and effects. These techniques produce outputs that can become inputs to other techniques such as fault tree analysis. They can be especially useful when technology with no failure mode track record is being introduced.

Although this is usually a qualitative or semiquantitative assessment, it can be quantitative when actual failure rates are available.

10.16.3 INPUTS

The critical inputs for FMEA include:

- A well-defined system
- Detailed information about the components of the system
- Information including design drawings, process details, and the system's operating environment
- Experts familiar with the system
- Brainstorming the ways each critical component of the system can fail
- Historical data on failure rates is essential for a quantitative analysis

10.16.4 PROCESS

An example set of steps of an FMEA process include (IEC, 2008):

- Review the process
- Brainstorm potential failure modes
- List potential effects of failure

- Assign severity rankings
- Assign occurrence rankings
- Calculate risk priority numbers
- Develop an action plan
- Take action
- Recalculate risk priority numbers

Each process requires a definition of the scope and objectives of the study and commissioning a team that understands the system to be analyzed. This usually includes breaking the system down into its components or steps. Then for each component, the team identifies:

- How each component can conceivably fail
- Mechanisms that can produce these modes of failure
- What the effects will be if the failures occur
- If the failure is a safe or unsafe one
- How the failure can be detected
- What provisions can be made to compensate for the failure

RISK PRIORITY NUMBERS

An FMEA identifies opportunities for failure or “failure modes” in each step of a process. Each failure mode gets a numeric score that quantifies (a) the likelihood that the failure will occur, (b) the likelihood that the failure will not be detected, and (c) the amount of harm or damage the failure mode may cause to a person or to equipment. The product of these three scores is the Risk Priority Number (RPN) for that failure mode. The sum of the RPNs for the failure modes is the overall RPN for the process.

An FMECA includes classification of each failure mode according to the combined influence of the severity of its consequences, its likelihood of occurring, and its detection possibility. This can be done with a risk priority number (see above box). Risk management actions are defined to reduce the effects or their likelihood of occurrence or to increase the detectability of the failure mode before it occurs. These actions should minimize the occurrence of the more significant failure modes. A without- and with-comparison of the Risk Priority Numbers provides a semiquantitative basis for assessing the action plan.

10.16.5 OUTPUTS

The primary output is a list of failure modes and their effects for each component. This list may or may not include an estimate of the likelihood of failure depending on whether it is FMEA or FMECA. Causes of failure are also provided along with the criticality of each failure mode.

10.16.6 STRENGTHS AND WEAKNESSES

Strengths:

- Ability to identify component fault modes, their causes, and their effects on the system
- Can avoid the need for costly equipment, component, and project modifications in service by identifying problems early in the design process
- System reliability and redundancies can be improved by the process
- Process is helpful in designing testing protocols when modes of failure have been anticipated

Weaknesses:

- Not useful when considering combinations of failure modes
- Can become costly and time consuming
- Frequently difficult and tedious when applied to complex multi-layered systems

10.16.7 EXAMPLES OF USE

Arabian-Hoseynabadi et al. (2010) provide an example of an application of FMEA to wind turbines. Stamatis (2003) provides an excellent introduction to this technique with numerous examples, and the U.S. Army Corps of Engineers makes extensive use of it in conducting screening and semiquantitative risk assessments of levees in the National Levee Safety Program.

10.17 FAULT TREE

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.17.1 OVERVIEW OF THE TECHNIQUE

Fault tree analysis is almost the mirror image of event tree analysis. While an event tree uses forward logic to proceed from a single initiating event to a number of potential outcomes, a fault tree begins with a single outcome and uses backward logic to proceed to a number of potential initiating events or causes. This technique is for identifying and analyzing factors that can contribute to a specific undesired outcome, fault, or failure, also called the top event, in order to understand and prevent problems. Causal factors are deductively identified, organized in a logical manner, and usually represented from top to bottom, rather than horizontally as in an event tree. The pathways through the tree show causal factors and their logical relationship to the top event. Fault tree analysis was invented and developed by Watson and Mearns of Bell Labs for use on the Minuteman Guidance System (Ericson 2005). A simple fault tree is shown in [Figure 10.11](#). It shows four possible causes of a pump failure.

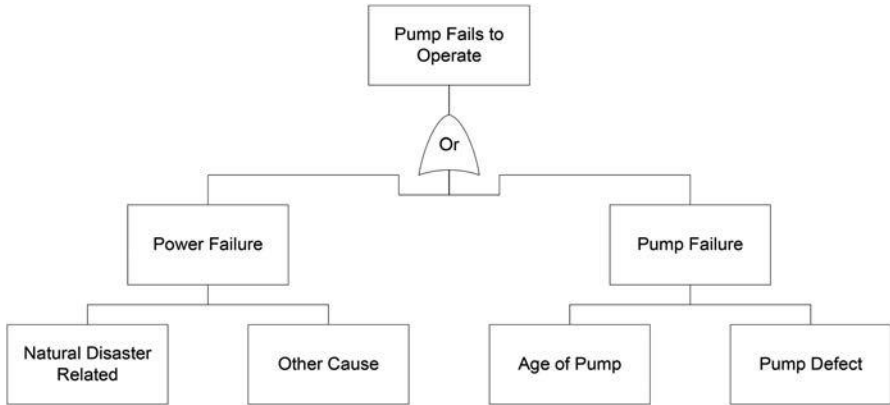


FIGURE 10.11 Fault tree showing sources of pump failure.

Each unique pathway through the tree describes a unique sequence of events that could have caused the fault. Thus, each pathway provides a visual depiction of a risk hypothesis.

10.17.2 HOW THE TECHNIQUE IS USED

Murder investigations and epidemiological outbreak investigations are good examples of fault tree applications. They begin with a failure or fault and work backwards to the most likely cause. Qualitative fault trees identify potential causes and pathways to a failure. Quantitative fault trees can be used to calculate the likelihood of the fault having been caused by any particular sequence of events, provided that you know the probabilities of causal events.

Fault trees are often used during the design stage of a system to identify potential causes of failure and to inform the ultimate choice of the design options, which can eliminate or mitigate the cause. They are used during operations to identify the relative importance of different pathways to major failure events. A fault tree can be used to analyze the causes of an unexpected failure by showing how different events could have come together to cause the failure in order to prevent recurrence. Fault trees can identify high-risk fault paths and their mechanisms. They can also be used to estimate the probabilities of these kinds of events (Ericson 2005).

10.17.3 INPUTS

The basic inputs to a fault tree include:

- Defined fault condition
- Identify potential causes of failure
- Conventional fault tree symbols, including input and output events, gates (e.g., and, or)
- Logic and probability theory
- Failure rates for all the basic events in the fault tree

10.17.4 PROCESS

The first step is to define the top event of the failure or fault of concern. This may be an actual failure, like a dam failure, or a broader outcome of that failure, like catastrophic loss of life due to a dam failure. Beginning with the top event, all the possible immediate causes or fault modes leading to the top event, that is, sequences of events, are identified using technical information and professional judgments. Continue to break down each element of these fault modes to identify the means by which it could have occurred. Consider the relationships between the elements to help you decide whether to use an “and” or an “or” logic gate. This process continues in a stepwise manner to successively lower system levels until further decomposition of the failure mode ceases to be productive. Finalize and review the completed diagram. The failure chain logic can only be terminated by some base event, for example, a human, hardware, or software error. For quantitative fault trees, evaluate the probability of occurrence for each of the lowest level elements and calculate the statistical probabilities from the bottom up. Even when quantification of probabilities is not feasible the trees are often useful for displaying causal relationships.

Ericson (2005) describes the tasks comprising the fault tree for design processes as follows:

1. Define the system
2. Identify the top undesired event
3. Establish boundaries
4. Construct the fault tree
5. Evaluate the fault tree
6. Validate the fault tree
7. Modify the fault tree
8. Document the analysis

10.17.5 OUTPUTS

The most useful output of a fault tree analysis includes the visual depiction of how the top event can occur. The trees are especially useful for showing interacting pathways where two or more simultaneous events must occur. They can also provide overall estimates of the probability of failure as well as the probabilities of individual pathways to failure when likelihood information is available and the model is not too complex.

10.17.6 STRENGTHS AND WEAKNESSES

Strengths:

- Can analyze a wide variety of factors including physical phenomena, human responses, and interactions of all these factors
- Top down approach focuses attention on those causes of failure that are directly related to the top event
- A good model for water and infrastructure systems with many interfaces and interactions

- System behavior can be readily understood by the visual depiction of failure modes
- Can identify combinations of events that could lead to failure
- Often useful in decomposing events so probabilities can be estimated
- May not be possible to estimate the probability of a complex failure all at once, for example, a dam failure; but after the chain of necessary and sufficient events is identified it may be feasible to estimate the probabilities of these events

Weaknesses:

- Can become quite large for complex systems
- Usually a high level of uncertainty in the calculated probability of the top event
- For some situations causal events are not bounded, and it is hard to know if all important pathways to the top event are included

10.17.7 EXAMPLES OF USE

Fault trees are useful for considering risks associated with the failure of complex systems. Engineers working in systems reliability, maintainability, and safety make extensive use of fault trees. As noted earlier, fault trees are also useful in cause-and-effect criminal and epidemiological investigations.

10.18 FRAGILITY CURVES

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.18.1 OVERVIEW OF THE TECHNIQUE

Fragility curves are functions that describe the probability of failure, conditioned on the load, over the full range of loads to which a system might be exposed (Schultz et al. 2010). Fragility curves describe how the reliability of a structure changes over the range of loading conditions to which that structure might be exposed. Usually, the curves describe the probability of a structure being damaged beyond a specific damage state conditional on a specific load (e.g., flooding, ground shaking) to assess the vulnerability of the structure. A fragility curve can be understood as an engineering adaptation of the dose-response curve concept. In the fragility curve concept, the dose is usually load or some physical parameter like the depth of water for flooding, while the response might be the probability a flood protection structure will fail. For earthquakes, the dose might be a ground motion for earthquakes and the response the probability of damage to a structure, like a bridge. The conditional probability that a system will reach, or exceed, a given damage threshold over some time period is usually the response of interest.

10.18.2 HOW THE TECHNIQUE IS USED

The shape of a fragility curve describes the uncertainty in a system's capacity to withstand a load or, alternatively, the uncertainty about what load will cause the system to fail. The fragility curve takes the form of a step function when there is little uncertainty in capacity or demand. The curve on the left of [Figure 10.12](#) conveys absolute certainty the system will fail at a critical load. Such a fragility curve is appropriate for brittle and well-understood systems. In elastic, poorly understood, or complex systems, the fragility curve takes the form of an S-shaped function as shown on the right side of [Figure 10.12](#). The S-shaped function suggests the failure state of the system can only be evaluated with some probability and it is appropriate when there is uncertainty in the capacity of the system to withstand a load.

10.18.3 INPUTS

A fragility curve requires the following inputs:

1. Well-defined system
2. Well-defined range of loads
3. Method to develop probability of failure estimates for a range of loads

10.18.4 PROCESS

Schultz et al. (2010) identify four methods for developing a fragility curve. These are: judgmental, empirical, analytical, and hybrid (Jeong and Elnashai 2007). Judgmental approaches are based on expert opinion or engineering judgment. Empirical approaches are based on observations.

Analytical approaches are based on models. Hybrid approaches are based on two or more of the other approaches. There is no one best approach. The choice of approach usually involves a trade-off between the cost and precision appropriate for the application. An analytical methods approach is most commonly found in the peer-reviewed literature.

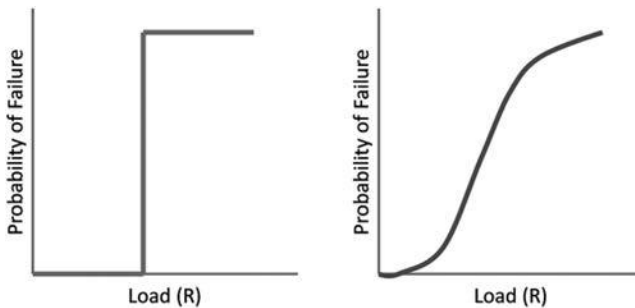


FIGURE 10.12 Conceptual fragility curves for two uncertainty conditions. (Adapted from Schultz, M. T. et al. 2010. "Beyond the Factor of Safety: Developing Fragility Curves to Characterize System Reliability." Water Resources Infrastructure Program, USACE.)

10.18.5 OUTPUT

The output of a fragility curve analysis is the fragility curve itself.

10.18.6 STRENGTHS AND WEAKNESSES

The strengths and weaknesses of fragility curves depend on the approach used to develop the curve. Schultz et al. (2010) offer the following assessment of strengths and weaknesses:

10.18.6.1 Judgmental Approach

Strengths:

- Not limited by data or models
- Fast and cheap method if consequences of potential inaccuracy are small
- Useful check on other fragility estimates

Weaknesses:

- Difficult to validate or verify
- Subject to biases of experts
- Not auditable
- Cannot improve over time

10.18.6.2 Empirical Approach

Strengths:

- Data may come from either controlled or natural experiments
- Useful and flexible if data are available
- Does not assume a correlation structure or a lognormal form for the fragility curve

Weaknesses:

- Data can be scarce and source specific
- Experiments can be expensive
- Difficult to validate independently of the dataset
- Difficult to extrapolate fragility curves to other structures

10.18.6.3 Analytical Approach

Strengths:

- Based on physical models that can be validated and verified, enhancing transparency
- Easier to extrapolate results to new situations
- Facilitates a distinction between aleatory and epistemic uncertainty

Weaknesses:

- May be based on simplifications and assumptions
- Requires the availability of data and models

- More time-consuming to implement
- Requires a higher level of training

10.18.6.4 Hybrid Approach

Strengths:

- Limitations of any particular approach can be overcome with a complementary approach
- Modeling results and observations can be combined to improve the “robustness” of fragility estimates using Bayesian updating

Weaknesses:

- Limitations are the same as the individual approaches

10.18.7 EXAMPLES OF USE

Originally developed for seismic risk, fragility curves are becoming increasingly common components of flood risk assessments. A report published by USACE (Schultz et al., 2010) shows that fragility curves have been used in risk assessments for buildings, bridges, flood protection, and industrial system components.

10.19 FREQUENCY NUMBER (FN) CURVES

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.19.1 OVERVIEW OF THE TECHNIQUE

Frequency number (FN) curves are cumulative distributions. They graphically present the frequency of a given number of adverse effects, usually fatalities, occurring for a specified hazard. They show the likelihood of a risk causing a specified level of harm to a specific population, usually in log-log space. Most often they show the cumulative frequency (F) at which N or more members of the population will be affected. High values of N that occur with a high frequency F are likely to be unacceptable risks.

Figure 10.13 shows an FN curve for a hypothetical quantitative risk assessment, where N is the number of fatalities per year and F is the cumulative frequency of N or more fatalities in a given year.

10.19.2 HOW THE TECHNIQUE IS USED

FN curves are one way of presenting the outputs of a risk assessment. It is not unusual for a risk profile to have a high likelihood of a low consequence outcome and a low likelihood of a high consequence outcome. An FN curve is a line describing this range of likelihood-consequence pairs rather than a single point representing one consequence likelihood pair.

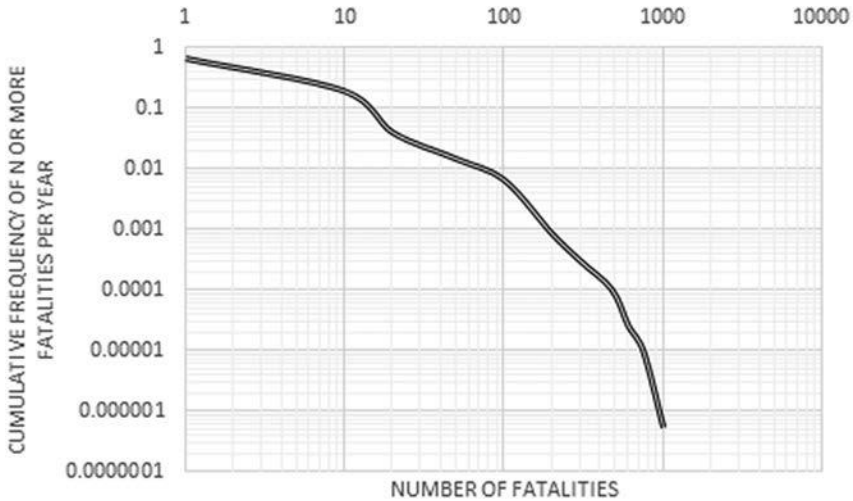


FIGURE 10.13 FN curve example for hypothetical quantitative risk assessment results.

FN curves have also been used to characterize “societal risk” (Wardman et al. 2007). They show the relationship between frequency and the number of people suffering from a specified frequency of harm in a given population from specific hazards. Plots with multiple FN curves can be used to compare the relative risks of hazards.

An FN curve can be used by risk managers to define societal levels of risk, as shown in Figure 10.14 (Goose 2010). The lines of demarcation have been drawn arbitrarily for this example, but they would be determined independently of the data by risk managers when used as a risk management tool.

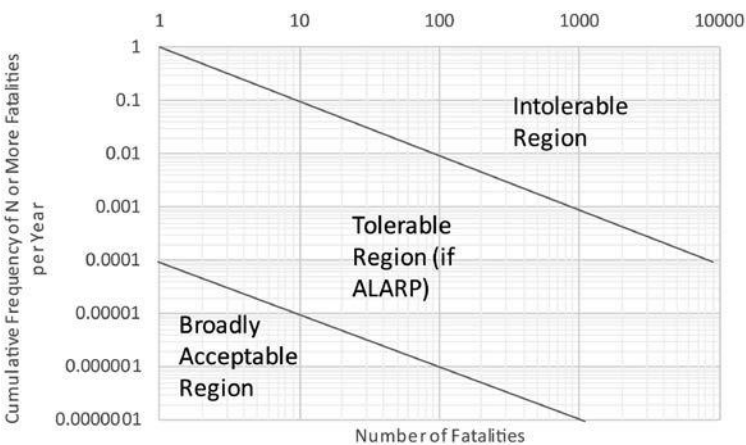


FIGURE 10.14 Hypothetical use of an FN curve to delineate acceptable, tolerable, and unacceptable levels of risk.

10.19.3 INPUTS

An FN curve is quite simple to generate; it requires only data:

- Pairs of frequency (f) and potential consequences (N)
- Conversion of the f - N pairs to a cumulative distribution

10.19.4 PROCESS

The process is quite simple. The available data are plotted onto a graph with the number of casualties forming the x -axis and (usually) the cumulative likelihood of N or more casualties forming the y -axis. Logarithmic scales are often used when the ranges of values are large.

FN curves have been generated using actuarial data and risk assessment model estimates. Generally, statistical curves are used to manage an existing system while theoretical curves are used to design or model a new or proposed system. When the existing data are insufficient, it is not unusual to use a mixture of statistical and theoretical data to derive a curve.

Table 10.4 presents a hypothetical set of f - N pairs that could represent the results of a quantitative risk assessment. N is the number of fatalities per year from a hypothetical event like a levee failure. Column f represents the annual probability of the N fatalities as derived from a risk assessment model. F is the cumulative frequency that N or more fatalities will be realized, it is the cumulative sum of the f values. When columns F and N are plotted the FN curve of Figure 10.12 results.

10.19.5 OUTPUTS

The output is a simple line graph like that shown in Figure 10.13, which represents the risk across a range of consequences. FN curves are a useful way of presenting and comparing risk information.

TABLE 10.4
Hypothetical Data Set of N , F , and F Values
Used to Produce the FN Curve of Figure 10.13

N	f	F
1000	0.00000054	0.00000054
750	0.0000091	0.00000964
600	0.000017	0.0000261
475	0.000085	0.000102
300	0.00022	0.000305
200	0.00063	0.00085
100	0.0059	0.00653
50	0.0087	0.0146
20	0.031	0.0397
10	0.16	0.191
1	0.5	0.66

10.19.6 STRENGTHS AND WEAKNESSES

Strengths:

- Data requirements are simple and well known
- Generally accepted as the best way to display societal risk
- Can be used for a wide range of risk types
- They are useful for making decisions about risk and safety levels
- They allow for comparisons between different types of risk

Weaknesses:

- They should not be used to compare different types of risks if the quantity and quality of data varies
- They can be difficult for the lay public and other nonexperts to interpret and evaluate

10.19.7 EXAMPLES OF USE

FN curves are used to show society's risk to a wide variety of hazards. These curves have been used extensively by chemical industries and by engineering firms. They are flexible enough to be used by any industry and for a wide variety of consequences. A good explanation can be found in *Societal Risk: Initial Briefing to Societal Risk Technical Advisory Group*, prepared jointly by the Health and Safety Laboratory and the Health and Safety Executive 2009 available at <http://www.hse.gov.uk/research/rrpdf/rr703.pdf> (accessed May 9, 2018).

10.20 GENERIC PROCESS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.20.1 OVERVIEW OF THE TECHNIQUE

A generic process begins with the familiar conceptual model, "Risk = Consequence × Probability." Each of these two factors are individually decomposed into the critical elements that explain the consequence and the probability for a specific risk issue. The elements of the consequences tend to be additive (\pm) if multiple consequences are relevant. The probability may be multiplicative when a series of independent elements must all be present for a nonzero probability of the risk to exist, or they could be additive when they represent separate exposures or pathways.

10.20.2 HOW THE TECHNIQUE IS USED

This technique is one of the most flexible qualitative techniques, and it can be adapted to a wide variety of uses. A generic process is best suited to risks that are routine in the sense of being numerous, repetitive, and similar. A generic process, once developed, can be used repeatedly to qualitatively assess the level of risk based on

consideration of both the probability and the consequences associated with a potential risk. The technique is useful for estimating the risk potential of a set of risks, ranking risks qualitatively, or for establishing risk management priorities.

10.20.3 INPUTS

The inputs to this process include:

- A well-defined set of risks to be assessed
- Decomposing consequences into the most critical consequence elements
- Decomposing probability into the sequence of events necessary for the consequences to occur
- A qualitative rating system for the consequence and probability elements
- Evidence for rating the elements qualitatively
- A method for tracking the uncertainty in the ratings
- An algorithm for synthesizing an overall consequence rating, an overall probability rating, and an overall risk rating

10.20.4 PROCESS

The process is to decompose the risk equation into consequence and probability elements sufficient for assessing the overall risk potential and uncertainty of a specific hazard or risk.

Imagine a common generic risk represented as:

$$\text{Risk} = \text{Consequence} \times \text{Probability}$$

Let us suppose the consequences of this risk can be separated into n different and independent consequences such that:

$$\text{Consequence} = C_1 + C_2 + \dots + C_n$$

Furthermore, suppose the probability of these consequences can be described by the following sequence of m events:

$$\text{Probability} = P_1 \times P_{2|1} \times P_{3|2} \times \dots \times P_{m|m-1}$$

where $P_{2|1}$ means the probability of event 2 given that event 1 has occurred.

The conditional probabilities could be replaced by independent probabilities that preserve the multiplicative form of probability. If any one of those probability elements is zero then the overall probability of establishment is zero and there is no risk. This is different from the overall consequence. Consequences could, for example, be economic, environmental, and political. They are considered additive because even if one kind of consequence is absent others may be present*.

* Note that alternative formulations are feasible. One can conjure circumstances where consequences could be multiplicative and probabilities could be additive or where each consequence has its own individual probability. The most likely formulation is presented to simplify the discussion.

High, medium, low, and no risk scenarios are defined clearly and unambiguously for each of the n consequence and m probability elements in the previous example. Using available facts and evidence, each of these $n + m$ elements is then rated a high, medium, low, or no risk potential. The rating is based on the nature of the scenario and is supported by the available evidence. An uncertainty rating can accompany each element rating. For example, assessors could rate the uncertainty for each of their element ratings from very uncertain to very certain.

The element ratings are aggregated up into an overall probability and an overall consequence rating. These two ratings are then used to develop an overall risk rating for the risk of concern.

10.20.5 OUTPUTS

The outputs of this process include individual risk ratings for each of the $n + m$ elements identified in the generic process, an uncertainty rating for each of these elements, an overall consequence rating and an overall probability rating that can be combined to yield an overall risk rating. When applied to a set of like risks the outputs can produce a ranking of the overall risk potential for each hazard/risk assessed.

10.20.6 STRENGTHS AND WEAKNESSES

Strengths:

- Comprehensive and flexible
- Can be applied to a wide variety of situations
- Almost any risk can be decomposed into a reasonable number of probability and consequence elements
- Logically sound when key elements are identified and the process is supported by evidence
- Can be performed with varying levels of resources and degrees of uncertainty
- Conducive to learning
- Repeated applications of a generic model result in a better understanding of the problems and their potential solutions
- Easily documented and readily open to evaluation

Weaknesses:

- Once developed there may be a tendency to rely on this qualitative method when a quantitative assessment is possible
- Produces specious results when assessment is not evidence-based

10.20.7 EXAMPLES OF USE

A method like this has been widely used for phytosanitary risk management around the world. This method was used to assess the risks of establishment of aquatic nuisance species in the Great Lakes and Mississippi River (GLMRIS, 2014). The method is

illustrated in the phytosanitary risk example of [Chapter 22](#). A formal generic process model can be found in the *Generic Nonindigenous Aquatic Organisms Risk Analysis Review Process* available at https://www.anstaskforce.gov/Documents/ANSTF_Risk_Analysis.pdf (accessed May 9, 2018).

10.21 HAZARD ANALYSIS AND CRITICAL CONTROL POINTS (HACCP)

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.21.1 OVERVIEW OF THE TECHNIQUE

Hazard analysis and critical control point (HACCP) is a risk management tool that incorporates risk assessment practices. The Pillsbury Corporation and NASA developed the HACCP control system in the 1960s to ensure food safety for the first manned space missions. An HACCP plan provides a structure for identifying hazards encountered in a process and putting controls in place at critical control points to protect against the hazards and to maintain the quality, reliability, and safety of the system's outputs. HACCP seeks to minimize risks by controlling the process rather than by end product inspection.

10.21.2 HOW THE TECHNIQUE IS USED

HACCP plans are used extensively by food companies to ensure food safety. It is used anywhere within the food chain to control risks from physical, chemical, or biological contaminants of food. HACCP operates on the principle of identifying things that can influence system output quality and identifying points in the process where critical parameters can be monitored so that these hazards can be controlled. Though applied extensively by the food safety community, HACCP is a principle that can and has been generalized to other technical systems.

10.21.3 INPUTS

Essential inputs for a HACCP include:

- Flow or process diagram that reveals the system or process of interest
- Potential hazards that can affect the quality, safety, or reliability of the system output or process
- Information about these hazards
- Critical control points for the hazards

10.21.4 PROCESS

An example for a fish stocking exercise is shown in [Figure 10.15](#). This diagram is adapted from a fish stocking HACCP plan for Fort Richardson found

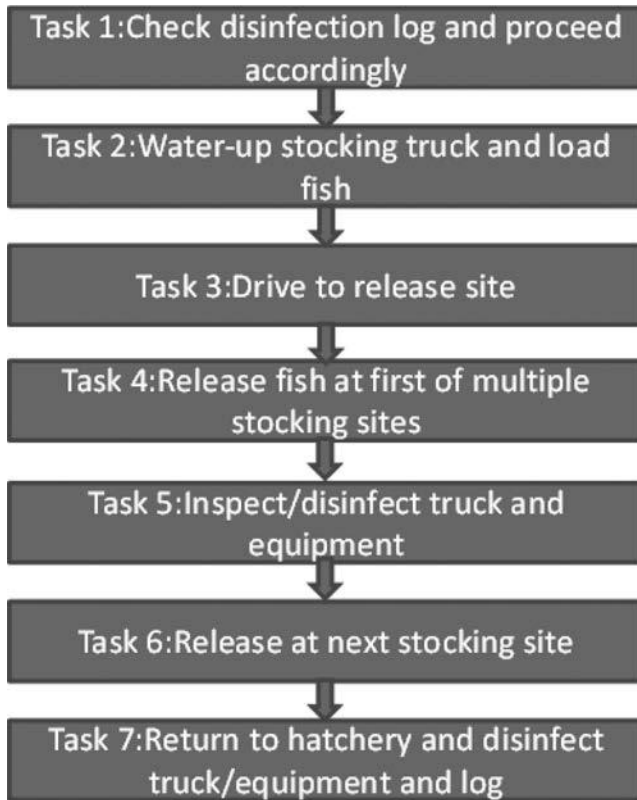


FIGURE 10.15 HACCP process diagram for a hypothetical fish stocking exercise.

at <http://haccp-nrm.org/Plans/AK/haccpstocking-1.pdf> (accessed March 24, 2018.). A HACCP plan is based on the following seven principles (IEC 2009):

1. Conduct a hazard analysis that identifies hazards and ways to prevent them.
2. Identify critical control points so that hazards are prevented, eliminated, or reduced to an acceptable level.
3. Establish critical limits for each critical control point, so each critical control point can be operated within maximum or minimum parameters to ensure the hazard is controlled.
4. Monitor the critical limits for each critical control point at defined intervals.
5. Establish corrective actions to be taken when monitoring indicates a deviation from an established critical limit.
6. Implement record keeping and documentation procedures for each corrective action.
7. Establish procedures for verifying the HACCP system is working as intended; this validation is to ensure the plan does what it was designed to do and verification is to ensure it is working as intended.

Potential hazards that can affect the quality, safety, or reliability of the system output or process need to be identified. The hazards for the fish stocking example include vertebrates, invertebrates, plants, and other biologics that could be moved or introduced during the stocking operation. Information about these hazards, their risks, and the ways in which they can be controlled are also inputs to an HACCP plan. Tasks 1, 5, and 7 in [Figure 10.15](#) are critical control points for this process.

The HACCP plan explains how the CCPs are to be handled. For example, in Task 1, checking the logs to verify inspection and disinfection is a CCP. The hazard at this point in the stocking process is “potential contamination of invasive species.” Checking to ensure that inspection and disinfection (the what) have taken place is done by examining the log (the how). This is done every time a truck is filled (the frequency) by the driver (the who). If there is failure to inspect and disinfect, loss of fish stocking privileges can result (the evaluation and corrective action). All of this is documented in the disinfection log (the supporting documentation).

10.21.5 OUTPUTS

The outputs of an HACCP process include:

- Process diagram
- Hazard analysis worksheet
- HACCP plan

The hazard analysis worksheet lists the hazards that could be introduced, exacerbated, or controlled at each step in the process. The worksheet also identifies whether a hazard presents a significant risk and provides evidence for the judgment. Potential risk management measures are identified for each hazard. Process steps where monitoring or control measures can be applied are identified as critical control points. The HACCP plan identifies the procedures to be followed to control a specific design, product, process, or procedure.

10.21.6 STRENGTHS AND WEAKNESSES

Strengths (IEC 2008):

- Structured process that provides documented evidence for quality control as well as identifying and reducing risks
- Focuses on practical means of preventing and controlling hazards
- Encourages risk control throughout the process rather than relying on final product inspection
- Can identify hazards introduced through human actions as well as means to control them at the point of introduction or subsequently

Weaknesses:

- Requires that hazards are identified and their significance understood as inputs to the process

- Requires risk definition of hazards
- Appropriate controls need to be defined in order to specify critical control points and their control parameters
- Action is only taken when the control parameters exceed defined limits
- Gradual changes in the process that are statistically significant and need correction could be missed

10.21.7 EXAMPLES OF USE

HACCP regulations for dairy, seafood, and juice industries have been enacted by the U.S. Food and Drug Administration. The U.S. Food Safety Inspection Service has promulgated a HACCP regulation to reduce the occurrence and numbers of pathogenic microorganisms on meat and poultry. HACCP plans could be developed for a variety of other repeatable processes, for example, to help assure water quality levels, for repeated physical processes like towboat lockages, or to control processes comprising a sequence of events. Food safety applications of HACCP are easily found on the Internet and in ISO 22000 Food Safety Management Systems. Natural resources examples can be found at the Planning Is Everything web site, see for example <http://haccp-nrm.org/listplans.asp> (accessed March 28, 2018).

10.22 HAZARD OPERABILITY STUDY (HAZOP)

Useful* for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.22.1 OVERVIEW OF THE TECHNIQUE

Hazard operability study (HAZOP) is the structured and systematic examination of a planned or existing product, project, process, procedure, or system to identify and analyze hazards and operational concerns. It is a qualitative technique that was originally developed by the Institute of Chemical Industry (ICI) in the United Kingdom in the 1970s (Ericson 2005) to analyze chemical process systems. It has since been extended for use in other systems and complex operations that include electrical and mechanical systems, complex procedures, software systems, organizational change, and even legal contract design and review. Its purpose is to identify risks to people, equipment, the environment, and/or organizational objectives before they occur. HAZOP was developed to supplement experience-based practices when a new design or technology is involved. Its use has expanded to almost all phases of a plant's life. A good HAZOP eliminates risks when and wherever possible.

* The IEC (2009) draft standard is acknowledged as the principle source for the information in this section.

10.22.2 HOW THE TECHNIQUE IS USED

HAZOP analysis investigates deviations from design intent for a process or system. The technique uses guide words to question how the design intention or operating conditions may not be achieved at each step in the design, process, procedure, or system. A multidisciplinary team usually conducts a HAZOP in a series of brainstorming meetings. It is especially useful for identifying and dealing with deviations from a design intent due to deficiencies in the design, component(s), planned procedures, or human actions. A HAZOP is usually not done until the detail design stage when a full plan and understanding of the intended process is available, but while design changes are still practical. HAZOPs can be conducted during operations, but required changes can be costly. HAZOP is based on the belief that experts with different backgrounds can interact and identify more problems working together than they would working separately and combining their results.

10.22.3 INPUTS

Essential inputs to a HAZOP include:

- Well-defined system to assess
- Well-chosen assessment team
- Current information about the system, process or procedure including the intention and performance specifications of the design
- Design documents including blueprints, drawings, specification sheets, flow sheets, process control and logic diagrams, layout drawings, operating and maintenance procedures, and emergency response procedures
- Knowledge of the elements of the procedure and their functions
- List of guide words

10.22.4 PROCESS

HAZOP reviews each part of the design and specification of the process, procedure, or system to learn what deviations from the intended performance can occur. It then considers their potential causes and likely consequences. This is usually done by using guide words to systematically examine how each part of the system, process or procedure will likely respond to changes in key parameters. Guide words can be customized, or generic words can be used that encompass all types of deviation (see previous page box). The basic formulation is:

$$\text{Guide Word} + \text{Parameter} = \text{Deviation}$$

The usual steps in a HAZOP include:

- Identify team leader
- Define objectives and scope of effort
- Establish a set of guide words

- Convene the HAZOP with appropriate knowledge of system and requisite expertise (should not be the same as the design team)
- Collect required documentation
- Split the system, process, or procedure into smaller tangible elements
- Agree on design intent for each element
- Apply guide words one after the other to identify possible deviations which will have undesirable outcomes
- Identify the cause and consequences of each undesirable outcome
- Identify treatment to prevent undesirable outcomes from occurring or to mitigate the consequences if they do
- Document the discussion and specific actions to treat the risks

GUIDE WORD EXAMPLES

No, less, more, reverse, also, other, fluctuation, early, late, as well as (more than), part of, reverse, where else, before/after, faster/slower, fails, inadvertent

PARAMETERS

Flow, pressure, separate (settle, filter), reaction, reduce (grind, crush), corrode, isolate, vent, inspection, surveillance, viscosity, instruments, corrosion, vibration, software data flow, temperature, level, composition, mix, absorb, erode, drain, purge, maintain, shutdown, startup, erosion, shock, density

Source: Ericson (2005).

The idea of HAZOP is to systematically review the plant or process in a series of meetings, during which a multidisciplinary team methodically “brainstorms” the plant/process design, following the structure provided by the smaller tangible elements or study nodes of the plant/process and the guide words. The primary advantage of this brainstorming is that it stimulates creativity and generates ideas. This creativity results from the interaction of the team and their diverse backgrounds. The team focuses on specific study nodes, one at a time. At each of these study nodes, deviations in the process parameters are examined using the guide words. For example, if design pressure or temperature are parameters being considered, guide words might include increasing, decreasing, high, low, zero, and the like. The guide words help the team to question how the design intention or operating conditions may not be achieved at each step in the design, process, procedure, or system. The team might identify a number of deviations suggested by the guide words that then must be considered so that their potential causes and consequences can be identified.

10.22.5 OUTPUTS

The primary output is the HAZOP meeting documentation or minutes. This should include the guide words used, the deviation(s) identified, their possible causes, actions

that can be taken to address the identified risk, and identification of the person responsible for the action.

10.22.6 STRENGTHS AND WEAKNESSES

Strengths:

- Ability to systematically and thoroughly examine a system and generate solutions to identified risks while involving a multidisciplinary team
- Can be applied to a wide range of systems
- Can accommodate human error as well as system failures
- Written record of the process can demonstrate due diligence

Weaknesses:

- Time consuming and expensive
- Requires a high level of system specification
- Major modifications can be expensive or untenable if performed too late in the design process
- Process can bog down if it focuses on detailed issues of design rather than broader risk issues
- Tend to rely heavily on the expertise of designers who may lack the objectivity to see problems in their designs

10.22.7 EXAMPLES OF USE

HAZOP has been used primarily in the process industries, that include oil and gas, chemical, petrochemical, fertilizers, power generation, and the like. It has also been used extensively in mining and extractive industries, pharmaceutical manufacturing, food additives production, water and waste water treatment, pulp and paper, and software design review.

10.23 HEAT MAP

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.23.1 OVERVIEW OF THE TECHNIQUE

A heat map is described by Wikipedia as “a graphical representation of data where the individual values contained in a matrix are represented as colors.” The term “heat map” was originally coined and trademarked by software designer Cormac Kinney in 1991, but the trademark lapsed, and the term has come to be used for an array of color-coded representations of data. As used here, a heat map is a type of risk matrix (treated in more detail elsewhere in this chapter), where the intensity or heat of the risk, as measured by consequence and probability, is conveyed by the color of the

corresponding matrix cell. There are many ways to display heat maps, but they all share the use of color to communicate relative risks. A risk matrix heat map is a special adaptation of this technique.

10.23.2 HOW THE TECHNIQUE IS USED

Heat maps can be used to rank risks, to display the results of risk profiles, and to set risk management priorities.

10.23.3 INPUTS

The essential inputs of a heat map include:

- Complete and well-defined risk matrix
- List of risks to rank
- Evidence upon which to base the rankings
- Subjectively grouped levels of risk to determine the colors of the risk map

10.23.4 PROCESS

A hypothetical example of a heat map is shown in [Figure 10.16](#).

Assessed risks are, typically, located in the appropriate matrix cell. In some instances, the exact placement of a risk in a cell is used to indicate slight differentiations in one or more of the dimensions of the risk. Here, differences in the consequence severity are depicted by the horizontal location of the dots representing different risks, which have been qualitatively assessed. Distinctions in vertical location are also possible. Businesses typically plot residual risks on a risk heat map.

10.23.5 OUTPUTS

The output of a heat map is a completed map, such as that shown in [Figure 10.16](#).

10.23.6 STRENGTHS AND WEAKNESSES

Strengths:

- A visual, big picture, holistic view to share while making strategic decisions
- Improved management of risks and governance of the risk management process
- Increased focus on the risk appetite and risk tolerance of the company

Probability	Consequence		
	Low	Medium	High
High		④	③
Medium	①	②	⑥
Low		⑤	

FIGURE 10.16 Example of a hypothetical risk heat map.

- More precision in the risk assessment process
- Identification of gaps in the risk management and control process
- Greater integration of risk management across the enterprise and embedding of risk management in operations

Weaknesses:

- Poorly constructed and executed risk matrices are common
- Coloring schemes can be subjective and subject to logical inconsistencies
- Risks cannot be considered cumulatively

Fenton and Neill (2011) describe a common weakness of the heat map or risk matrix as its inability to consider risks cumulatively. Three relatively low or “green” risks characterized the 2008–2009 subprime loan crisis. They were: (1) defaults on subprime loans, (2) growth in the novelty and complexity of financial products, (3) failure of American International Group, Inc. Individually and alone none of these risks was especially great. However, when they occurred together the total risk greatly exceeded the individual risk. In retrospect, it may have made no sense to consider these risks separately.

10.23.7 EXAMPLES OF USE

Risk heat maps are widely used by firms that practice enterprise risk management. Accounting and financial firms, in particular, make extensive use of this technique. An example guide to producing risk heat maps is made available by the Society of Actuaries in Ireland, it can be found at <https://web.actuaries.ie/sites/default/files/erm-resources/communicate-risks-using-heat-map.pdf> (accessed March 26, 2018).

10.24 HUMAN RELIABILITY ASSESSMENT

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.24.1 OVERVIEW OF THE TECHNIQUE

There are a great many human reliability assessment (HRA) methods. They are generally designed to estimate the likelihood that particular human actions that may prevent hazardous events will not be taken when needed and that other human actions that may cause hazardous events by themselves or in combination with other conditions will occur. These are examples of “human errors.” They do not imply that people are necessarily personally responsible or culpable in some way, just that an action was omitted or taken that adversely influenced safety.

10.24.2 HOW THE TECHNIQUE IS USED

HRA deals with the impact of humans on system performance, and it can be used to evaluate human error effects on a system or process. The potential for human

error in a process is especially great when the time available to make decisions is short. Although the consequences of many human errors are small, there are times when human action is the only defense against an initial fault progressing towards an accident. Critical human errors have frequently contributed to a catastrophic sequence of events. These accidents warn us against risk assessments that focus solely on the hardware and software in a system. The dangers of ignoring possible human error are often too great to ignore.

On January 13, 2018, a little after 8 A.M. Hawaii Standard Time, an alert was sent to cell phones in Hawaii: “BALLISTIC MISSILE THREAT INBOUND TO HAWAII. SEEK IMMEDIATE SHELTER. THIS IS NOT A DRILL.” The message was also broadcast on local television and radio. This was a human error that caused panic throughout Hawaii.

HRA can be qualitative or quantitative. Qualitative analysis can identify the potential for human error and its causes so the likelihood of error can be reduced. Quantitative analysis can produce data on human failures that can be used with other techniques.

10.24.3 INPUTS

Inputs to an HRA process include:

- Definition of the tasks that people must perform
- Knowledge of the kinds of errors that occur in practice and the potential for new errors
- Expertise on human error and its quantification is also needed and it is not often a staff area of expertise for many organizations

10.24.4 PROCESS

The International Electrotechnical Commission (IEC) identifies the following steps for a general HRA process:

- Problem Definition—Identify the types of human involvement that will be included in the analysis.
- Task Analysis—Identify how the task will be performed and the type of resources needed to support safe performance of the task.
- Human Error Analysis—How can task performance fail? What errors can occur? How can they be recovered?
- Representation—How can these errors or task performance failures be integrated with other hardware, software, and environmental events to enable overall system failure likelihoods to be calculated?

- Screening—Are there any errors or tasks that do not require detailed quantification?
- Quantification—How likely are individual errors and failures of tasks?
- Impact Assessment—Which errors or tasks are most important, that is, which ones have the highest contribution to reliability or risk?
- Error Reduction—How can higher human reliability be achieved?
- Documentation—What details of the HRA need to be documented?

Limitations and gaps in relevant data sources can be expected. Expert elicitation processes are likely to be useful in overcoming these uncertainties.

10.24.5 OUTPUTS

A qualitative or quantitative estimate of the risk posed by the different errors is the end product. The output of the analysis is a list of errors that can occur and the identification of risk management measures that can reduce them, preferably through redesign of the system. The analysis includes identification of error modes, error type causes, and consequences.

10.24.6 STRENGTHS AND WEAKNESSES

Strengths:

- Provides a formal mechanism to include human error in consideration of risks associated with systems where humans play an important role
- Provides formal consideration of human error modes and risk management options for reducing the likelihood of failure due to human error
- Very useful for pass/fail tasks

Weaknesses:

- Limited in its utility by the complexity and variability of humans
- Difficult to anticipate all the ways that humans can err
- Defining simple failure modes and estimating their probabilities is difficult
- Has trouble addressing partial failures, quality failures, and poor decision making

10.24.7 EXAMPLES OF USE

Wreathall et al. (2003) provides an HRA example in rail transportation. Bell and Holroyd (2009) present a review of 17 HRA methods considered useful to the Health and Safety Executive of the UK.

10.25 INCREASE OR DECREASE RISK

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.25.1 OVERVIEW OF THE TECHNIQUE

The simplest way to assess the effect of any change in conditions on an identified risk is to consider the available evidence and judge whether the risk has increased, decreased, or remained unchanged.

10.25.2 HOW THE TECHNIQUE IS USED

For some simple decision problems, it may be enough to know if things are getting more or less risky. What has the storm done to the dunes along the coast? What did the power outage do to the food in cold storage? How has the towboat affected lock operation after hitting the lock gates? Being able to say the risk has increased or decreased and to present the evidence or rationale for why we think so may be the simplest form of a qualitative risk assessment. This is a technique used to evaluate changes in risk conditions, it is not a technique used to identify risks.

10.25.3 INPUTS

The inputs include:

- Identified risk
- Clearly identified change in conditions that could affect the risks
- Judgment of the effect of each changed condition as well as the evidence that judgment is based upon

10.25.4 PROCESS

Given a risk and a change in conditions, the task is to determine whether we now have more or less risk than we had before. It is helpful to use the “Risk = Consequence × Probability” definition to do this. Think separately about the consequence and probability of the risk. What has happened to make the consequences of the risk more or less severe? What evidence do you rely on to make that judgment? What uncertainty makes you unsure of your judgment? What has happened to make the risk more or less likely to occur as a result of the changed condition? Again, marshal the supporting evidence and the most significant uncertainty. Assess the effects of each change in conditions and then consider the overall effects of all the changes in conditions on the identified risk. If you have reasons and evidence to support the notion that the consequences may be more severe and the risk is more likely to occur it is easy to conclude the situation is riskier. Take care to identify the elements of your judgment that are uncertain.

When some circumstances tend to increase a risk while others tend to decrease a risk, this technique will be of less value. When the impacts of events are cumulatively aligned, this technique can be a useful simple tool. Simply identifying the direction of change in a risk and the specific reasons for that change can be a positive step forward in emergency situations. The evidence and rationale that support the judgments made are the most critical parts of this method.

This method is useful for assessing changes in risk in the immediate aftermath of a change while uncertainty is greatest. It provides analysts with an opportunity to identify relevant risks and the likely changes in those risks while highlighting the critical uncertainties.

10.25.5 OUTPUTS

The outputs of this technique include:

- Enumerated changes associated with an identified risk
- The effects of these changes on the risk
- Identification of key remaining uncertainties
- An overall assessment of all changed conditions on the risk

10.25.6 STRENGTHS AND WEAKNESSES

Strengths:

- Evidence-based
- Easy to apply
- Provides an initial characterization of an identified risk

Weaknesses:

- Not good for netting out changes in risk factors
- Substantial uncertainty usually accompanies characterization of risks

10.25.7 EXAMPLES OF USE

This is a technique that may be immediately valuable in postevent assessments. If a tow boat has hit the gates of a lock, the risks of loss of pool, interruption of navigation traffic, and costly gate repairs have risen. When a flock is vaccinated against disease, the risk of disease has decreased. It may be possible to assess such situations based on what was observed during the incident. Identifying critical uncertainties, like conditions beneath the low water line or the efficacy of the vaccine, helps to identify the most fruitful first steps to further reduce uncertainty and/or to manage the risk more intensively.

10.26 INTERVIEWS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.26.1 OVERVIEW OF THE TECHNIQUE

Conducting structured or semistructured interviews can be an important and useful technique for addressing uncertainty. Using this technique, individual

experts are asked a set of prepared questions. Structured interviews adhere to the prescribed questions while semistructured interviews allow the conversation to explore issues and topics that arise during the interview. Well-constructed interviews can encourage experts to see problems from new perspectives (IEC 2008).

10.26.2 HOW THE TECHNIQUE IS USED

Interviews can reveal useful information. They are most useful when it is impractical or undesirable to get people together for brainstorming or more formal processes, like a Delphi process. The structure of an interview usually assures more productive outcomes than a free-flowing discussion in a group. Interviews can be used to identify risks or to assess the efficacy of risk management options (IEC 2008). The ease with which interviews can be conducted makes them useful tools for gathering stakeholder input to a risk management process.

10.26.3 INPUTS

The inputs to an interview process include:

- Clear articulation of the objectives of the interviews
- Study design
- List of people to be interviewed
- Set of questions to ask
- Interview(s)
- Transcription of interview results
- Analysis of interview results
- Report of interview process and results

10.26.4 PROCESS

The set of questions to ask is a critical input. In qualitative research, open-ended questions are preferred when possible. The questions should be simple, and each one should address a single topic or issue. The language should be appropriate to the interviewee. Use engineering jargon for engineers but not for the public, for example. Interview questions should include follow-up questions. In other words, the answer to one question may trigger a sequence of questions to follow. For example, if a person's home was flooded in the last flood, they will be asked different questions than a person whose home was not flooded. All questions should be pretested for clarity. The prepared questions are then asked of each interviewee. Care should be taken to use good interview techniques.

10.26.5 OUTPUTS

The output of the interview process is a documented record of the interviewees' views on the interview's subject matter, including specific answers to specific questions.

10.26.6 STRENGTHS AND WEAKNESSES

Strengths:

- Useful for large groups
- Structure assures uniformity of coverage of an issue
- One-to-one communication allows conversation to meander (semistructured)
- A record of information obtained

Weaknesses:

- Prior approval(s) may be required before conducting an interview survey
- Time-consuming and labor-intensive
- Benefits of group interaction are absent, that is, bias is more likely than in group discussion, imagination is not triggered
- Interviews are underutilized in risk assessment

10.26.7 EXAMPLES OF USE

Interviews are commonly used with peers, stakeholders, and experts for a wide variety of topics. It is common practice to seek input and insight from the experience of others when faced with a novel situation. If those conversations seek information to use in a decision problem, it can help to conduct a structured or nonstructured interview to ensure the comprehensiveness and relevance of the conversation.

Self-interviews are a novel and underutilized technique for documenting decisions. Individual analysts are often required to provide estimates of values ranging from budget number inquiries to model inputs about which there may be uncertainty. It may be helpful for the analyst to construct and complete a short interview of oneself to document potentially important thought processes. An interview format can reduce uncertainty while documenting efforts to do so.

10.27 LAYER OF PROTECTION ANALYSIS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.27.1 OVERVIEW OF THE TECHNIQUE

Wiley (2014) defines layer of protection analysis (LOPA) as a simplified risk assessment methodology used to understand how a process deviation can lead to a hazardous consequence if it is not interrupted by the successful operation of a safeguard called an independent protection layer (IPL). An IPL is a safeguard that can prevent a scenario from progressing to an undesirable consequence. The combined effect of the IPLs associated with a hazard scenario are compared against risk tolerance criteria to determine if additional risk reduction measures are required to reach a tolerable level of risk. A variety of LOPA methods are available.

10.27.2 HOW THE TECHNIQUE IS USED

When used qualitatively, LOPA reviews the layers of protection between a hazard or causal event and an outcome. A semiquantitative LOPA application adds some rigor to the screening processes. LOPA can be used to help allocate risk reduction resources effectively by analyzing the risk reduction produced by each layer of protection.

10.27.3 INPUTS

The essential LOPA inputs include:

- Basic information on risks including hazards, causes, and consequences
- Information on proposed or in place controls
- Probabilities for initiating events
- IPLs
- Protection layer failures
- Measures of consequence
- A definition of tolerable risk

Optionally, a process hazard analysis can be useful. The risk tolerance criteria are necessary because without them there is a tendency to keep adding safeguards in the belief that the more safeguards, the safer the process. This can be a false assumption that leads to unnecessary investment in safety.

10.27.4 PROCESS

Summers (2003) identifies six steps to describe a representative LOPA process as follows:

1. Record all reference documentation, including hazards analysis documentation.
2. Document the process deviation and hazard scenario under consideration by the team.
3. Identify all the initiating causes for the process deviation and determine the frequency of each initiating cause.
4. Determine the consequence of the hazard scenario.
5. List the IPLs that can completely mitigate all listed initiating causes.
6. Provide specific implementable recommendations.

An IPL Must meet the following four criteria (Summers 2003):

- Specificity—The IPL can detect and prevent or mitigate the consequences of specified, potentially hazardous event(s).
- Independence—An IPL is independent of all the other protection layers associated with the identified potentially hazardous event, that is, its performance is not affected by the failure of another protection layer and it is independent of the initiating cause.

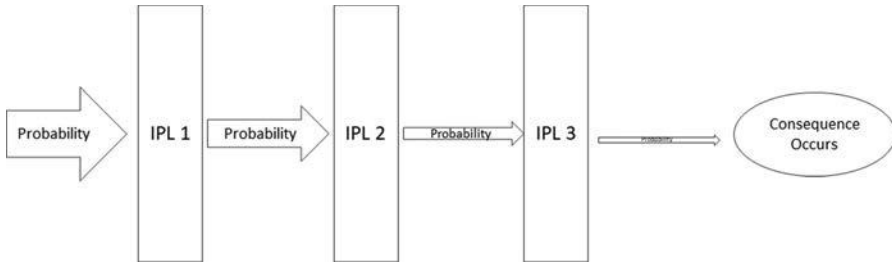


FIGURE 10.17 IPLs reduce the likelihood of an adverse consequence.

- **Dependability**—The IPL reduces the identified risk by a known and specified amount.
- **Auditability**—Regular periodic validation of the protective function is possible.

LOPA analyzes risks one specific cause-consequence pair at a time. Once the team has an understanding of the frequency and consequence of the potential hazardous event, a risk matrix is often used to determine whether the risk is acceptable or whether IPLs are required for further risk reduction. Layers of protection that can prevent the cause from proceeding to the undesired consequence are identified and analyzed for their effectiveness. Each individual protection layer (IPL) is analyzed for its effectiveness. The combined effect of the IPLs associated with a hazard scenario is compared against risk tolerance criteria to determine if additional risk reduction measures are required to reach a tolerable level of risk. This comparison can be qualitative or semiquantitative. [Figure 10.17](#) illustrates how LOPA conceptually works to reduce the probability of a risk. Each IPL makes the occurrence of the risk less likely. Alternatively, IPLs could be designed to reduce the consequence of the risk.

10.27.5 OUTPUTS

The outputs of a LOPA are recommendations for where additional risk reduction controls are required. The effectiveness of the recommended controls in reducing risk should be described.

10.27.6 STRENGTHS AND WEAKNESSES

Strengths:

- Takes less time than a fault tree analysis or fully quantitative risk assessment while remaining more rigorous than qualitative subjective judgments
- Helps identify and focus resources on the most critical layers of protection while identifying operations, systems, and processes for which there are insufficient safeguards
- Focuses on the most serious consequences
- Useful for addressing situations where catastrophic failure of infrastructure and protection systems are possible

Weaknesses:

- Focuses on a cause-consequence pair and one scenario at a time
- Complex interactions among risks or risk controls are not considered
- Quantification relies on the assumption that the layers of protection are independent from each other and the initiating event, that is, there are no common mode failures

10.27.7 EXAMPLES OF USE

The book *Layer of Protection Analysis: Simplified Process Risk Assessment* by the Center for Chemical Process Safety Copyright, American Institute of Chemical Engineers provides excellent examples. Chambers et al. (2009) provide an example of LOPA used to address fuel tank storage overflow at <http://www.hse.gov.uk/research/rrpdf/rr716.pdf> (accessed March 26, 2018).

10.28 MARKOV ANALYSIS

Useful for: Hazard identification Consequence assessment
 Likelihood assessment Risk characterization Uncertainty characterization
 Risk management options Other

10.28.1 OVERVIEW OF THE TECHNIQUE

A Markov analysis provides a means of analyzing the reliability and availability of systems that can be described by different states, such as available, partially available, or failed. For example, consider a system that is “available.” This system will transition to some other state if a component of the system fails during a time interval, or a failed system could transition to another state if a component that was already failed is repaired and returned to service during a time interval. A Markov analysis reveals the probabilities that a system will be in an available, partially available, or failed state; alternatively, it might be used to estimate the average time the system spends in each of these states before the system moves into another state.

A Markov chain is said to be “memoryless.” In a Markov analysis, the future is independent of the past and the future is best predicted by current information. In other words, the next state of the process only depends on the previous state and not the sequence of states leading up to it. This simple assumption makes the calculation of conditional probability easy and enables this algorithm to be applied in a number of scenarios. If we view time as a chain of such events we have the basis for the simplest Markov model, called a Markov chain. Output from a Markov analysis can be used to describe the reliability, availability, and resource utilization of the system of interest.

10.28.2 HOW THE TECHNIQUE IS USED

A Markov analysis uses a state transition diagram that portrays the operational and failure states of a system. A Markov process can be used to evaluate the probability of a

system jumping from one known state into the next logical state until the system reaches the final state. For example, the first state may be the system working as designed. The next state is the first item fails, and this continues until the system failed state is reached.

A Markov analysis is often used to analyze repairable systems that can exist in multiple states including (IEC 2009):

- Independent components in parallel
- Independent components in series
- Load-sharing system
- Stand-by system, including the case where switching failure can occur
- Degraded systems

10.28.3 INPUTS

The IEC (2009) identifies the essential inputs to a Markov analysis as:

- A list of various states that the system, subsystem, or component can be in (e.g., fully operational, partially operation [i.e., a degraded state], failed state, and so on)
- A clear understanding of the possible transitions that are necessary to be modeled; for example, failure of a lock gate needs to consider the state of any spare gates as well as the frequency of inspection
- Rate of change from one state to another, typically represented by either a probability of change between states for discrete events, or a failure (λ) or repair (μ) rate for continuous events

10.28.4 PROCESS

The inland waterway navigation system provided by a system of locks in series will be used to illustrate the technique. A Markov analysis centers around the concept of “states,” and the transition between these states over time based on a constant probability of change. Consider a navigation system of locks that can be in only three states: functioning, degraded, or failed. Call these states S_1 , S_2 , and S_3 , respectively. Each day, the navigation system exists in one of these three states. A transitional probability matrix is used to describe the transition between each of the states to allow the calculation of the various outputs. Table 10.5 shows the probability that the navigation system will be in state S_i tomorrow, where i can be 1, 2, or 3.

TABLE 10.5
Markov Transition Matrix for a Hypothetical Navigation System

		State Today		
		S_1	S_2	S_3
State tomorrow	S_1	0.95	0.30	0.20
	S_2	0.04	0.65	0.60
	S_3	0.01	0.05	0.20

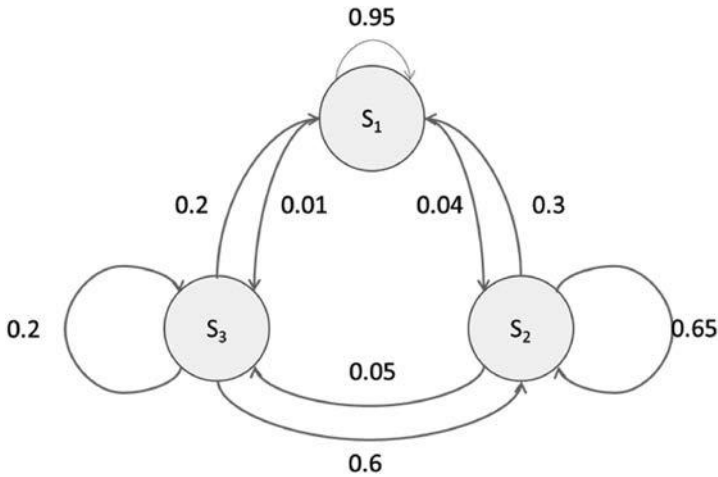


FIGURE 10.18 Markov diagram for navigation system.

The sum for each of the columns in the transition matrix is 1. If the system is in state S₁ today, there is a 95% chance it will be in S₁ tomorrow, with a 4% chance it will be in S₂ and a 1% chance it will be in S₃. It is also possible to represent the system by a Markov diagram, shown in Figure 10.18, where the circles represent the states and arrows represent the possible transitions with the transition probability indicated alongside the arrow.

Now we define P_i to represent the probability of finding the navigation system in state i, that is, P_i = P(S_i). The transition matrix gives rise to three simultaneous equations to be solved. They are:

$$P_1 = 0.95P_1 + 0.30P_2 + 0.20P_3$$

$$P_2 = 0.04P_1 + 0.65P_2 + 0.60P_3$$

$$P_3 = 0.01P_1 + 0.05P_2 + 0.20P_3$$

Because these three equations are not independent, they cannot be solved for the three unknowns. However, the following equation can be substituted for any one of the above equations:

$$1 = P_1 + P_2 + P_3$$

The solution for this set of equations reveals P₁ = 0.85, P₂ = 0.13, and P₃ = 0.02. Thus, the system is fully functioning 85% of the time, 13% of the time in the degraded state, and 2% of the time in the failedstate.

For continuous events the mathematics are a bit more complex, but the principle is the same.

Ericson (2005) describes the tasks comprising the Markov process as follows:

1. Define the system
2. Identify the system states
3. Construct the state diagram
4. Develop mathematical equations
5. Solve mathematical equations
6. Evaluate the outcome
7. Recommend corrective action
8. Hazard tracking
9. Document the Markov analysis

10.28.5 OUTPUTS

The outputs from a Markov analysis are the probabilities of being in the various states. These probabilities provide one of the essential components of a risk. Alternative outputs are possible, depending on the structure of the problem.

10.28.6 STRENGTHS AND WEAKNESSES

Strengths:

- Enables analysts to calculate the probabilities for systems with a repair capability and multiple degraded states
- An analytical method, and the reliability parameters for the system are calculated in effect by a formula

Weaknesses:

- Assumes all events are statistically independent since future states are independent of all past states
- Requires knowledge of all probabilities of a change state

10.28.7 EXAMPLES OF USE

The Markov chain is a reasonably simple concept that can help explain many real time processes. It has been used extensively for engineering reliability studies, equipment breakdowns, arrival patterns, radioactive decay, and is increasingly being used in innovative ways for such applications as speech recognition, text identifiers, path recognition, and many other artificial intelligence tools.

10.29 MONTE CARLO PROCESS

Useful for: Hazard identification Consequence assessment
 Likelihood assessment Risk characterization Uncertainty characterization
 Risk management options Other

10.29.1 OVERVIEW OF THE TECHNIQUE

The Monte Carlo process is a numerical technique used to replace uncertain point estimates of parameters and values in models and calculations with probability distributions that represent the natural variability and knowledge uncertainty in those inputs. The Monte Carlo process samples an individual value from each probability distribution in the model. These values then replace the point estimates in the model's equations and calculations so that the model's calculation can be completed and outputs can be produced. This process is repeated the desired number of times to generate a distribution of output values. The Monte Carlo process is the topic of [Chapter 15](#).

10.29.2 HOW THE TECHNIQUE IS USED

The Monte Carlo process is a popular simulation technique that enables analysts to propagate the uncertainty in a decision problem and produce a numerical description of the range of potential model outputs. These output distributions can be subjected to statistical analysis to inform decision making. When the Monte Carlo process is included in a simulation model, the model is often called a Monte Carlo simulation.

This process can be used to replace point estimates in any kind of model. Easy-to-use commercial software has made the method popular to use in spreadsheet models. Thus, the process can be used in any spreadsheet model where one or more model inputs are uncertain, that is, subject to natural variability or a matter of some knowledge uncertainty. This makes it a widely applicable tool for assessing risks. Its use is not restricted to spreadsheet models, however. It can be employed in virtually any quantitative model.

10.29.3 INPUTS

Inputs for this method include:

- A model with uncertain inputs
- Knowledge of the source and nature of the uncertain inputs
- Probability distributions to represent the uncertainty and knowledge of those distributions
- Monte Carlo software that can produce the required output(s)

10.29.4 PROCESS

Imagine estimating the number of containers offloaded at a port in a month as part of a risk assessment. Clearly this is a variable quantity. It can be calculated simply by multiplying the number of vessels calling at the port by the average number of containers offloaded per vessel. The number of vessels calling at a port will vary naturally with the volume and type of commodities shipped and received, the size of the vessels that call at the port, competition with other ports, weather conditions, and the like. Let the average number of vessels that call per month be 38 with a Poisson distribution of vessel arrivals as shown on the left of [Figure 10.19](#). Imagine there is no data about the average

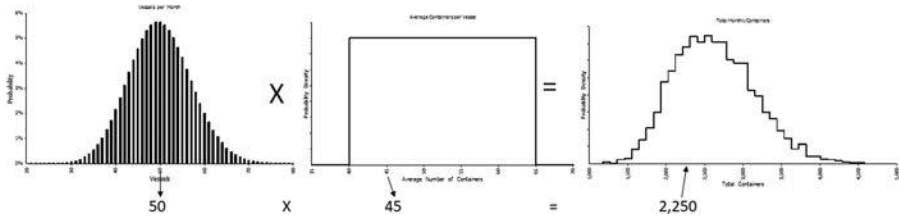


FIGURE 10.19 An illustration of the use of the Monte Carlo process.

number of containers offloaded per call but the average is estimated to be between 40 and 65, as seen in the middle distribution. This is a simple multiplication that uses two probability distributions rather than two point estimates. Arithmetic operations with distributions are complex and often have no closed form. Consequently, it is convenient and useful to estimate such models using the Monte Carlo process.

In this example, random values 50 and 45 were selected from the two input distributions via the Monte Carlo process. These values were handled according to the structure of the model, in this case a simple multiplication. They yielded an estimate of 2,250 containers per month. This is one iteration of the Monte Carlo process. The process is repeated 10,000 times, and it yields the distribution on the right of the figure that characterizes the uncertainty about how many containers are offloaded in a month. The output distribution reflects the natural variability about the number of calls each month and knowledge uncertainty about the average number of containers offloaded per call.

The Monte Carlo process, itself, consists of two steps. The first step is to generate a simple random number between 0 and 1. A number of efficient algorithms for generating simple random numbers are well known. The second step is to transform that number into a value useful for a specific probability distribution. A number between 0 and 1 is not useful to estimate a mean number of containers believed to be between 40 and 65. The transformation step is a mathematical calculation that is more or less difficult depending on the distribution used. See [Chapter 15](#) for an example.

10.29.5 OUTPUTS

The outputs of the Monte Carlo process are distributions of values calculated by the models. These distributions can include the actual input values used in the calculations, intermediate calculations, or model outputs. These distributions can be analyzed using statistical techniques to support decision making. A close-up view of the output in the simple model above is shown in [Figure 10.20](#).

The monthly total number of containers is an uncertain value. It is uncertain because there is natural variability in the number of vessel calls and because the mean number of containers offloaded is an uncertain parameter. The prior estimate shows that the number of monthly containers is between 801 and 4,132 containers with an expected value of 1,995 per month. Based on this analysis we can be 90% confident the actual total will be between 1,353 and 2,748 containers (see the delimiters). The probability of a specific outcome can be identified. There is a 5% chance there will

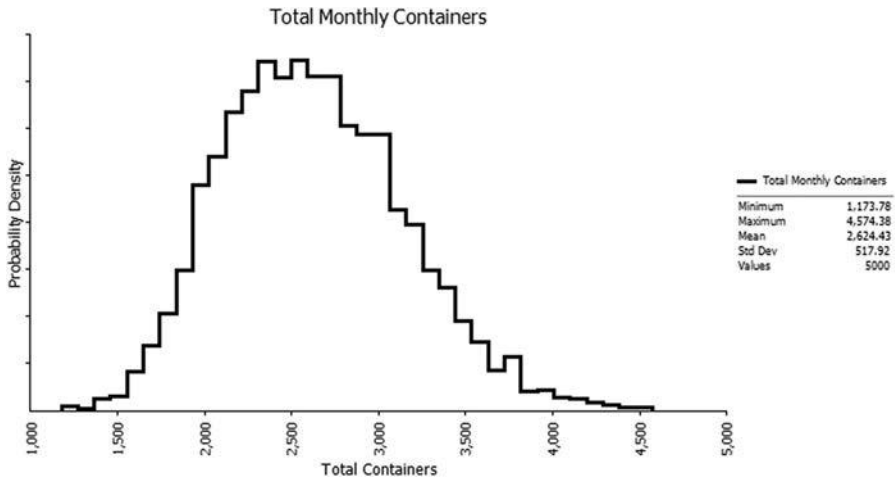


FIGURE 10.20 Monte Carlo process simulation results.

be more than 2,748 containers per month. Additional statistical analyses are also possible.

10.29.6 STRENGTHS AND WEAKNESSES

Strengths:

- Widespread applicability
- Natural and physical systems too complex to analytically assess the effects of uncertainty can be assessed by describing input uncertainties and running simulations that sample the inputs to represent possible outcomes
- Can examine complex situations that are difficult to understand and solve by other means
- Models are relatively simple to develop
- They can represent virtually any influences or relationships that arise in reality
- Can accommodate a wide range of distributions in an input variable, including empirical distributions derived from observations of real phenomena
- Large amounts of data that can be generated lend themselves readily to sensitivity analysis to identify strong and weak influences on outputs
- Commercially available software makes it relatively easy to apply this numerical technique to any spreadsheet model

Weaknesses:

- Solutions are not exact and their usefulness may depend on the number of iterations or simulations completed
- It is not a transparent process
- The process is so easy, analysts may overlook analytical solutions in favor of a simulation

10.29.7 EXAMPLES OF USE

This technique is used extensively in many fields of endeavor. Palisade Corporation maker of @RISK and the DecisionTools® Suite, which were used in the preparation of this text, provide a library of example models and user forums that illustrates the breadth of use of this technique on their web site.

10.30 MULTICRITERIA DECISION ANALYSIS

Useful for: Hazard identification Consequence assessment
 Likelihood assessment Risk characterization Uncertainty characterization
 Risk management options Other

10.30.1 OVERVIEW OF THE TECHNIQUE

Multicriteria decision analysis (MCDA) is a well-established operations research technique used for making trade-offs of quantitative or qualitative information that involves the personal preferences of decision makers. It is designed for decision problems that involve multiple criteria. Many different decision algorithms or methods of weighing and combining the criteria and decision-maker preferences are included in the MCDA toolbox. Among the more common methods are the analytic hierarchy process (AHP), ELECTRE (Outranking), multi-attribute utility theory (MAUT), PROMETHEE (Outranking), and Simple Multi-Attribute Rating Technique (SMART), among others.

10.30.2 HOW THE TECHNIQUE IS USED

MCDA helps risk managers sort through a prespecified set of alternatives to identify those alternatives with the characteristic of interest, that is, greatest risk potential, greatest risk reduction potential, and so on. The quality of information used in MCDA can be scientifically derived hard data or it can accommodate subjective interpretations of ratings for one or more criteria. MCDA, like risk assessment, does not produce decisions; it produces information upon which informed decisions can be based. MCDA has proven to be especially useful for group decision-making processes.

10.30.3 INPUTS

The inputs to an MCDA process include:

1. Problems
2. Alternative solutions to the problems
3. Criteria upon which a decision will be based
4. Evidence (i.e., measurements of the criteria for each alternative)
5. Decision matrix of alternative and criteria measurements
6. Subjective weights for the criteria
7. Synthesis algorithm

TABLE 10.6
Comparing Plans by Contrasting the Differences in Their Effects on Decision Criteria

	Cost	Flood Damage Reductions	Habitat Units	Property Value Effects	User Days of Urban Recreation
RMO A	15	10	46	Neutral	700
RMO B	15	800	0	Positive	0
RMO C	23	60	50	Neutral	850
RMO D	33	80	90	Negative	2,000
RMO E	20	35	85	Positive	1,000
RMO F	27	50	75	Negative	800
RMO G	53	100	116	Neutral	3,000
RMO H	68	900	116	Positive	3,000

10.30.4 PROCESS

Consider the data in [Table 10.6](#) for an example of a decision problem where eight (A through H) RMO configurations are being considered to address flood risk, ecosystem degradation, and quality of life values in a small urban floodplain. The decision criteria for this example include the following: flood damage reductions measured in thousands of dollars of expected annual damages reduced, annual habitat units produced, annual urban recreation user days produced, impacts on property values in the watershed, and first costs of implementation in millions of dollars.

Using the inputs described above, the first step is to develop a simple hierarchical model as seen in [Figure 10.21](#). For this example, Logical Decision* software was utilized to analyze a multipurpose risk management problem.

There are eight alternative RMOs from which the best RMO is to be selected based on the decision criteria and the subjective weights assigned to them. The subjective weights established for the criteria are shown in [Figure 10.22](#). In this example, costs and benefits were assumed to be equally important. Using a 100-point total, 50 points were allocated to costs and 50 points to benefits. There are four equally important benefit categories, so each benefit criterion received 12.5 points.

Logical Decisions software was used for the information synthesis and sensitivity analysis. The Simple Multi-Attribute Rating Technique (SMART) was used to combine preferences and evidence to assist the decision process. SMART originates from multi-attribute utility theory.

10.30.5 OUTPUTS

A variety of outputs can be produced from an MCDA analysis. [Figure 10.23](#) shows the most basic output, which calculates a score for each plan. The largest score indicates

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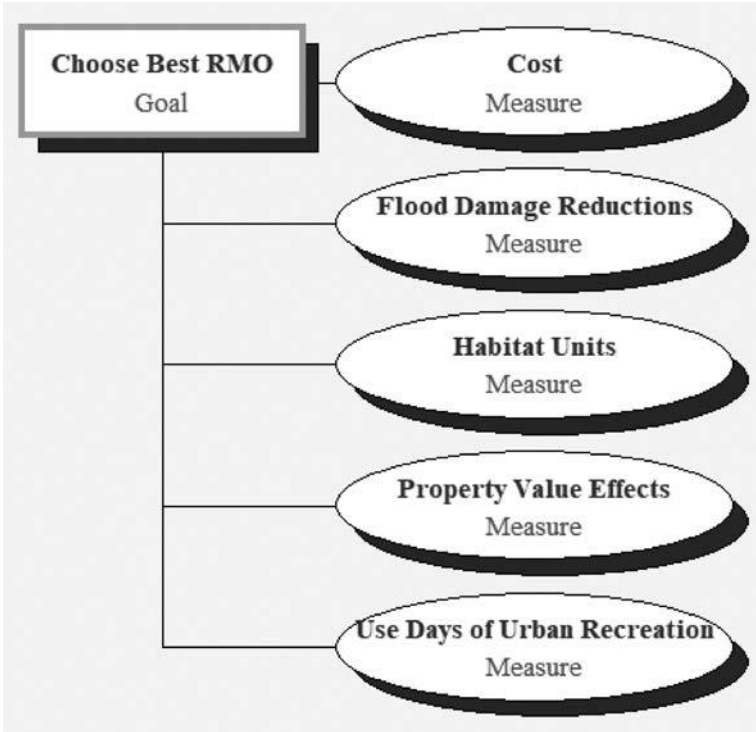


FIGURE 10.21 Hierarchical MCDA model for choosing the best RMO.

the best plan based on the criteria identified, their measurements, and weights. In this example, RMO B with a score of 0.736 is the best plan, based on the weights assigned and the evidence entered for each criterion.

The shading of the horizontal bars shows the relative contribution of the five criteria to each RMO’s score. RMO B makes the smallest contribution of any plan to habitat units and user days, hence it does not offer any advantage over the lowest ranked plan for those criteria. Many MCDA methods offer a variety of options for sensitivity analysis or other means for exploring the potential effects of uncertainty

	Least Preferred Level	Most Preferred Level	Scaling Constant (Weight)
Flood Damage Reductions Measure (\$ Thousands EAD)	10	900	0.125
Habitat Units Measure (Annual Habitat Units)	0	116	0.125
Use Days of Urban Recreation Measure (Annual User Days)	0	3000	0.125
Property Value Effects Measure (labels)	Negative	Positive	0.125
Cost Measure (\$ Millions)	68	15	0.500

FIGURE 10.22 Direct entry of subjective weights for MCDA criteria.

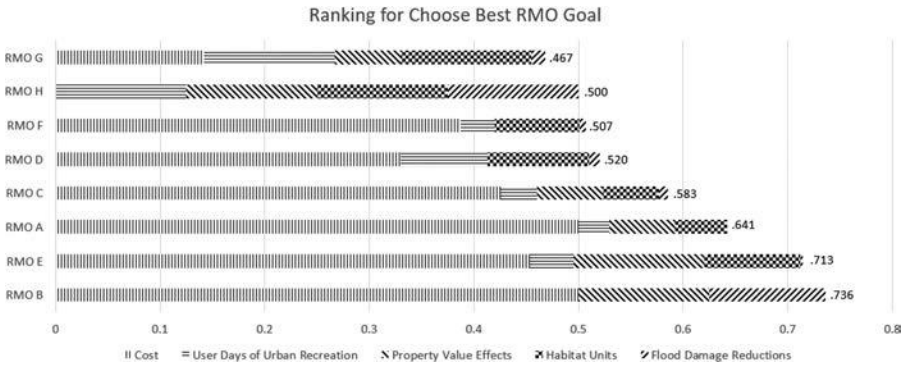


FIGURE 10.23 MCDA decision scores for individual RMOs.

on the decision. Figure 10.24 presents one example of such a sensitivity analysis. The position of the vertical line represents the current weight of the cost criterion. The slanted horizontal lines represent the eight RMOs. The intersection of the vertical line with the horizontal lines represents the relative rankings of the RMOs with the current weight assigned to cost. At the current weight, RMO B is the highest ranked. If the importance given to cost increases, RMO B remains the best choice. If it decreases (moves left), RMO E would overtake RMO B once the weight dropped from 50 to about 30%. The relative ranking of the other RMOs changes as well. This is one example of how the uncertainty about the relative importance placed on these criteria by different stakeholders can be explored.

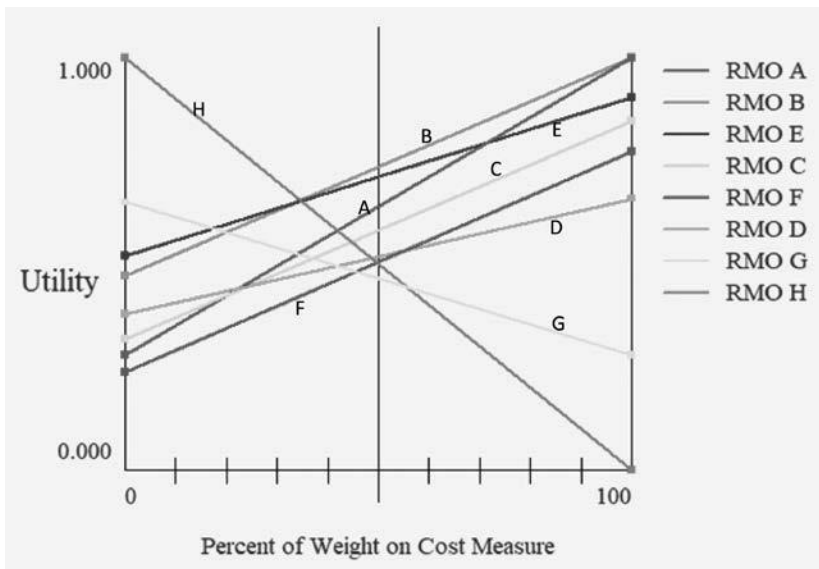


FIGURE 10.24 Sensitivity of best plan to importance of habitat units.

10.30.6 STRENGTHS AND WEAKNESSES

Strengths:

- Ability to answer a multiple criteria decision question
- Enables decision makers to explore the sensitivity of the solution to different weights and, in some methods, to a range of uncertain criteria values

Weaknesses:

- Requires a subjective assignment of weights
- Most appropriate set of weights is often difficult to discern and agree on
- Different synthesis algorithms may yield different rankings of alternatives

10.30.7 EXAMPLES OF USE

MCDA has been successfully used in a wide range of decision problems including: managing contaminated sediments (Linkov et al., 2006), selecting a solid waste treatment site (Hokkanen and Salminen, 1997), evaluating interventions to improve food safety (Fazil et al., 2008), human health (Baltussen and Niessen, 2006) and ranking risks of food pathogens (Ruzante et al., 2010).

10.31 ORDERING TECHNIQUES

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

Putting things in order is an instinctive process. It is used all the time in decision making. We look down a menu and make a selection. We surf the channels of our television and stop at the program we want. We scan a web page and choose what to read. It is all instinctive. When pressed for reasons, we can say what we like and dislike and why. Risk assessors are sometimes called on to put hazards, pathways, mitigation measures, potential risks, and the like in some sort of order. When we make such decisions jointly, or for an organization, or as stewards of some public trust, it is important to make the rationale explicit. That comprises the evidence upon which decisions are based as well as the relative importance of that evidence.

Ordering techniques, which include chronologies, screening, rating, and ranking tools, can be especially useful for separating things and establishing priorities. They are handy for going from a long list of things to a short list of things and are useful tools to consider.

10.31.1 CHRONOLOGY

10.31.1.1 Overview of the Technique

One of the most elementary techniques for ordering information is the chronology. Showing the sequence and timing of events from first to last or most recent can sometimes reveal cause-and-effect relationships that are essential to risk identification.

10.31.1.2 How the Technique Is Used

Chronological ordering is sometimes not only a handy way to present information, but it can be important as well. Chronologies better enable us to see patterns, identify important events, and recognize significant gaps in our understanding of cause-and-effect relationships.

10.31.1.3 Inputs

The essential inputs to a chronology are:

- A set of things to be placed in chronological order
- Events to consider in the chronology
- Evidence for the timing of each item

10.31.1.4 Process

A chronology may be needed to place a list of items or events in order or it may require the assessor to determine the chronological sequence of events necessary for a risk to occur. A simple chronology places all the items or events in the desired chronological order. A good chronology begins with the earliest significant date/time or the initiating event, it identifies a list of all the events relevant to the risk, of interest, and an appropriate time or sequence is assigned to each event to obtain the chronological order.

10.31.1.5 Outputs

The output is a simple chronology of items or a sequence of events. A timeline is an effective display for a chronology. Putting the date or time first, followed by the description, preserves the chronology. For a variation that may provide additional insight, put the primary chronology in context by adding additional chronologies. Thus, in addition to the chronology for the risk itself, you might add a chronology with a matching timeline to show what was going on at the same time in your organization, with your competitors, the nation, the stock market, weather conditions, or any other contextual environment that may be helpful in understanding the primary chronology. The juxtaposed detailed sequence(s) of events often enables us to draw inferences about the risk.

10.31.1.6 Strengths and Weaknesses

Strengths:

- Logical flow
- Evidence-based
- Simple to understand
- Succinct summary
- Shows cause and effect

Weaknesses:

- One-dimensional

10.31.1.7 Examples of Use

Wikipedia has numerous chronologies for a great number of events. See for example the timeline of the Deepwater Horizon oil spill.

10.31.2 SCREENING

10.31.2.1 Overview of the Technique

Screening or sorting is a basic ordering technique. It is the process of separating elements into one or more categories of interest through a systematic evidence-based process.

10.31.2.2 How the Technique Is Used

Usually there are two screening categories which are some versions of “in” or “out.” Screening criteria can be chosen to either screen items onto the short list of interest (in) or to screen items off of the long list (out). Screening can be used to identify hazards of potential concern or of no concern to risk managers. For example, screening techniques can be used to say which commodity-pathogen pairs, concrete monoliths, or street corners in a city are of potential concern. Budget priorities can be screened for funding this year or not. It is the tool to use to create categories or “collections” of things. It is not the tool to use to find the most important items among the collections.

THINGS THAT CAN BE ORDERED

The ordering techniques discussed in this section are useful anytime analysts need to reduce a long list of things to a shorter list of things. This is often done when the need for action exceeds the resources available for taking action and decision makers have to make risk-based choices. Screening puts things into categories. Rating and ranking have the additional benefit of sorting the things into ever finer categories. Ordering can be used to assess potential hazards (pathogens associated with poultry, stone rubble breakwaters in most need of repair), risks (risk of injury to a population, pump motors failing, tainter gates not operating), risk management options (final array of alternative plans, O&M strategies, technology to use to control ANS, budget strategies), or virtually any other set of “things.”

10.31.2.3 Inputs

Inputs for screening include:

- Items to be screened
- Carefully defined categories
- Evidence-based criteria to use for separating items into categories
- Weights for the criteria
- Evidence
- A synthesis algorithm for using evidence-based measurements for the criteria to separate a long list of items into discrete and separate categories of items

10.31.2.4 Process

Given a list of items to be screened and the categories they are to be separated into, screening criteria are identified for each item to be screened and measurements of the screening criteria are obtained. If there is more than one criterion, an algorithm for considering the evidence, weighing the criteria and sorting the items is needed. A description of some common algorithms follows.

The domination procedure requires an item to be better or worse over all criteria than all other items. This could be used to separate the best or worst (if an item is dominated by every other item) from the rest of a population of items. A conjunctive procedure requires an item to meet all predetermined criteria thresholds for inclusion in a category. A disjunctive procedure requires an item to meet at least one criterion threshold to pass on to the category of interest. Elimination by aspects begins by identifying the most important criterion from the set of criteria. A cut-off value is set for it. All items that do not meet the cut-off value are eliminated or screened out. The next most important criterion is then identified, a cut-off is set for it, and all items that do not meet it are eliminated. This process continues until the desired subset of screened-in items is produced.

10.31.2.5 Outputs

The output of a screening process is a list of elements that have been successfully sorted into the mutually exclusive and collectively exhaustive categories of interest.

10.31.2.6 Strengths and Weaknesses

Strengths:

- Reliance on evidence
- Ease of documentation

Weaknesses:

- Items in categories cannot be differentiated from one another
- Only the categories are differentiated

10.31.2.7 Examples of Use

Screenings are ubiquitous as a first step in priority setting. Organizations routinely use screening techniques to sort through issues of interest or concern to them.

10.31.3 RATINGS

10.31.3.1 Overview of the Technique

Rating is an activity that individually scores or rates each item of interest to the decision maker. It systematically separates elements into multiple categories of varying degrees of interest and similar ratings.

10.31.3.2 How the Technique Is Used

Items with like ratings are gathered into like groups where the groups usually, but not always, have an ordinal logic to them. Think of the Motion Picture Association of

America rating system for movies: G, PG, PG-13, R, and NC-17. The National Dam Safety Program's dam safety action classes DSAC I (greatest risk) through DSAC V (least risk) provide a handy example of a rating system. Ratings can be used for a wide variety of risk elements. For example, hazards may be rated high, medium, or low. Probabilities of risks may be rated from rare to common. Consequences could range from negligible to catastrophic.

10.31.3.3 Inputs

The inputs for a rating system are essentially the same as those for a screening system, they include:

- Items to be rated
- Carefully defined rating categories
- Evidence-based criteria to use for rating
- Criteria weights
- Evidence
- A synthesis algorithm for using evidence-based measurements for the criteria to rate the items

10.31.3.4 Process

The ratings process is to compile the list of elements to be rated and then carefully define the rating categories and the criteria that define them. This means more than simply saying items will be rated high, medium, or low. It means objectively defining the evidence-based criteria for rating an item high, medium, or low. This is a critical step. If the rating of high, medium, or low cannot be determined on the basis of objective evidence, then the rating system will be of limited utility in risk assessment. Once the criteria are established, evidence-based objective measurement of each criterion is estimated for each item. These measurements are combined via a synthesis algorithm and an overall rating is assigned.

10.31.3.5 Outputs

The output is a rating for each item in the list of things to be rated.

10.31.3.6 Strengths and Weaknesses

Strengths:

- Flexibility
- Evidence-based
- Reproducibility
- Finer degree of discernment than a simple screening provides

Weaknesses:

- Process is sometimes abused
- Ratings may be assigned subjectively without tying the rating explicitly to any objective evidence

10.31.3.7 Examples of Use

Ratings are used extensively for all sorts of reasons. Restaurants and movies, for example, are familiar examples of five-star ratings. Risk profiling and priority setting are common situations encountered by risk managers where ratings come in handy.

10.31.4 RANKINGS

10.31.4.1 Overview of the Technique

Ranking distinguishes differences among individual items and assigns a position to one thing relative to other things. It is capable of producing first to last, best to worst kinds of rankings.

10.31.4.2 How the Technique Is Used

Ranking is a systematic process used to put items in an ordinal sequence in a qualitative setting. Ranking can also be a cardinal or scalar ranking when quantitative data are available.

10.31.4.3 Inputs

The inputs for a ranking system are essentially the same as those for a screening or rating system, they include:

- Items to be ranked
- Evidence-based criteria to use for ranking
- Criteria weights
- Evidence
- A synthesis algorithm for using evidence-based measurements for the criteria to rank the items

10.31.4.4 Process

Ranking is a simple process when objective criteria measures are available. A ranking process is described in detail in [Chapter 22](#). The basic process is to compile the list of items to be ranked and then to carefully define the evidence-based criteria upon which to base the rankings. Evidence for each criterion and item to be ranked are then gathered. These measurements are combined via a synthesis algorithm, and an overall ranking is determined for each individual item.

10.31.4.5 Output

A ranking process results in a complete inventory of qualitative, semiquantitative, or quantitative ranks for each item of interest. Qualitative and semiquantitative rankings are ordinal. Quantitative rankings may be cardinal or scalar.

10.31.4.6 Strengths and Weaknesses

Strengths:

- Flexibility
- Evidence-based

- Reproducible and transparent
- Criteria can be weighted
- Unique list of rank for each individual item

Weaknesses:

- Weights are subjectively determined
- Ratings may be assigned subjectively without tying the rating explicitly to any objective evidence

10.31.4.7 Examples of Use

Rankings are routinely used to set priorities and for screening risk assessments. That is, a ranking process can, for example, be used to identify hazards that warrant a more detailed risk assessment.

10.32 PRELIMINARY HAZARD ANALYSIS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.32.1 OVERVIEW OF THE TECHNIQUE

A preliminary hazard analysis (PHA) is often the first attempt to identify and categorize hazards or potential hazards as well as their causes, effects, level of risk, and mitigating design measures associated with the operation of a proposed system, process, or procedure. It is frequently a precursor to a more detailed risk assessment. PHA focuses on identifying weaknesses early in the life of a system, thus saving time and money that might be required for major redesign if the hazards were discovered at a later date. Done well, it provides a rationale for hazard control and indicates the need for more detailed analyses. This technique is most useful for new systems and new technologies for which there is little information on design details or operating procedures. It was formally introduced in MIL-STD-882 (1969) which describes the Department of Defense's standard practice for system safety.

10.32.2 HOW THE TECHNIQUE IS USED

PHA is not a true risk identification; it focuses only on identifying the hazard, that is, the thing or event that might cause harm. It makes little effort to estimate the probability or consequences of that harm. PHA is rarely the only tool used to assess risks but it can be a useful first technique especially when the existence of a hazard is in question. It can also be used to prioritize hazards for existing systems. This technique is generally used when more rigorous techniques are either not possible or not necessary.

10.32.3 INPUTS

The inputs for a PHA include:

- Understanding the intended purpose of the system being assessed
- Consideration of appropriate details of the system design
- PHA team with the requisite expertise to identify hazards

10.32.4 PROCESS

The process is simple. It produces a list of hazards and potentially harmful events or risks that could occur. There is no one PHA technique but the steps of a representative technique described by the OSHA Academy (<https://www.oshatrain.org/notes/2bnotes18.html> (accessed July 13, 2018) are as follows:

- Define the activity or system of interest
- Define the accident categories of interest and the accident severity categories
- Conduct review
- Use the results in decision making

This means specifying and clearly defining the boundaries of the activity or system of interest. Then the problems the risk assessment will address, for example, health and safety concerns, are identified. The team then specifies the accident severity categories that will be used to prioritize resources for risk reduction efforts before identifying the major hazards and associated accidents that could result in undesirable consequences. The PHA might also identify design criteria or alternatives that could eliminate or reduce the hazards or it might direct resources to assessing the risks associated with the hazards of greatest potential concern to the PHA team. The PHA itself focuses predominantly on identifying and classifying hazards rather than evaluating them in detail.

The results of a PHA can be described in a simple narrative or in tables and trees.

10.32.5 OUTPUTS

The output of this technique is a list of hazards, hazard causal factors, the resulting consequence, and/or risk level of risk when they can be identified. This list is expected to lead to recommendations for accepting the potential risk, recommending control measures, creating design specifications, or conducting more detailed and sophisticated risk assessments.

Following are examples of PHA results for automated train doors:

- Train starts with door open
- Door opens while train is in motion

- Door opens while improperly aligned with the platform
- Door closes while someone is in the doorway
- Door that closes on an obstruction does not reopen or reopened door does not reclose
- Doors cannot be opened for emergency evacuation

Source: http://www.safeware-eng.com/White_Papers/Preliminary%20Hazard%20Analysis.htm (accessed January 18, 2018).

10.32.6 STRENGTHS AND WEAKNESSES

Strengths:

- Can be used when there is limited information about risks
- Early identification of potential risks

Weaknesses:

- Limited by its reliance on preliminary information
- Does not help risk managers know how to manage a risk

This methodology has two primary limitations. The quality of the result is highly dependent on the knowledge of the team and a PHA generally requires additional follow-up analyses.

10.32.7 EXAMPLES OF USE

Several techniques described in this chapter are considered examples of PHA by some. These techniques include: “What-If” studies, checklist studies, hazard operability studies (HAZOP), fault tree analysis (FTA), and Failure Modes and Effects Analysis (FMEA), to name a few examples.

These techniques are used in a wide variety of applications. An example of a PHA for implementing standards in a laboratory is found at <https://prod.wsvdigital.com.au/sites/default/files/2018-06/ISBN-Implementing-standards-in-a-laboratory-a-practical-example-2006-07.pdf> (accessed October 30, 2018).

10.33 QUALITATIVE RISK ASSESSMENT MODELS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.33.1 OVERVIEW OF THE TECHNIQUE

Qualitative risk assessment is not a lesser kind of assessment, rather it is a different kind of assessment. The difference is in the level of quantitative details. When the

quantitative details are not needed or are not available for risk management decision making, qualitative risk assessment may be the most appropriate choice.

Qualitative techniques are often used for screening or separating risks to determine which risks merit risk management's attention or, perhaps, a more detailed quantitative assessment. Qualitative assessments can also be used, however, to provide all the information needed for risk management decision making. Qualitative assessment provides an effective means of compiling, combining, and presenting evidence to support a statement about risk sufficient for decision making. A formal qualitative process provides consistency and transparency in decision making. It is an organized, reproducible method based on science, sound evidence, and the four generic risk assessment steps presented in [Chapter 4](#). Done well, qualitative assessment is flexible and consistent, easy to explain to others, and it supports risk management decision making.

Because of these attributes, qualitative assessment has proven especially useful when theory, data, time, or expertise are limited. When uncertainty is great, a qualitative risk assessment may be the best available option. It can also be useful for dealing with broadly defined problems where multiple quantitative risk assessments are impractical. This is especially true for problems intended to establish risk management priorities.

Qualitative risk assessments are used in regulatory guidance and requirements documents for international trade, food safety, and health risk assessment. They are also widely applied internally by organizations to support ERM decision making. Many of these techniques have no specific name and it is these that are summarized here as qualitative risk assessment models (QRAM).

10.33.2 HOW THE TECHNIQUE IS USED

Many qualitative risk assessment techniques have been developed by and for a variety of practitioner communities. QRAMs are often based on a qualitative rendering of an existing risk assessment model. [Chapter 4](#) offers four application-free steps in risk assessment:

1. Hazard or opportunity identification
2. Consequence assessment
3. Likelihood assessment
4. Risk characterization

Many practitioner communities have developed their own specific steps for conducting a risk assessment. For example, in the food-safety community, there are a variety of risk assessment models. Some are summarized in [Table 10.7](#). Read down the columns to see the risk assessment steps.

A QRAM simply completes the established steps using qualitative data. The qualitative Center for Veterinary Medicine model (U.S. FDA 2003) shown in [Figure 10.25](#) relies on the now-familiar evidence-based ratings of high, medium, or low for each of the major steps in the animal health risk assessment. These are subsequently combined to obtain an overall risk estimate.

TABLE 10.7
Risk Assessment Steps from Selected Food Safety Risk Assessment Models

Microbial Risk Assessment	Pesticide Risk Assessment	Pest Risk Assessment	Antimicrobial Resistance Risk Assessment	Nutrient Risk Assessment
Hazard identification	Identify residue of interest	Pest categorization	Release assessment	Problem formulation
Hazard characterization	Toxicity studies	Assessment of the probability of introduction and spread	Exposure assessment	Hazard identification
Exposure assessment	Determine NOAEL	Assessment of potential economic consequences	Consequence assessment	Hazard characterization
Risk Characterization	Select safety factor Determine ADI Identify MRL Exposure assessment (intake) Risk characterization (ADI/intake)	Degree of uncertainty Conclusion of the pest risk assessment stage	Overall risk estimate	Dietary intake assessment Risk characterization

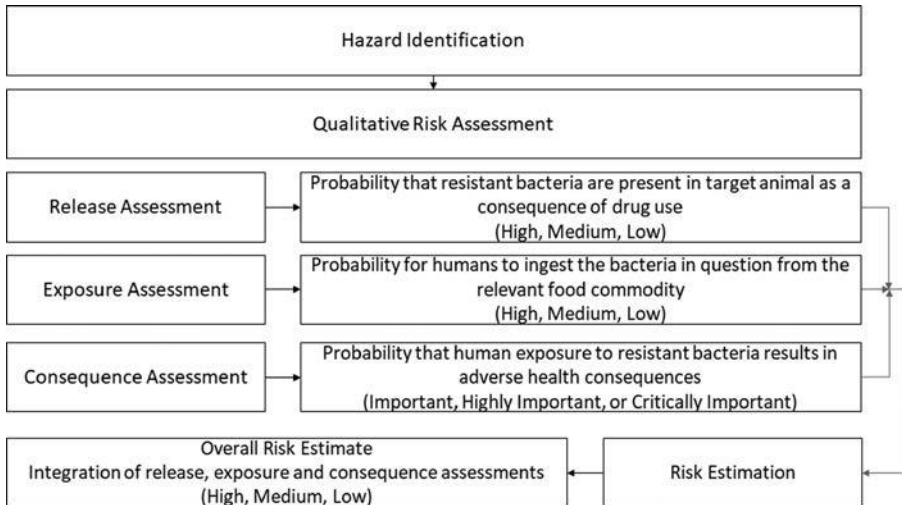


FIGURE 10.25 Components of a qualitative antimicrobial resistance model. (Adapted from FDA 2003.)

QRAMs like this one are adaptations of more general notions about risk to a specific application. Earlier in this chapter, the generic process was built around the $\text{Risk} = \text{Consequence} \times \text{Probability}$ notion. An alternative approach is to adapt this sort of qualitative method to other models of risk, like the CVM antimicrobial risk assessment of [Figure 10.25](#).

10.33.3 INPUTS

The inputs required for a QRAM include:

- Conceptual or quantitative risk assessment model
- Qualitative rendering of the model
- Evidence to support the qualitative judgments
- Qualitative risk characterization of the relevant risks

10.33.4 PROCESS

The QRAM process is unique for each model adapted for qualitative use. The generic process of Section 10.20 and the risk matrix of Section 10.37 provide examples of QRAM processes. The steps of a risk assessment are identified and a process is prescribed for qualitatively summarizing the relevant evidence for each step leading up to one or more qualitative estimates of the risk accompanied by risk narratives. A QRAM may also include qualitative risk characterizations for assessing the efficacy of risk management measures.

10.33.5 OUTPUTS

The primary output of a QRAM is a qualitative characterization of the relevant risks. This would ordinarily include one or more qualitative risk estimates with accompanying risk narratives that include a clear discussion of the instrumental uncertainty encountered and, possibly, qualitative assessments of risk management options.

10.33.6 STRENGTHS AND WEAKNESSES

Strengths:

- Comprehensive and flexible
- Can be applied to a wide variety of risk situations
- Logically sound when key elements are identified and the process is supported by evidence
- Can be performed with varying levels of resources and degrees of uncertainty
- Easily documented and readily open to evaluation

Weaknesses:

- Once developed there may be a tendency to rely on this qualitative method when a quantitative assessment is possible
- Produces specious results when assessment is not evidence-based

10.33.7 EXAMPLES OF USE

A great deal of the risk assessment for private sector enterprise risk management organizations may be based on QRAM techniques. As Table 10.7 indicates, the food safety community of practice makes extensive usage of QRAMs.

10.34 RELIABILITY-CENTERED MAINTENANCE

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.34.1 OVERVIEW OF THE TECHNIQUE

Reliability-centered maintenance (RCM) is a process designed to produce low operational risk and high equipment reliability at least cost maintenance, that is, the most effective maintenance approach. It was initially developed to meet the needs of commercial aviation in the late 1960s. This led to the publication of the Maintenance Steering Group document MSG-3 that is the basis of the modern RCM (see box). It is now an approved and well-established methodology in industry. RCM is a process used to identify applicable and effective preventive maintenance requirements for equipment in accordance with the safety, operational and economic consequences of identifiable failures, considering the degradation mechanism responsible for those failures. The process supports decision-making about the necessity of performing a maintenance task.

MSG-3 (MAINTENANCE STEERING GROUP)

“Operator/Manufacturer Scheduled Maintenance Development” is a document developed by the Airlines for America (A4A) (formerly ATA). It presents a methodology used to develop scheduled maintenance tasks and intervals, acceptable to the regulatory authorities, operators, and manufacturers. The main idea of this RCM document is to recognize the inherent reliability of aircraft systems and components, avoid unnecessary maintenance tasks, and achieve increased efficiency.

10.34.2 HOW THE TECHNIQUE IS USED

RCM is risk-based. It focuses on situations where potential failures may be eliminated or reduced in frequency and/or consequence by carrying out maintenance tasks. The goal is to avoid breakdown maintenance and to minimize reactive maintenance in favor of predictive maintenance. RCM is used to make decisions about safety based on consideration of personnel, the environment, and operational or economic concerns. The criteria considered depend on the nature of the problem. The analysis should be targeted to equipment where failure would have serious safety, environmental, economic, or operational effects. RCM is generally applied during the design and development phase and implemented during operation and maintenance.

10.34.3 INPUTS

Inputs required for an RCM include:

- Understanding the equipment and its structure
- Knowledge of the operational environment, associated systems, subsystems, and items of equipment
- Knowledge of possible failures and the consequences of those failures

10.34.4 PROCESS

The basic steps of an RCM program include:

- Initiation and planning
- Functional failure analysis
- Task selection
- Implementation
- Continuous improvement

The functional failure analysis begins by selecting and limiting the target area, then answering questions like the following (<http://www.ramentor.com/theory/rcm/> [accessed March 28, 2018]):

- What are the functions of the target and what is the expected performance level for it in the current operating circumstances?
- In what ways does the target fail and is therefore unable to perform the required operations?
- What are the causes for each functional failure?
- What happens with each failure?
- What is the effect of each of the failures? What are their consequences?
- What can be done to predict or prevent each of the failures?
- What should be done if a suitable predictive action is not available?

All of these actions rely on paying attention to personnel, environment safety, operational, and financial factors. RCM is a method used to create a preventive maintenance program that can justifiably and effectively allow the structure and equipment to reach the required safety and availability levels, while leading to improved safety, availability, and financial factors in operations.

Performing RCM means identifying required functions and performance standards. Functional failures that may result can be used to identify equipment and components associated with those functions. Figure 10.26 illustrates this idea with a degradation curve. The interval P-F shows the time between when a budding failure reveals itself (point P) and when the equipment can no longer be used because its performance has degraded to an unacceptable level (point F). Consider the example of a pump designed to pump a specific flow. When wear and tear degrade the pump's performance, point P occurs when a lower flow is first noted. When the pump cannot produce an adequate flow, point F has been reached. The pump still operates. It has not broken down, but it is no longer meeting its minimum functional duty.

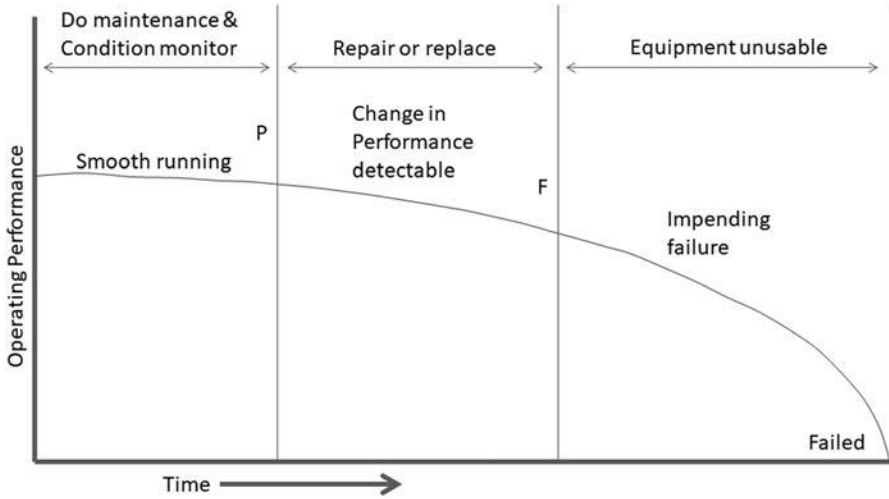


FIGURE 10.26 Conceptual degradation curve.

The degradation curve concept can be applied to every part of a project, that is, every part has its own P-F interval. Condition monitoring is used to observe the P. Usually, only the vital parts that lead to a breakdown are monitored. The P-F interval is identified based on the worst-case failure suffered on-site with the equipment item by using the failure history from comparable operations or by making a reliability failure assessment of the item. RCM risk assessment consists of estimating the frequency of each failure without maintenance being done. The goal is to avoid breakdown maintenance and to minimize reactive maintenance in favor of predictive maintenance.

10.34.5 OUTPUTS

Defining maintenance tasks such as condition monitoring, scheduled restoration, scheduled replacement, failure-finding or no preventive maintenance required to prevent failures are the outputs of RCM. Other risk management actions that can result from RCM analysis include redesign, changes to operating or maintenance procedures, or additional training for personnel. Task intervals and the required resources are identified for each risk management response.

10.34.6 STRENGTHS AND WEAKNESSES

Strengths:

- Lowest cost/low risk/high reliability payoff comes with effective preventive maintenance

Weaknesses:

- Reliance on performance data
- Data are frequently missing and expert elicitations are used to fill data gaps

10.34.7 EXAMPLES OF USE

The airline industry makes extensive use of this method. Any engineered system with significant operation and maintenance expenses could make profitable use of this method.

10.35 RISK CONTROL EFFECTIVENESS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.35.1 OVERVIEW OF THE TECHNIQUE

Risk control effectiveness (RCE) evaluates the total effectiveness of all the controls that act upon a particular risk. This includes controls that affect the probability of the risk, sometimes called “preventive controls,” and those that affect the consequences, sometimes called “mitigating controls.” Alternatively, controls may be categorized as preventative when they are intended to reduce the likelihood of a situation occurring, detective if they are to identify failures in the current control environment, and corrective when they reduce the consequence and/or rectify a failure after it has been discovered (Paladin Risk Management Services, <https://paladinrisk.com.au/risk-tip-2-measure-control-effectiveness/> [accessed January 27, 2018]).

RCE can be used to ask if existing risk management measures are adequate. To answer that question, one must know:

- What the existing (or proposed) management measures are for controlling a particular risk
- If those controls are capable of adequately reducing the risk to a tolerable level of residual risk
- If the risk management measures are operating in an intended manner
- If the controls can be demonstrated to be effective when required

RCE is sometimes, but rarely, applied to separate risk controls within a suite of controls or a risk management option.

10.35.2 HOW THE TECHNIQUE IS USED

Residual risks are important to RCE. An RCE assessment should always estimate and communicate them. This can be done for existing risk management measures by considering the existing (or proposed) risk management measures' effectiveness in reducing an existing (or future) risk in order to estimate the level of residual risk.

To answer the questions above with evidence and confidence, proper assurance processes, such as an audit or a risk control self-assessment, must be undertaken. Risk control effectiveness analysis can be used to provide an assessment of the actual level of risk control that exists in the current state of a system. This can be compared to the level of risk control that is reasonably achievable for a particular risk.

10.35.3 INPUTS

The inputs for a risk control effectiveness analysis include:

- Intimate knowledge of the existing risk management measures
- An effective qualitative or quantitative means for rating or ranking their effectiveness

10.35.4 PROCESS

Assessing the effectiveness and adequacy of risk controls is difficult unless the performance of the risk controls has been documented. This documentation must include a description of the control, its purpose, and its design intent. Validating its effectiveness requires evidence of the operation of the control, which should also be documented. In private industry, it is usual for assurance providers to conduct audits of the risk control, which will include documentation and other evidence of the operation of the control.

It is not always easy to accurately express the level of effectiveness for a particular risk management option in an evidence-based manner, but it is valuable to do so as part of the risk management monitoring, evaluation, and modification process. It is important to know when risk management efforts can be improved through further or different risk treatment. A measure of RCE can serve this purpose, and an evidence-based qualitative rating for RCE has proven useful at times. The IEC (2008) offers examples of qualitative ratings presented below:

- *Fully effective*: There is nothing more to be done except to review and monitor existing controls. Controls are well designed for the risk, they address the root causes and management believes that they are effective and reliable at all times.
- *Partially effective*: Most controls are designed correctly and are in place and effective. Some more work can be done to improve operating effectiveness or management has doubts about operational effectiveness and reliability.
- *Ineffective*: While the design of controls may be largely correct in that they treat most of the root causes of the risk, they are not currently very effective. Or, some of the controls do not seem correctly designed to treat root causes, those that are correctly designed are operating effectively.
- *Totally ineffective*: There are significant control gaps. Either control does not treat root causes or they do not operate at all effectively.
- *Not effective*: There is virtually no credible control. Management has no confidence that any degree of control is being achieved due to poor control design and/or very limited operational effectiveness.

10.35.5 OUTPUTS

The output of an RCE is a documented rating of each individual risk control and the overall risk management option.

10.35.6 STRENGTHS AND WEAKNESSES

Strengths:

- Evidence base supplants subjective assessments of control effectiveness
- Positively impacts the safety, operational efficiency, and cost performance of systems

Weaknesses

- Requires evidence-based evaluations which may require audits
- Not especially useful for evaluating individual risk controls in isolation

10.35.7 EXAMPLES OF USE

This method is easy to do qualitatively. It is used in a wide variety of industries, from finance to those with complex physical systems.

10.36 RISK INDICES

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.36.1 OVERVIEW OF THE TECHNIQUE

A risk index is a semiquantitative measure of risk that is closer to a qualitative technique than a quantitative one. A risk is broken down into a small number of components, for example, probability and consequence; hazard, exposure, and consequence; contaminant characteristics, range of possible exposure pathways, impact on the receptors, and the like. Scores are applied to each component of the risk and aggregated to an overall risk score that, though numeric, is qualitative in nature. The riskiness of an event or situation is represented by a number generated using a scoring approach that relies on ordinal scales. Risk indices are used to compare and rate a set of risks.

10.36.2 HOW THE TECHNIQUE IS USED

Indices are used as a scoping or priority-setting device for many different types of risk. They are used to identify risks that require a more detailed or possibly quantitative assessment. When based on evidence and validated, indices are useful as a comparative tool as long as the underlying models are understood.

10.36.3 INPUTS

The required inputs for a risk index are:

- A risk of interest
- Knowledge of the sources of the risk

- A set of risk components
- Numerical ratings for significant distinctions within a component
- Evidence to establish the numerical rating for a characteristic
- An algorithm for combining characteristic ratings

10.36.4 PROCESS

The inputs for a risk index are derived from the system, situation, or set of risks under study. A good understanding of the sources of risk, the possible pathways, and the range of consequences is needed. Because the choice of ordinal scales for the index is arbitrary, sufficient evidence is required to validate the index. It is neither sufficient nor acceptable to simply assign a number to a risk or a risk component.

Step one, when using a risk index, is to understand and describe the system or set of risks of interest. Once the risks are defined, the components of the risks can be identified and developed in a way that provides a composite index. For an ecological risk, for example, the index components might include sources, pathways, and receptor(s) to be scored. A navigation example might have hazard, exposure, and consequence components.

Suppose the interest is identifying the riskiest locations (i.e., risk components) in a waterway segment, where the risk is defined as a marine casualty, that is, a grounding, allision, or collision. An index can be defined using the following underlying risk model:

$$\begin{aligned} \text{Risk index} &= \text{Probability the hazard is present} \\ &\quad \times \text{Probability the asset(s) at risk comes in contact with the hazard} \\ &\quad \times \text{Adverse results of an exposure} \end{aligned}$$

The ordinal scales might look like those below. Let us define the hazard as other vessels. The probability the hazard is present:

- 1 = very unlikely (once a year)
- 2 = unlikely (once a month)
- 3 = likely (weekly)
- 4 = very likely (daily)
- 5 = inevitable (several times a day)

Let the probability that the asset(s) at risk comes in contact with the hazard be defined as:

- 1 = rare/never
- 2 = infrequent (monthly)
- 3 = frequent (weekly)
- 4 = high (daily)
- 5 = constant

The consequences or adverse results of an exposure may be defined as:

- 1 = minor damage to vessels
- 2 = serious damage to vessels
- 3 = major damage to vessels
- 4 = multiple casualties or serious environmental damage
- 5 = at least one fatality or major environmental damage

Each location on the waterway is rated for each component based on the available evidence. The consequence is usually defined as the maximum credible consequence. Thus, the number assigned to the component is not as important as the evidence upon which that numerical judgment is based. The individual scores are combined multiplicatively. The maximum risk index is 125. A subjective judgmental interval scale may be defined as follows:

- High Risk ≥ 75 : top priority, action is required now
- Medium Risk ≥ 27 and < 75 : deal with this risk over the next few weeks/ months
- Low Risk < 27 : deal with this risk if attention is warranted

The scores must be internally consistent and relative. Scores may be compiled by adding, subtracting, multiplying, and/or dividing according to the high-level model adopted at the outset of the exercise. Cumulative effects can be taken into account by adding scores. For example, scores can be added for multiple locations on a waterway segment in order to compare the relative risks of waterway segments.

Remember, it is not valid to apply mathematical rigor to ordinal scales. The arithmetic used is for approximating risk potential. A location with an index of 75 is not 50% worse than one with an index of 50. All we can say is that a 75 indicates a greater risk than a 50. Uncertainty can be addressed by sensitivity analysis. Scores can be varied or even entered as a range to reflect uncertainty.

10.36.5 OUTPUTS

The output of the risk index technique is a series of indices that establish the relative order of a set of risks. Risk indices, though numerical, are essentially a qualitative approach. Such numerical indicators of qualitative risks are called semiquantitative risks.

10.36.6 STRENGTHS AND WEAKNESSES

Strengths:

- Good scoping tool for ranking different risks associated with a similar problem, activity, or location
- Allows for multiple evidence-based components that affect the level of risk
- Simple to apply

Weaknesses:

- The results may be meaningless if the process and its output are not evidence based
- Numerical values for risk may be misinterpreted
- The method is lacking in rigor
- Numerical values used to compile the risks are likely to lack consistency if not defined

10.36.7 EXAMPLES OF USE

Risk indices are used primarily for risk ranking, a priority setting task, or sometimes a part of risk evaluation.

10.37 RISK MATRIX (OPERATIONAL RISK MANAGEMENT)

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.37.1 OVERVIEW OF THE TECHNIQUE

The risk matrix, sometimes known as operational risk management (ORM), is another qualitative technique based on the simple equation, “Risk = Consequence × Probability.” It can be an effective screening/rating tool. It is commonly used in enterprise risk management to complete a risk profile. The U.S. military (USDOD 2000) has used it to identify the appropriate level of risk management that is responsible for a risk.

COX’S CAVEAT

Qualitative risk rating systems tend to make two types of errors: (1) *Reversed rankings*, that is, assigning higher qualitative risk ratings to situations that have lower quantitative risks; and (2) *Uninformative ratings*, for example, frequently assigning the most severe qualitative risk label (such as “high”) to situations with arbitrarily small quantitative risks. This results in assigning the same ratings to risks that differ by many orders of magnitude.

Consequently, despite their consensus building appeal, flexibility, and the appearance of thoughtful process in input requirements, qualitative rating systems do not always provide enough information to support accurate discrimination between quantitatively small and quantitatively large risks. As a consequence, the value of information (VOI) they provide to risk managers can be low to zero if most risks are small with a few large risks, as qualitative ratings are sometimes unable to confidently distinguish the two risks. This suggests quantitative risk assessment methods should be considered when qualitative ones may prove unreliable.

Source: Cox et al. (2005).

TABLE 10.8
Sample Risk Matrix

	None	Remote	Occasional	Probable	Frequent
Catastrophic	a	b	c	d	e
Critical	f	g	h	i	j
Marginal	k	l	m	n	o
Negligible	p	q	r	s	t
None	u	v	w	x	y

10.37.2 HOW THE TECHNIQUE IS USED

The consequence dimension of the risk defines one dimension of the risk matrix. The continuum of consequences is broken into a number of qualitative categories such as negligible, marginal, critical, and catastrophic. These categories should extend from the maximum credible consequence to the lowest consequence that is of concern. The probability dimension of the risks forms the other dimension of the matrix and is broken into qualitative segments or categories. Although the segments could be defined quantitatively, they are usually not. Categories like remote, occasional, probable, and frequent are used and they would usually be defined qualitatively in a narrative manner. When constructing the probability scale, remember that the lowest likelihood should be acceptable for the highest defined consequence, otherwise all elements with the highest consequence may be identified as unacceptable and the matrix will fail to discern among the many elements. It is usual to identify three to five categories for each risk dimension. Definitions for probability and consequence categories need to be as clear and unambiguous as possible. A sample matrix is shown in [Table 10.8](#).

When the probability and consequence categories are given evidence-based or quantitative definitions, it is possible to examine the evidence and assess the risk of a list of items based on the available evidence. Consider, for example, the risk associated with a firm’s product lines. Each product line would be slotted into the matrix cell based on the definitions of the probability and consequence categories and the available evidence for each individual product line.

10.37.3 INPUTS

Risk matrix inputs include the following:

- List of risks to assess or items to rate
- Carefully constructed evidence-based definitions of a limited number of consequence categories spanning the relevant range of potential consequences
- Carefully constructed evidence-based definitions of a limited number of probability categories spanning the interval [0,1]
- A matrix with risk management priorities identified
- Evidence for categorizing each item by probability and consequence
- A risk assessment team

10.37.4 PROCESS

The process is critical to this technique. Carefully defining sets of mutually exclusive and collectively exhaustive evidence-based consequence and probability categories is the most critical aspect of this process. Then, gathering evidence to support the rating for the probability and consequence of each potential risk becomes the basis for this evidence-based assessment technique. It is common practice to begin by selecting the maximum credible consequence category that best fits the situation, then identifying the likelihood with which those consequences will occur.

The cell in the lower left of [Table 10.8](#) is clearly the least risky combination of probability and consequence that can be obtained. The cell in the upper right is unambiguously the riskiest. Risk clearly increases as we move along the northeast axis from low risk to high risk.

Within any row we know that moving east (right) increases the risk, that is, *r* is riskier than *q*. Within a column moving north (up) increases risk, so that *c* is riskier than *h*. Once we attempt to compare cells in different rows and columns, it becomes more difficult to judge the relative risk. For example, which is riskier, *h* or *n*? The probability of one is occasional with marginal consequences; the other is probable with negligible consequences. If these two combinations described the risk of fire to your home, which would you prefer? Which is the greater risk? Such conundrums are common in the matrix.

10.37.5 OUTPUTS

The output of this process is a list of potential risk items individually assigned to a cell in the matrix, each of which has a probability and consequence rating that has been documented on the basis of the available evidence. Usually the cells are grouped into subjective ordinal clusters of cells, shown as shades of gray in [Table 10.8](#). The darkest shade might indicate unacceptable risk, the second darkest identifies risks to be carefully monitored, the third darkest indicates risks of no immediate concern, and the lightest indicates no risk at all. That is one potential output of this process.

The USDOD (2000) defines catastrophic consequences as those that “could result in death, permanent total disability, loss exceeding one million dollars, or irreversible severe environmental damage that violates law or regulation.” A rating of catastrophic consequences for a risk would then be based upon tangible evidence of one or more of these conditions. A frequent probability has two different definitions: one for a specific item or individual, and another for a fleet or inventory. The first definition says the risk is “likely to occur often in the life of an item, with a probability of occurrence greater than 0.1 in that life.” The inventory definition says the risk is “continuously experienced.” Alternative formulations of the frequency definitions may specify a frequency based on an interval of time, such as happens daily, weekly, monthly, annually, and so on. As with a consequence rating, the integrity (and hence the utility) of a probability rating stands and falls on the quality of the evidence used to provide and support it.

The Department of Defense (DOD 2000) has also attempted to number the cells from least to most risk and then assigned risk management decision-making authority based on the level of risk. Low levels of risk are handled at the lower end of the command chain and the greatest risk decisions are made by senior commanders.

10.37.6 STRENGTHS AND WEAKNESSES

Strengths:

- Systematically addresses both the consequences of a potential risk and its probability of occurring based on the available evidence
- Technique is easy to explain and understand
- If uncertainty or confidence ratings accompany the analysis it is possible to convey the remaining levels of uncertainty

Weaknesses:

- One of the most easily abused risk assessment tools
- Use is subjective
- Ratings can vary among raters
- Ratings of consequence and probability are often assigned arbitrarily and without direct regard for the available evidence
- Matrix coloring schemes can be fraught with inconsistencies

If this technique is not data driven, it may, as Hubbard (2009) suggests, be less than worthless. Cox (2008a,b, 2010) has gone on to a far more sophisticated critique of the manner in which the resulting matrix is used to rank risks. Hubbard and Cox have been scathing in their justified criticism of this technique in particular. Cox points out that the matrices are not usually subjected to rigorous validation studies, and there are potential pitfalls in their usage. To the extent that they are evidence-based and they help to clarify an organization's risk priorities, they can be useful.

10.37.7 EXAMPLES OF USE

The risk matrix is one of the most commonly used risk assessment tools because of its simplicity and its logical appeal, which paradoxically, lead to the frequent abuse of this assessment technique. The risk matrix is commonly used for developing risk profiles in enterprise risk management that assess and rate or rank all of the risks of concern at the enterprise level of an organization. The resulting risk profile is then compared to the organization's risk tolerance and risk appetite to guide future risk management efforts.

A common misuse occurs when the risk matrix is used to allocate risk management resources. If items with frequent and catastrophic consequences are the items most likely to be funded, then the "winning strategy" may become assigning the highest possible rating to each potential risk rather than objectively assessing the evidence in order to attract more resources. This destroys the value of the technique and the integrity of the decision-making process and produces junk analysis along the way.

10.38 RISK NARRATIVE

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.38.1 OVERVIEW OF THE TECHNIQUE

A risk narrative is a simple story that characterizes and describes an identified risk. It includes a narrative description of each of the four generic risk assessment steps: identify hazard or opportunity, consequence assessment, likelihood assessment, and risk characterization. It may be a simple standalone risk assessment or part of the risk characterization of a more sophisticated risk assessment.

10.38.2 HOW THE TECHNIQUE IS USED

A simple narrative uses the available evidence to answer the following questions about an identified risk: What can go wrong? How can it happen? What are the consequences if it happens? How likely is it the consequences will occur? A risk narrative answers these questions honestly and directly. Answering these four questions is a useful organizing technique. A narrative describes the risky situation and supports the description with the facts that are available while honestly communicating what remains uncertain. Think of this narrative as a risk hypothesis.

10.38.3 INPUTS

The inputs to a risk narrative include:

- Qualitative evidence for the four generic risk assessment steps
- Narrative that describes and bounds the risk

10.38.4 PROCESS

The best narratives tell the story of the whole of the risk. When appropriate, tell the risk story as well as the risk reduction story which would describe the effectiveness of the risk management options. Then tell the story of the residual, transferred, or transformed risks. In quantitative risk assessments, a risk narrative should accompany every risk estimate. In qualitative risk assessment, the narrative may provide all that is needed for a risk management decision. Risk narratives are robust and flexible tools that can be used for the entire risk or any of the risk assessment tasks.

10.38.5 OUTPUTS

The outputs include:

- Answers to the four informal risk assessment questions
- A qualitative assessment of the risk evident in the nature of the narrative description

10.38.6 STRENGTHS AND WEAKNESSES

Strengths:

- A description of the risk as complete as possible given the available evidence
- An accounting of the available evidence
- A risk hypothesis that identifies the remaining uncertainty

Weaknesses:

- Incomplete risk hypotheses when uncertainty is great
- Can discourage more complete quantitative risk assessments by appearing more complete than is true

10.38.7 EXAMPLES OF USE

Risk narratives are suitable as a first-step risk assessment in many situations. They can provide sufficient information for decision making in some instances, and this makes them a valuable component of any risk profiling effort. A risk narrative is applicable to any stage of the risk assessment process and to any kind of risk. It is a versatile but limited tool. Risk narratives are routinely used as part of a more complex risk assessment to put the meaning of quantitative estimates of risk into a context useful for risk management and risk communication.

10.39 ROOT-CAUSE ANALYSIS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.39.1 OVERVIEW OF THE TECHNIQUE

When a problem occurs, if you only fix the symptoms you can expect to have to fix them again and again. Looking deeper to figure out why the problem occurs enables one to fix the underlying systems and processes that cause the problem. Root-cause analysis or root-cause failure analysis is used to identify what, how, and why something happened, so that recurrences can be prevented. Sometimes referred to as “the five whys,” it is often used to analyze major asset losses, and it is conducted after a failure event. When the process is applied to economic or financial losses it is called loss analysis.

10.39.2 HOW THE TECHNIQUE IS USED

Root-cause analysis is used for accident investigations and to enhance occupational health and safety. It is also used to improve reliability and maintenance of technological, engineering, and infrastructure systems, as well as for quality control.

10.39.3 INPUTS

Essential inputs include:

- Extensive knowledge of the system investigated
- Domain experts
- Evidence gathered from the failure or loss
- Evidence from similar failures may also be useful

10.39.4 PROCESS

The essential logic of root-cause analysis relies on the assumption that systems and events are interrelated. An action or event in one area triggers an action or event in another until it results in the observed failure. Root-cause analysis traces back these sequences of events to discover where the problem started and how it grew into the loss under investigation.

The simplest way to perform a root-cause analysis is to ask “why?” five times. Here is an example applied to a situation where a laboratory aide was cut while cleaning a dissection laboratory:

Why? The laboratory aide was cut by a dissection knife.

Why? The knife was left by the sink.

Why? The area was not cleared on the previous day.

Why? Clearing is not a daily habit.

Why? Standard operating procedures/documentation for clearing do not exist.

Source: Williams, P. 2001. Baylor University Medical Center Proceedings 14(2): 152–157.

Mind Tools* (N.D.) identifies three groups of causes. Physical causes involve tangible, material items that failed in some way. For example, a gate chain breaks. Human causes result when people do something wrong or fail to do something that was needed. Human causes can lead to physical causes. For example, the chain may have failed because it was not maintained or inspected for wear and tear. Organizational causes reflect faulty systems, processes, or policies used to make decisions. For example, gate chain inspections are eliminated because gate chains rarely fail.

The process begins by establishing the scope and objectives of the root-cause analysis. This is followed by gathering data from the failure or loss. Next, a structured analysis is conducted to determine the root cause. Solutions are developed, and recommendations are made, implemented, and monitored. Mind Tools (N.D.) identifies a simple five-step process.

* http://www.mindtools.com/pages/article/newTMC_80.htm (accessed October 12, 2016).

Step One: Define the Problem

- What do you see happening?
- What are the specific symptoms?

Step Two: Collect Data

- What proof do you have that the problem exists?
- How long has the problem existed?
- What is the impact of the problem?

Step Three: Identify Possible Causal Factors

- What sequence of events leads to the problem?
- What conditions allow the problem to occur?
- What other problems surround the occurrence of the central problem?

Step Four: Identify the Root Cause(s)

- Why does the causal factor exist?
- What is the real reason the problem occurred?

Step Five: Recommend and Implement Solutions

- What can you do to prevent the problem from happening again?
- How will the solution be implemented?
- Who will be responsible for it?
- What are the risks of implementing the solution?

10.39.5 OUTPUTS

The outputs of a root-cause analysis include the data and evidence gathered, hypotheses considered, conclusions about the most likely root causes for the failure or loss, and recommendations for corrective action.

10.39.6 STRENGTHS AND WEAKNESSES**Strengths:**

- Experts are involved in a structured analysis conducted in a team environment
- Can consider all likely hypotheses and documents the outputs

Weaknesses:

- Required expertise may be difficult to find
- Critical evidence may be destroyed during the failure or removed during clean-up
- Danger exists that the team may not allow enough time or resources to fully evaluate the situation

10.39.7 EXAMPLES OF USE

This technique is most likely to be used to examine and reduce the risks of infrastructure and equipment failures by a wide variety of organizations. Virtually any industry or organization concerned with understanding the cause of failure can and does use RCA. Health care, energy, transportation, and public works are but four examples of sectors making extensive use of this technique.

10.40 SAFETY ASSESSMENT

10.40.1 OVERVIEW OF THE TECHNIQUE

A safety assessment seeks to determine whether a situation meets or fails to meet a specific safety requirement rather than to try to identify a specific level of risk. A safety assessment usually consists of some form of a ratio of an actual value compared to a standard or value considered to be safe for the population. The ratio components are determined in the assessment.

10.40.2 HOW THE TECHNIQUE IS USED

The process is to calculate the value of the numerator, usually a safety measure, and the value of the denominator, usually an exposure or demand measure, of a safety factor and to compare the two. Ratio values that exceed the safety threshold (often a value equal to one) are considered less safe and in need of risk management action.

10.40.3 INPUTS

The inputs for safety assessment require:

- Population of things to be evaluated
- Well-defined numerator and denominator for the quotient
- Defined safety threshold
- Measurement data for the quotient for each thing to be evaluated

10.40.4 PROCESS

This method requires some authority to make a specific determination of a level of performance that will be considered safe. The denominator contains the safety standard and the numerator contains the measurement of the exposure or hazard. Some of the most familiar examples are from the food safety arena where the quotient is (Estimated daily intake/Acceptable daily intake) for a given food additive of concern. An ADI is determined using toxicological studies, an EDI is determined using intake studies, and the two values are compared. In engineering, safety analyses might compare (demand/capacity) for a structural component like a rebar, a concrete monolith, electrical component, and the like. Most safety assessments simply require comparing two analytically derived values. When the quotient exceeds one, the situation is considered less safe than when the quotient is one or less. Conversely, a different factor of safety threshold might be defined, for example a safe situation might be defined to exceed a ratio of 2.

TABLE 10.9
Sample Factor of Safety Analysis for a Tension Bar

Random Variables	Mean	Standard Deviation	Distribution
Ultimate tensile strength, F_t (ksi)	40	4	N (40,4)
Load, P (kips)	15	3	N (15,3)
Constant			
Area, A (in ²)	0.5		
Limit state			
Factor of safety, $FS = F_t/A/P$	1.33		

A safety assessment is usually more valid for populations than it is for any one member of a population. Thus, an $(EDI/ADI) > 1$ does not guarantee that an individual who consumes more than the acceptable daily intake will become ill, nor does it mean an individual with an $(EDI/ADI) < 1$ will not become ill. However, across a population, those with a ratio in excess of 1 can expect adverse health effects more often than those with a ratio less than 1.

There are slightly more involved safety assessments. For example, assume for simplicity a limit state or factor of safety for a tension bar defined as $(F_t A/P)$, where F_t is ultimate tensile strength in ksi, A is area in square inches, and P is load measured in kips. Note that this safety factor flips the quotient, and values less than one are considered unsafe. Let the arguments for this factor of safety be as defined below, where F_t and P are described by normal distributions with the parameters shown in Table 10.9. A sample calculation of the factor of safety is shown below. However, there are two random variables whose precise values are uncertain.

A Monte Carlo process was used to generate 100,000 separate estimates of the factor of safety. The results are shown in Figure 10.27. Notice that 8.3% of the

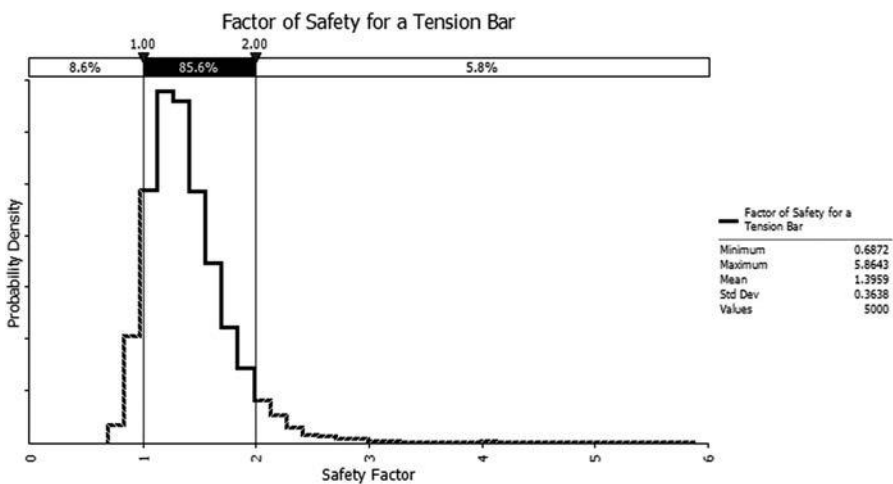


FIGURE 10.27 Distribution of calculated limit states to obtain a factor of safety.

calculations resulted in a factor of safety less than one. In this instance values less than one are undesirable. This is the probability of an unsatisfactory performance $P(u)$ and reliability is defined as:

$$R = 1 - P(u) \text{ thus, the tension bar reliability is } 91.7\%$$

10.40.5 OUTPUTS

The output is a so-called determination of “safe” or “not safe.” We say “so-called” because such a bright line determination of safety requires a standard for determining safety. Standards require someone to make a value judgment about the level of performance that is considered safe, given the nature of the evidence and analysis used to create the safety factor.

10.40.6 STRENGTHS AND WEAKNESSES

Strengths:

- Can be used relatively quickly to screen whether a situation could result in adverse consequences
- Much of the data, presumably including the standard, are already available
- Method is consistent in its data requirements and the calculation of safety factors
- Method has a conservative bias that is sometimes favored by decision makers

Weaknesses:

- May not use all available study data because it focuses on a ratio of values
- Conservative bias is also a weakness

10.40.7 EXAMPLES OF USE

Safety assessments are used extensively for assessing the safety of food additives as well as chemical toxins in the environment. Industrial hygiene uses these ratios as does the engineering profession. So-called “bright line” standards or thresholds are used in a wide variety of regulatory settings.

10.41 SCENARIO ANALYSIS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.41.1 OVERVIEW OF THE TECHNIQUE

Scenario analysis examines well defined scenarios. This distinguishes it from scenario planning in which distinctly different discrete scenarios are identified and analyses of importance are conducted within these different scenarios.

Scenarios are coherent narratives created to describe uncertain conditions. These may be historical, existing, baseline, no action, failure, improved, or ideal conditions. The most common scenarios usually describe some future condition. Scenario analysis enables assessors to identify one, a limited number, or a full array of scenarios in order to explore how different risks might unfold in an uncertain future.

STRUCTURING SCENARIOS

Informal scenarios can be as simple as a narrative sequence of plausible events. Formal scenarios may depend on complex models like event trees, decision trees, process risk models, and the like. If probabilistic methods are used the team must possess skill in the use of these methods. Scenario construction, especially when evaluating the effectiveness of risk management options, can require imagination to think about the future without necessarily extrapolating from the past. Other times, for example when constructing fault tree scenarios, scenario construction can require intimate knowledge of complex systems.

10.41.2 HOW THE TECHNIQUE IS USED

Scenario analysis is used to explore different sets of assumptions about the future conditions of effects of interest, for example decision criteria, in an uncertain future. Think of scenarios, in this context, as the sequences of events that lead to risks. Once a scenario is defined it can be constructed and analyzed in a wide variety of ways. Scenario analysis focuses on specific outputs of interest and the values they may assume in an uncertain future.

This is most easily illustrated with a quantitative example. Consider a flood risk that is estimated by the expected annual damages (EAD) it causes. [Table 10.10](#) illustrates different estimates of this risk for four different scenarios.

EAD values are estimated for each scenario. Decision relevant information may be obtained from the individual scenarios or from comparisons between them. Scenario analysis is most useful when it is necessary to compare the similarities and differences between alternative scenarios. For example, comparing the future EAD without risk mitigation to EAD with a levee in place we see a reduction of \$30,000,000. It is a valuable tool for anticipating how risks of all kinds might develop over short- and long-term time frames.

**TABLE 10.10
Flood Risk in Expected Annual Damages for Four Different Scenarios**

Scenario	Existing	Future without Risk Mitigation	Future with Levee	Future with Channel Improvements
Expected annual damages	\$25,000,000	\$35,000,000	\$5,000,000	\$10,000,000

10.41.3 INPUTS

The inputs for scenario analysis include:

- A well-defined question to be answered or problem to be examined
- An interdisciplinary team of people that can identify the appropriate number of scenarios and an appropriate level of detail for each
- Differentiated scenarios
- A scenario structuring tool, which may be informal or formal
- Analysts to do the appropriate analysis within each scenario identified

10.41.4 PROCESS

Scenarios are the stories we tell about how a situation arises or is resolved in the future. A qualitative scenario is best described in a narrative similar to a newspaper article written about a specific future condition. Significantly, a scenario is different from the analysis that can be done within a scenario. Once a future, or other, scenario is defined, it can be constructed and analyzed in a wide variety of ways. Scenario analysis is the name given to the development of this broad array of stories about the future, descriptive models, and the analysis that can be done with them.

10.41.5 OUTPUTS

The outputs of a scenario analysis are important effects like decision criteria that have been analyzed and estimated for the various scenarios. For example, a specific risk estimate may be prepared for a number of different scenarios as was illustrated in [Table 10.10](#).

Monolithic scenario analysis (MSA) relies on the development of a single unchallenged scenario to describe an uncertain situation or future. A simple example would be to argue that EAD from flooding in the future will be \$35,000,000, the future with no risk mitigation. Relying on this one scenario denies the possibility of other future scenarios where the community may take action to reduce their flood damages.

Deterministic scenario analysis (DSA) defines and examines a limited number of discrete and specific scenarios. This tends to rely on a small number of possible future states of the system being modeled. For example, one might examine best case, worst case, and most likely future scenarios. A best-case future without risk mitigation could be \$30,000,000 (not shown) a worst case could be \$40,000,000 (not shown), with a most likely case of \$35,000,000.

Alternatively, more specific scenarios, like the levee and channel improvement scenarios of [Table 10.10](#), could be investigated. This approach has limitations too. Only a limited number of scenarios can be considered, and the likelihoods of these scenarios cannot be estimated with much confidence. This approach can prove inadequate for describing the full range of potential outcomes when there is considerable uncertainty about the effects of interest in these alternative futures.

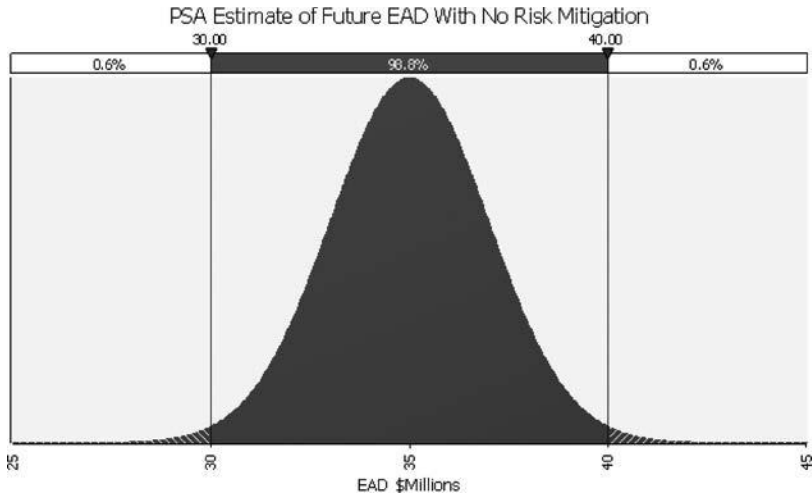


FIGURE 10.28 Probabilistic scenario analysis of expected annual damages in a future with no new risk mitigation for flooding.

Probabilistic scenario analysis (PSA) can overcome these limitations by combining probabilistic methods, for example the Monte Carlo process, with a scenario generation method like an event tree or a process model. [Figure 10.28](#) displays the results of a PSA estimate of expected annual damages obtained from a Monte Carlo simulation. The full range and likelihood of the various EAD outcomes in the future with no risk mitigation are shown.

Many quantitative risk assessment models could be considered PSAs. PSAs are useful for exploring the range of potential outcomes that may be encountered in the future. [Chapter 16](#) provides a detailed description of PSAs.

10.41.6 STRENGTHS AND WEAKNESSES

Strengths:

- DSA and PSA can take a range of possible scenarios into account
- Useful for exploring situations where there is little current knowledge on which to base predictions or where risks are being considered in the longer-term future, for example, sea level change
- Useful when the future can be dramatically different under varying sets of conditions

Weaknesses:

- Scenarios are sometimes unrealistic, and unrealistic results may not be recognized as such
- The availability of data and the ability of the analysts and decision makers to be able to develop realistic scenarios are the two most common constraints of this method

10.41.7 EXAMPLES OF USE

Scenario analysis is used extensively when there are specific aspects of a decision problem that are uncertain in the future. Food safety risk assessment makes extensive use of this tool. It is common to estimate the number of illnesses caused by a commodity-pathogen pair under existing conditions and then to reestimate the number of illnesses with a specific proposed risk management option in effect. Natural resources planning studies also make extensive use of scenario analysis. In fact, many risk assessments that rely on Monte Carlo methods are actually PSAs.

10.42 SCENARIO PLANNING

Useful for: Hazard identification Consequence assessment
 Likelihood assessment Risk characterization Uncertainty characterization
 Risk management options Other

10.42.1 OVERVIEW OF THE TECHNIQUE

Scenario planning is used when there are fundamentally and profoundly different possibilities in how an uncertain future can unfold. It is a process that developed in a planning context. The failure of traditional planning methods that tend to rely on a single description of the future, along with the growing emphasis on the need to address uncertainty in a more intentional manner, has given rise to the use of scenario planning in an increasing number of applications.

EXAMPLE: ECOSYSTEM RESTORATION

Consider an ecosystem restoration project where new legislation reducing phosphorous loading in the watershed has been passed. How does one forecast the future performance of the project when it is unknown how successful the law will be in reducing phosphorous loads and it is unknown whether the future will comprise relatively dry or relatively wet years?

These two uncertain variables create four rather distinct future scenarios: high phosphorous and wet years, low phosphorous and wet years, high phosphorous and dry years, and low phosphorous and dry years. Each of these is a significantly different future scenario.

The first use of scenarios in a planning context is thought to have been in the military strategy studies done by the RAND Corporation for the U.S. Government in the 1950s. The theoretical foundations of scenario forecasting, an important component of scenario planning, were principally developed in the 1970s. Royal Dutch Shell is regularly credited with popularizing and modernizing the use of scenario planning for strategic planning in the early 1970s (Wack 1985a,b). Scenario planning was developed into its current state during the second half of the twentieth century primarily in Europe.

10.42.2 HOW THE TECHNIQUE IS USED

A typical planning process compares the most likely alternative condition for the firm or the study area, whichever the case may be, without an RMO in place to the most likely alternative future condition with an RMO in place in order to estimate the effects of the RMO. This is repeated for each alternative RMO, and the results are used to decide which is the best RMO. Scenario planning would be used when there are a few uncertainty drivers that make it impossible to identify any one scenario as most representative of the future. It differs from scenario analysis in this regard.

Scenarios, in this context, are not predictions or variations around a theme as they are in scenario analysis. Neither are they alternative forecasts of a key variable or decision criterion. Scenarios are narratives that describe distinctly different plausible alternative views of the future. Once described, the analytical work required for decision making is completed consistent with the assumptions and framework of each scenario. Thus, scenario planning is to be used when a single without condition scenario cannot adequately characterize the potential shape of a very uncertain future. Or, it may be used when a single with condition cannot adequately characterize the effects of a specific RMO. Typically, this will occur when there exist one or more critical uncertain quantities or conditions that could alter the shape of the future in significantly different ways.

10.42.3 INPUTS

The inputs for scenario planning include:

- Well-articulated planning problem
- Need for alternative views of the future, that is, significant uncertainties that cannot be resolved in another way
- Planning team with knowledge of the scenario planning process

10.42.4 PROCESS

Scenario planning identifies key drivers of future uncertainty and uses them to produce a small number (usually two to four) of future scenarios, as seen in [Figure 10.29](#), where the different scenarios are given descriptive names. Runoff and phosphorous loading are the drivers in the example. Technical analyses are conducted under each of the alternative scenarios. Referring to the preceding text box example (Ecosystem Restoration), water quality analyses, for example, would be completed for each of the four phosphorous/runoff scenarios. The size of bird colonies could be drastically different under each of these scenarios because of water quality.

Ralston and Wilson (2006) describe the scenario planning process in 18 steps arranged in four major tasks as follows:

- I. Getting Started
 1. Develop case for scenarios
 2. Get executive support and participation
 3. Define decision focus
 4. Design process

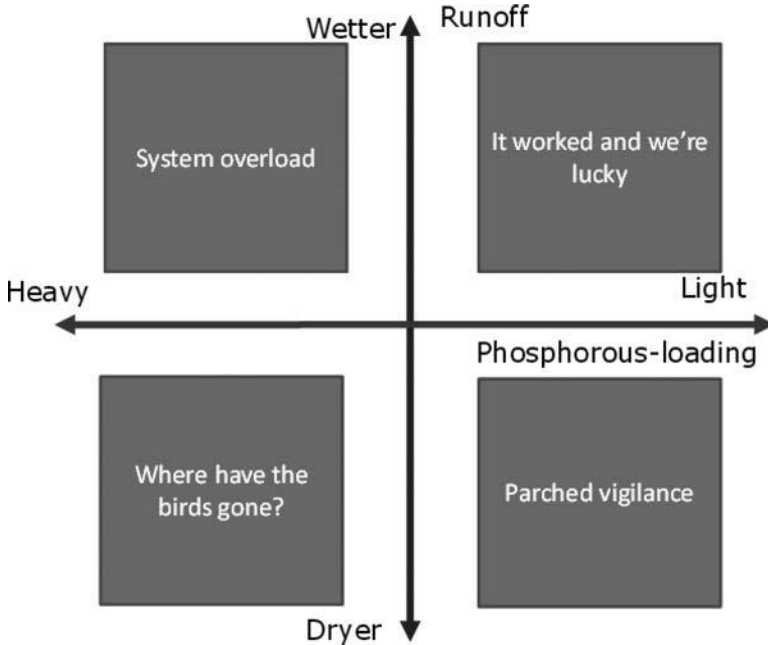


FIGURE 10.29 Four different scenarios considering runoff and phosphorous loading as the axes of uncertainty.

5. Select facilitator
6. Form scenario team
- II. Laying Environmental-Analysis Foundation
 7. Gather data and view
 8. ID key decision factors
 9. ID critical forces and drivers
 10. Conduct focused research on key issues, forces, and drivers
- III. Creating the Scenarios
 11. Assess importance and predictability/uncertainty of forces/drivers
 12. ID key axes of uncertainty
 13. Select scenario logics to cover uncertainties
 14. Write stories for scenarios
- IV. Moving from Scenarios to Decisions
 15. Rehearse future with scenarios
 16. Decision recommendations
 17. Identify signposts to monitor
 18. Communicate results

10.42.5 OUTPUTS

This scenario planning approach will typically result in the identification of one to three uncertainty drivers that will produce two to eight different scenarios.

“Newspaper article” narratives are written to describe each scenario. In the traditional practice of scenario planning, key effects and decision criteria would be quantified using the conditions for each scenario. These multiple analyses would more fully characterize the range of potential effects of a project so that more robust solutions could be identified. Scenario planning would, therefore, produce solutions that can be effective no matter which view of the future is ultimately realized.

10.42.6 STRENGTHS AND WEAKNESSES

Strengths:

- All involved in the planning process must challenge their own world views
- Exposes blind spots about existing uncertainties
- Analysts are better able to address the uncertainty in a risk management activity using these techniques or those described in the preceding chapter

Weaknesses:

- Effort required
- Technical complexity of conducting analyses under multiple sets of assumptions

10.42.7 EXAMPLES OF USE

Scenario planning has been used by Shell for more than four decades. It has been used extensively by European planning agencies and organizations. It is most useful for situations where key uncertainties could produce dramatically different views of the future.

10.43 SEMIQUANTITATIVE RISK ASSESSMENT EXAMPLE

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.43.1 OVERVIEW OF THE TECHNIQUE

Semiquantitative risk assessment modeling techniques are many and varied. Several have been described in this chapter. Any qualitative methods that make limited use of numerical estimates of risk can be called a semiquantitative assessment. Instead of using qualitative ratings, the technique produces semiquantitative estimates of risk that require careful interpretation.

10.43.2 HOW THE TECHNIQUE IS USED

Whereas many qualitative techniques rely on ordinal and narrative ratings and rankings with such scales as high, medium, low, or good, average, poor, and the like, some fundamentally qualitative techniques employ numbers instead of letters or nominal scales. Risk indices, in this chapter, provide a prime example of such a technique.

10.43.3 INPUTS

Inputs required for a semiquantitative risk assessment include:

- Well-defined risk(s) to be assessed
- Decomposition of the risk into component parts
- Evidence for the component parts
- Synthesis algorithm
- User interface

10.43.4 PROCESS

An example, adapted from the Ross and Sumner (2002) process, is used here. Consider a conceptual example focused on levee safety. With thousands of levees in the United States to consider it may be useful to first screen the levees using a semiquantitative method. Let us suppose the questions to be answered by this process are: Which nonfederal levees present the greatest potential risk to life and property? Which levees should be the first to be subjected to a complete technical risk assessment?

Using the “Risk = Consequence × Probability” model as a starting point, the challenge is to identify criteria that aid assessment of the probability of an unsatisfactory performance as well as an assessment of the consequences. Suppose the criteria and potential scenarios (or ratings) developed for this purpose are the following:

- A. How old is the levee?
 1. Unknown
 2. 10 years or under
 3. Over 10 and up to 25 years
 4. Over 25 and up to 50 years
- B. Who owns the levee?
 1. Unknown
 2. More than one owner
 3. Private levee
 4. State or local ownership
 5. Federal ownership
- C. How well is it maintained?
 1. Unknown
 2. Regular maintenance by known authority
 3. Periodic maintenance by known authority
 4. Irregular maintenance
 5. No maintenance
- D. Construction quality?
 1. Unknown
 2. State-of-the-art engineering design and construction
 3. Standard engineering design and construction
 4. Substandard design and construction

- E. Number of flows confined in the last ten years?
 1. Unknown
 2. None
 3. One
 4. Two or more
- F. Any known problems?
 1. Unknown
 2. Yes
 3. No

The above criteria capture the essence of the probability element. To capture the consequence, the following criteria are considered:

- G. How vulnerable is the population?
 1. Unknown
 2. Highly vulnerable (low income, elderly, low education, minority)
 3. Moderately vulnerable (housing close to levee, much housing in flood plain)
 4. Low vulnerability (housing removed from the levee, less housing in flood plain)
- H. How large is the population at risk?
 1. Unknown
 2. Less than 1,000
 3. 1,000 to 10,000
 4. 10,000 to 100,000
 5. 100,000 to 1,000,000
 6. Over 1,000,000

Evidence is gathered to rate each levee against each criterion. The selected answer for each criterion is converted to an order of magnitude.* The “riskiest” response for a criterion is rated a 1, the second riskiest 0.1, the third riskiest 0.01, etc. An unknown entry is rated a 0. The product of all eight entries is calculated. The range between the largest and smallest possible products is normalized over the [0,100] interval. The calculated product is interpolated from this range, and the normalized value is the levee's rating.

For example, consider the hypothetical levees in [Table 10.11](#). This is a semiquantitative method. Although the rating is numerical it has only ordinal qualities and remains qualitative in information content. A levee rated 75 is not more than twice as risky as a levee rated 35; it is merely riskier.

All the levees in the region can be assessed, and their semiquantitative ratings enable assessors to answer the risk manager's questions. The levees with the highest numerical ratings have the greatest risk potential. It is understood that this assessment proceeds under conditions of considerable uncertainty. When the very rudimentary data of this tool are not available the levee rating is zero, acknowledging that the levee

* The algorithm described here is adapted from the Ross and Sumner article. See it for a detailed description of the algorithm.

TABLE 10.11
Semiquantitative Risk Scores for Three Hypothetical Levees

		Risk Assessment Element						
A	B	C	D	E	F	G	H	Risk Score
2	3	3	4	3	2	3	4	45
5	4	2	2	4	3	4	4	35
5	2	5	4	4	2	2	2	75

cannot even be ranked. Presumably, such an assessment would highlight the need for additional data at some sites, while enabling risk managers to identify those levees that should be subjected to a more rigorous technical risk assessment first.

10.43.5 OUTPUTS

The output of this example is a clear ordinal ranking of the risks of the candidate levees. Ordinarily, a semiquantitative assessment will produce results suitable for ordering a set of risks or hazards.

10.43.6 STRENGTHS AND WEAKNESSES

Strengths:

- Produces a clear ranking of elements
- Evidence-based
- Transparent criteria
- Reproducible
- Answering questions is simple

Weaknesses:

- Simplifying questions can cause loss of critical detail
- Results can be misused if treated as cardinal in quality
- Lack of transparency in algorithm is possible
- Levels of discrimination may be low

10.43.7 EXAMPLES OF USE

The Ross and Sumner (2002) article provides an example assessment of viruses in oysters. A copy of the model used by Ross and Sumner is available at <http://www.foodsafetycentre.com.au/riskranger.php> (accessed March 29, 2018).

10.44 SENSITIVITY ANALYSIS

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.44.1 OVERVIEW OF THE TECHNIQUE

Sensitivity analysis is used to systematically investigate how the variation in a risk assessment output can be apportioned, qualitatively or quantitatively, to different sources of knowledge uncertainty and natural variability among the inputs. This may be accomplished by varying an assumption to see how a point estimate output responds to a change in the assumption, by sophisticated analysis of probabilistic outputs, or by any number of methods between these extremes. Some risk assessment outputs and the decisions that rely on them may be sensitive to minor changes in assumptions, scenarios, models, or inputs of all kinds. When this is the case it is critically important to convey that information to risk managers and other decision makers. Sensitivity analysis is treated at length in [Chapter 17](#).

10.44.2 HOW THE TECHNIQUE IS USED

Sensitivity analysis focuses the attention in a risk management activity on understanding the things that are not known and their importance for decision making. Sensitivity analysis is sometimes called “what if” analysis. It may be the single best way to increase both the assessor's and manager's confidence in the results of a risk assessment. It provides an understanding of how analytical outputs respond to changes in the inputs. Because risk assessments can be qualitative or quantitative, sensitivity analysis can likewise be qualitative or quantitative.

10.44.3 INPUTS

The essential inputs for a sensitivity analysis include:

- A completed risk assessment or other risk-informed analysis
- Awareness of the most significant sources of uncertainty
- One or more sensitivity analysis technique

10.44.4 PROCESS

Qualitative sensitivity analysis is used to identify the sources of uncertainty that exert the most influence on the risk assessment outputs. A basic methodology for qualitative sensitivity analysis includes:

- Identifying specific sources of uncertainty
- Ascertaining the sources of instrumental uncertainty
- Qualitatively characterizing the instrumental uncertainty

Making assumptions about uncertain values is one of the most common and expedient ways of addressing uncertainty. To the extent that assumptions are used to address uncertainty one should routinely test the sensitivity of assessment outputs to those assumptions. The simplest way to do this is to first construct a list of the key assumptions of the risk assessment. There are two kinds of assumptions, those

we know we make, that is, explicit assumptions, and those we do not know we are making, that is, implicit assumptions. Explicit assumptions should be identified and preserved for the attention of assessors and managers. Peer review by multidisciplinary reviewers is often needed to identify implicit assumptions that become embedded in the way that disciplines or organizations function.

Challenge each assumption. Do the outputs change? Do the answers to the risk manager's questions change? Can any of these changes affect the risk management decision? If so, that information needs to be conveyed to the risk managers.

There are four classes of quantitative sensitivity analysis tools. These are: scenarios, mathematical, statistical, and graphical analysis. Some of the more common tools from these groups include:

- Nominal range sensitivity (one-at-a-time analysis)
- Difference in log-odds ratio
- Break even analysis
- Automatic differentiation technique
- Regression analysis
- Analysis of variance
- Scatter plots
- Tornado plots
- Spider plots

The purpose of sensitivity analysis is to understand the uncertainties that could influence decisions and to develop appropriate strategies to address those uncertainties. An additional purpose may be to apportion output uncertainty to specific input uncertainties.

10.44.5 STRENGTHS AND WEAKNESSES

Strengths:

- Easy to run the sensitivity analysis
- Simple methods can reveal sensitivities that are useful to decision making
- Commercially developed software supports useful sensitivity analysis techniques

Weaknesses:

- Limited by the assessor's awareness of uncertainty
- Some tools are quite sophisticated and require quantitative skills that are not always found on staff

10.44.6 EXAMPLES OF USE

Sensitivity analysis has become an expectation of microbiological risk assessment in the food safety community. It is frequently, but by no means regularly, conducted for a wide variety of other kinds of risk assessments. Sensitivity analysis should be considered essential to best practice risk assessment.

10.45 STRUCTURED WHAT-IF TECHNIQUE (SWIFT)

Useful for*: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.45.1 OVERVIEW OF THE TECHNIQUE

The structured what-if technique (SWIFT) was originally designed for chemical and petrochemical plant hazard studies. It is a simpler alternative to a hazard operability study (HAZOP). Like HAZOP, it is a systematic, team-based assessment that relies on the use of a set of “prompt” phrases or “what-if” questions to stimulate the team to identify risks. This structured brainstorming technique is used to explore how a system, plant item, organization, or procedure will be affected by deviations from normal operations and behavior. More specifically, SWIFT is used to examine the consequences of changes in operations and the risks that can be altered or created by these changes. This makes it a useful tool for examining changes in the way things are done. SWIFT is applied at considerably less detail than a HAZOP.

10.45.2 HOW THE TECHNIQUE IS USED

This technique requires careful definition of the procedure, project, plant item, and/or change that is being investigated. The external and internal contexts of the proposed changes or deviations are usually established through interviews and the study of documents, plans, and drawings by the facilitator. Usually, the process or change is subdivided into its key elements. A successful process requires an experienced and expert study team of from four to 20 people.

10.45.3 INPUTS

The inputs required for a SWIFT include:

- List of prompt words or what-if questions
- Common understanding of the system or change and both its external and internal contexts
- Known risks and hazards
- Previous experience and incidents
- Known and existing controls and safeguards
- Regulatory requirements and constraints

10.45.4 PROCESS

This technique begins with an identified change or situation to be considered. The team identifies a set of what-if questions that will serve as prompt phrases. These

* The IEC (2008) is acknowledged as the primary source for the material in this section.

“what-if” phrases include: “what if...?”, “what would happen if...?”, “how could...?”, “could someone or something...?”, “has anyone or anything ever...?” and the like. These phrases are combined with prompt words that are either prepared in advance or that arise during the course of the discussion. These prompts are intended to help the team explore the causes, consequences, and likelihoods of potential risk scenarios. The team answers the what-if questions, recording the resulting potential risks identified. The team then can consider whether they have adequate controls in place, augmenting those instances where they do not with new risk management treatments.

Additional iterations of the what-if questions can be used to identify further risks until no new risks are identified. SWIFT may be combined with other risk ranking techniques to determine the priority of risks identified in the process.

10.45.5 OUTPUTS

The principle output of this process is a register with suggested risks that could result from the anticipated change and risk management treatments suitable for addressing them. These risk management options form the basis for a risk management plan.

10.45.6 STRENGTHS AND WEAKNESSES

Strengths:

- Wide application to many kinds of physical plant, systems, situations, circumstances, organizations, and activities
- Not data intensive
- Requires relatively little time to prepare
- Effective in identifying major hazards rapidly
- Helps identify opportunities for improving processes and systems
- Usable outputs

Weaknesses:

- Requires experienced and knowledgeable team members as well as an effective facilitator
- Preparation must be carefully undertaken
- Preparing a set of prompt phrases is a critical task
- Less than comprehensive prompt lists will not reveal complex or hidden risks

10.45.7 EXAMPLES OF USE

SWIFT is most likely to be used with engineering and infrastructure systems, but it may also be useful when examining any potential changes in the way things are done. SWIFT might be a useful first iteration tool to examine potential unintended consequences of changes in any aspect of a project’s lifecycle from planning through deauthorization. An example can be found in the *Handbook of Occupational Safety and Health*, Second Edition, edited by Lou Diberardinis, [Chapter 6](#), “Risk Assessment Techniques,” Thomas M. Dougherty, pp. 127–178, John Wiley and Sons, 1999.

10.46 SUBJECTIVE PROBABILITY ELICITATION

Useful for: Hazard identification Consequence assessment
 Likelihood assessment Risk characterization Uncertainty characterization
 Risk management options Other

10.46.1 OVERVIEW OF THE TECHNIQUE

Subjective probability elicitation can be considered a special case of expert elicitation where the specific purpose of the elicitation is to capture an expert's knowledge about the uncertain probability of some event. This topic is treated at length in [Chapter 14](#).

10.46.2 HOW THE TECHNIQUE IS USED

Probability is the language of uncertainty. The variability in the world can often be well described by frequency data when they are available. Knowledge uncertainty, however, is usually better described by the belief type of probability most often called subjective probability. Subjective probabilities are also useful for describing natural variability when data are insufficient for doing so.

Experts can be expected to vary in their judgments about the subjective probability of an event. Consequently, there are no "correct" subjective probabilities. The quality of a subjective probability estimate will always depend on the knowledge and experience a person has and the process used to elicit that information in a useful format.

Subjective probabilities are not preexisting numbers waiting within us to be revealed to the world. According to the subjectivist view, the probability of an event (including an event such as $P(X) > x$) is a measure of a person's degree of belief that it will occur. Thus, probability is not a property of the event but a property of the expert's judgment (Morgan and Henrion 1990). These are values that must be carefully constructed when needed and they are best constructed through a rigorous elicitation process. The elicitation technique matters because expert's statements of probability are likely made in response to the question asked rather than based on preanalyzed and preformed coherent beliefs. The purpose of elicitation is to represent the expert's knowledge and beliefs accurately in the form of a good probability distribution (O'Hagan et al. 2006).

A formal elicitation process is not necessary for every uncertain probability for which data are lacking. Uncertainties that occur routinely should be treated routinely. Much of the time these uncertain probabilities will be described using uniform, triangular, pert, or other nonparametric distributions for which the individual assessor will estimate the defining values.

A formal elicitation process should be used when a problem is complex, highly visible, involves a controversial issue, or trust in the analytical work is an issue. To develop useful elicitation procedures and to obtain useful probability estimates it helps to understand the

heuristics and rules of thumb experts use in forming judgments about uncertain quantities (Tversky and Kahneman 1974). Several of these heuristics are addressed in [Chapter 14](#).

10.46.3 INPUTS

The inputs to a subjective probability elicitation include:

- Well-defined elicitation problem
- Group of experts
- Expert facilitator
- Elicitation protocol

10.46.4 PROCESS

The process is somewhat variable; but once the problem, the experts, and the facilitator are identified, an elicitation protocol best describes the process. A five-step protocol for elicitation developed by O'Hagan et al. (2006) is summarized here:

- Background and preparation—the client identifies quantities to be elicited
- Identify and recruit experts
- Motivating and training the experts
- Structuring and decomposition—precisely define quantities to be elicited, explore dependencies and functional relationships
- Elicitation

10.46.5 OUTPUTS

The actual elicitation itself can vary but it is likely to be seeking one of three kinds of information: a point estimate of some sort, a probability distribution, or the parameters of a specific probability distribution.

10.46.6 STRENGTHS AND WEAKNESSES

Strengths:

- Can produce estimates of probabilities that are otherwise unavailable
- Rigor of the process can be adjusted to the needs of the assessment

Weaknesses:

- Experts are poorly calibrated and are well known to produce poor estimates of subjective probabilities absent training to offset the heuristics people rely on and calibration to help them recognize their bias
- Unacceptable nonrigorous protocols may be accepted

10.46.7 EXAMPLES OF USE

Cooke and Goossens (2008) summarize more than 67,000 expert subjective probability distributions from the following sectors: nuclear applications, chemical industry, gas

industry, groundwater, water pollution, dike ring, barriers, aerospace sector, space debris, aviation, occupational sector, health, banking, volcanos, dams, and other applications.

10.47 UNCERTAINTY DECISION RULES

Useful for: Hazard identification Consequence assessment
Likelihood assessment Risk characterization Uncertainty characterization
Risk management options Other

10.47.1 OVERVIEW OF THE TECHNIQUE

Risk managers must address uncertainty in their decision making, especially when the consequence of making a wrong decision is a concern. A number of decision rules have been developed for making decisions under uncertain conditions. Some of the more common ones include:

- Maximax criterion—choosing the option with the best upside payoff
- Maximin criterion—choosing the option with the best downside payoff
- Laplace criterion—choosing the option based on expected value payoff
- Hurwicz criterion—choosing an option based on a composite score derived from preference weights assigned to selected values, for example, the maximum and minimum
- Regret (minimax) criterion—choosing the option that minimizes the maximum regret associated with each option

This topic is treated at length in [Chapter 19](#).

10.47.2 HOW THE TECHNIQUE IS USED

These are rules that can be used in lieu of deterministic decision rules like choosing the option the boss favors. They are specifically suited to uncertain decision criteria, especially when there are alternative choices with alternate states of the world possible for each alternative.

10.47.3 INPUTS

The inputs required for uncertain decision rules include:

- Uncertainty estimates for the risk manager's decision criteria
- Alternative decision choices
- Knowledge of the mechanics of the rule used to address the decision uncertainty

10.47.4 PROCESS

Imagine that a new strategy for operating and maintaining a set of projects or systems is being considered and the accumulated present value of the difference in operation

TABLE 10.12
Hypothetical Savings for Three O&M Strategies
under Three Different Future States of the World

State of the World	Strategy 1	Strategy 2	Strategy 3
Pessimistic	−\$8,876,515	−\$12,451,560	−\$10,578,176
Most Likely	\$7,028,208	\$130,636	\$817,531
Optimistic	\$12,767,740	\$97,733,095	\$11,559,042

and maintenance (O&M) costs over a decade are summarized in [Table 10.12](#). A pessimistic view of the uncertain future will result in greater O&M expenditures while the most likely and optimistic view will produce net savings.

The maximin criterion chooses the alternative that yields the “best” of the worst outcomes. In this case, it maximizes the pessimistic outcome with strategy 1. The maximax criterion leads to the selection of strategy 2, the best of the maximum payoffs. The Laplace criterion appeals to the risk neutral and is based on expected values. Using equal weights for each state of the world, strategy 1’s expected value is \$3.6 million, strategy 2’s is \$28.2 million, and strategy 3’s is \$0.6 million, making strategy 2 the preferred approach.

The weighted payoff is defined:

$$\text{Hurwicz payoff} = \alpha(\text{maximum payoff}) + (1 - \alpha)(\text{minimum payoff})$$

If $\alpha = 0.4$, the Hurwicz payoffs of the three alternatives in millions are: −\$0.2 million, \$31.6 million, and \$2.7 million, making strategy 2 the preferred strategy.

The regret, or minimax, criterion is based on the economic concept of opportunity cost. Strategy 2 minimizes the maximum regret at \$6.9 million. This criterion is illustrated in [Chapter 19](#). Each of these rules produces a decision based on a defined set of preferences.

10.47.5 OUTPUTS

The outputs usually include a ranking of alternative solutions to the decision problem that includes the best option.

10.47.6 STRENGTHS AND WEAKNESSES

Strengths:

- Rules lead to a decision

Weaknesses:

- Rules rely on a limited amount of information when applied to a probabilistic risk assessment
- Rule choice is subjective and different rules can result in different decisions

10.47.7 EXAMPLES OF USE

These rules would most likely be used in situations where the risk manager exercises some discretion over decision making. They can be applied whenever decision criteria are uncertain.

10.48 VULNERABILITY ASSESSMENT

Useful for: Hazard identification Consequence assessment
 Likelihood assessment Risk characterization Uncertainty characterization
 Risk management options Other

10.48.1 OVERVIEW OF THE TECHNIQUE

Vulnerability assessment identifies a system's vulnerabilities to specific threats that could result in adverse consequences. These systems include, but are not limited to, information technology, energy supply, water supply, food supply, transportation, communication, infrastructure, and natural systems. In practical terms, a system may be defined as a facility or process. Threats have a broad spectrum and include natural, criminal, terrorist, and accidental threats against a given system.

10.48.2 HOW THE TECHNIQUE IS USED

Vulnerability implies the presence of a threat. Vulnerability assessment is used to identify elements of a system that are most vulnerable to the threat, so that vulnerability can be reduced through risk management measures. Since the events of 9/11, vulnerability assessment has tended to focus more frequently on terrorist threats. Consequently, vulnerability, as used here, means that a person intent on doing harm to others can recognize the desired target, gain access to it, complete the attack undetected, and withdraw from the target. One's vulnerability is enhanced if the attack has the desired effect and recovery is difficult. Note that vulnerability to other kinds of threats can be covered by vulnerability techniques.

10.48.3 INPUTS

Inputs required for a vulnerability assessment include:

- Well-defined system to be defended
- Well-defined threats to that system
- A vulnerability assessment team
- A vulnerability assessment methodology
- An intimate understanding of the system to be assessed

10.48.4 PROCESS

There are numerous vulnerability assessment techniques. The Department of Defense (DoD) has long used the CARVER method as an offensive target analysis tool. Since

9/11, it has become a very effective defensive tool for critical infrastructure protection known as CARVER + Shock (FDA, 2007). We will use it for an example.

CARVER is an acronym for the following six attributes used to evaluate the attractiveness of a target for attack:

- **Criticality**—measure of the adverse impacts of a successful attack
- **Accessibility**—ability of attacker to physically access and egress from target
- **Recuperability**—ability of the system to recover from an attack
- **Vulnerability**—ease of accomplishing attack once the target is accessed
- **Effect**—amount of direct loss from an attack as measured in appropriate units (lives lost, production lost, service disruption, and so on)
- **Recognizability**—ease of identifying the target

A seventh attribute, Shock, has been added to the original six to assess the combined health, economic, and psychological impacts of a successful attack on the target.

AN EXAMPLE OF CRITICALITY SCORING FOLLOWS

Criticality	Scale
>10,000 lives lost, damage >\$100 billion	9–10
1,000–10,000 lives lost, damages \$10–100 billion	7–8
100–1,000 lives lost, damages of \$1–10 billion	5–6
<100 lives lost, damages of \$0.1–1 billion	3–4
0 lives lost, damages < \$0.1 billion	1–2

The attractiveness of a specific target can be ranked for each of the seven attributes on a scale from 1 to 10 on the basis of scales developed for the specific vulnerability attribute. Conditions that are associated with lower attractiveness, or lower overall vulnerability, are assigned lower values (e.g., 1 or 2), whereas, conditions associated with higher attractiveness as a target, or higher overall vulnerability, are assigned higher values (e.g., 9 or 10). Once all seven elements of a target have been assessed, the total score is calculated and targets can then be ranked based on their individual vulnerability. The most vulnerable targets are then hardened to reduce their vulnerability.

The steps in a CARVER + Shock vulnerability assessment (FDA 2007) are summarized as follows:

- *Establish Parameters:* Answer the question of what you are trying to protect and from what you are trying to protect it.
- *Assemble Experts:* Convene a team of subject matter experts to conduct the assessment.
- *Detail System Assessed:* Develop a description of the system under evaluation including any subsystem, complexes, components, and nodes (its smaller structural parts) that could be a specific target.

- *Assign Scores*: Once the infrastructure has been broken down into its smallest parts, these are ranked or scored for each of the seven CARVER+Shock attributes to calculate an overall score for that node.
- *Apply What Has Been Learned*: Once the critical nodes of the system have been identified, develop a plan to put countermeasures in place that minimize the attractiveness of the nodes as targets.

10.48.5 OUTPUTS

After an assessment is completed, every potential target identified in the process will have an overall vulnerability score that can be used to identify targets that need to be hardened against attack.

10.48.6 STRENGTHS AND WEAKNESSES

Strengths:

- The CARVER + Shock method is a well-established and tested methodology
- Software tools have been developed to conduct these analyses for food production infrastructure
- Additional adaptations of such software tools are possible if warranted

Weaknesses:

- CARVER + Shock is based on the assumption that “good guys” can look at a system and see what “bad guys” see
- Vulnerability assessments are limited by their focus on known vulnerabilities

10.48.7 EXAMPLES OF USE

CARVER + Shock is used extensively in the food defense community by individual food producers and processors. The U.S. Food and Drug Administration provides an overview to the technique at <https://www.fda.gov/Food/FoodDefense/FoodDefensePrograms/ucm376791.htm> (accessed March 29, 2018).

10.49 SUMMARY AND LOOK FORWARD

This chapter briefly describes dozens of tools that are available to risk assessors. They include tools suitable for complete risk assessments as well as tools for specialized uses like hazard identification or likelihood assessment. The toolbox includes qualitative, semiquantitative, and quantitative tools, and it will continue to expand as new tools are developed and new communities of practice continue to practice risk analysis.

Risk assessment models make use of a great many of these tools. The next chapter presents a model building process that comprises thirteen steps. It is designed to help those new to the risk assessment process to build models. The chapter then turns its attention to a discussion of the skills required to build models in a spreadsheet

environment. This includes the technical skills that consists of the knowledge and proficiencies modelers must have and the craft skills that address the art and practice of modeling in that spreadsheet environment.

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11 The Art and Practice of Risk Assessment Modeling

11.1 INTRODUCTION

Quantitative risk assessment relies on models. A model is an abstraction of reality used to gain clarity about a problem or its solutions by reducing the variety and complexity of a situation to a level we can understand. This simplification enables us to gain insight into systems, processes, events, scenarios, problems, and their possible solutions. These insights can help us understand or control some aspect of a problem or opportunity. Models help us to address complex phenomena, force us to synthesize knowledge, and enable us to solve problems, test hypotheses, examine strategies, set priorities, and communicate all of this to others in a cost-effective and time-efficient manner.

It is not always easy to understand what people mean when they use the word “model.” Sometimes there are models within models and the language can be confusing. A risk assessment model, for example, may actually comprise a consequence model, a likelihood model, and a risk characterization model along with numerous computational components. So, a model could be the entirety of all these parts or any one of the component parts. “Probability model,” right or wrong, is a phrase often used to describe a probability distribution used in a Monte Carlo simulation. So, in this chapter, *model* refers to the overarching representation of a process, that is, the whole of the risk assessment model rather than its component parts. The parts that comprise a model are called modules or components. The content of this chapter applies to these as well.

Risk assessment models have many practical uses and yield a number of important benefits in addition to those mentioned previously. A valid model accurately represents the relevant characteristics of the decision problem. Valid models are a relatively inexpensive way to learn about the potential effects of uncertainty. Uncertainty often ensures that important data will not become available until some point in the future. Risk assessment is designed to address such uncertainty, and its models help bridge the gap between what we know and what we do not know in a way that aids timely decision making. These models enable us to explore more or less desirable futures from the present. They also help us explore the effectiveness of things that are currently impossible to do in reality. We use them to understand failure scenarios that have not occurred and improvement scenarios that have not been implemented. Assessing the risk of risk management option (RMO) failure modes (levee failures,

nuclear accidents, financial collapses, oil spills, and other catastrophic incidents) affords us the opportunity to anticipate future risks. Models empower us to examine the likely efficacy of these measures before they are actually implemented.

A wide variety of model types are available for use by risk assessors, and this chapter begins by discussing some of them. The chapter then narrows its focus to mathematical simulation models built in a spreadsheet environment. This is one of the easiest model building environments in which one can work. A 13-step model-building process is offered to help guide the efforts of novice model builders. The remainder of the chapter is devoted to a discussion of model-building skills. These skills are broken into technical skills and craft skills. Technical skills might be likened to the science of modeling while craft skills are more like the art and practice of modeling.

11.2 TYPES OF MODELS

There are many ways to discuss and categorize models. The most common models are mental, visual, physical, mathematical, and spreadsheet models (Powell and Baker 2007). Mental models are conceptual notions and ideas about how things work in reality. They are internal representations of external realities, that is, mental images translated to verbal or written descriptions. Mental models are abstract models. The risk management and risk assessment models of [Chapters 3 and 4](#) are good examples of mental models. Many of these models tend to be informal or conceptual frameworks, although well-worked-out formal theories can be mental models as well.

Visual models include maps, figures, graphics, and charts that show how things work in reality or how ideas are related to one another. When coaches draw plays on the sidelines, they are using visual models. When someone gets up at a meeting and goes to the whiteboard and begins to sketch the ideas being discussed, they are using visual models.

Physical models are usually analog or iconic models. Analog models look like the reality they represent. Cockpit simulators are used to train airline pilots, bridge simulators to train ship captains and pilots. Working in replicas of the planes and ships they will command, pilots can practice a wide variety of situations and circumstances. Analog simulators of all types are becoming more common. Model engines used in shop classes and models of human body parts used in doctors' offices are examples of other kinds of analog models.

Iconic models are scaled-down replicas of the object, system, or process under study. They have been used to design cars, buildings, and new pieces of equipment. Master planners rely on iconic models to communicate their visions. Beach cross sections can be designed and tested in a wave tank before beach nourishment projects are built. The plastic models we built as children are additional examples. In the not-too-distant past, iconic models of watersheds were quite common.

There is also a class of models intended to represent a critical or interesting physical dimension of reality or to give a physical dimension to an abstract concept without replicating it or scaling it down. Examples include models of DNA molecules and models of three-dimensional mathematical functions like the utility functions of economics.

There are many kinds of mathematical models, and they are used in every area of scientific endeavor. Mathematical models generally rely on functional relationships among dependent and independent variables. Every quantitative risk assessment model is a mathematical model. Their basic characteristic is that they use mathematics to describe a system, situation, object, or problem. Mathematical models can be categorized as prescriptive, predictive, or descriptive models (Ragsdale 2001).

A prescriptive model produces the best value for a dependent variable. Examples of prescriptive models include things like linear, integer, and nonlinear programming models, networks, and so on, that can be optimized. They prescribe the most unambiguous course of action for the risk manager when they are available.

Predictive models predict the value of a dependent variable based on the specific values of the independent variables. When the functional form of the relationship between the dependent and independent variables is known, we often have prescriptive models. When that functional form is unknown and has to be estimated, we have predictive models. Many risk assessment models are predictive models. Such models are used to route flood waters and to anticipate hurricane tracks, to estimate pathogen growth, as well as to predict the performance of markets and other complex systems. Examples of predictive models include regression and time-series analysis.

The third category of models, descriptive models, may be the most common in risk assessment. These models are characterized by their uncertainty. That uncertainty may include uncertainty about the functional form of a relationship or, when very precise functions are known, they may include uncertainty about the exact values of one or more independent variables. These kinds of models describe the range of outcomes or behaviors that are possible in a system that is plagued by uncertainty. Simulations, queuing, and inventory models are examples of descriptive models.

Mathematical models can also be described in accordance with the family tree of system models seen in Figure 11.1. A deterministic model has no stochastic, that is, random, components. Thus, the next state of the system is always determined by predictable actions built into the model. In a static model, time is not a significant variable, that is, the data do not “age.” The passage of time is a significant consideration

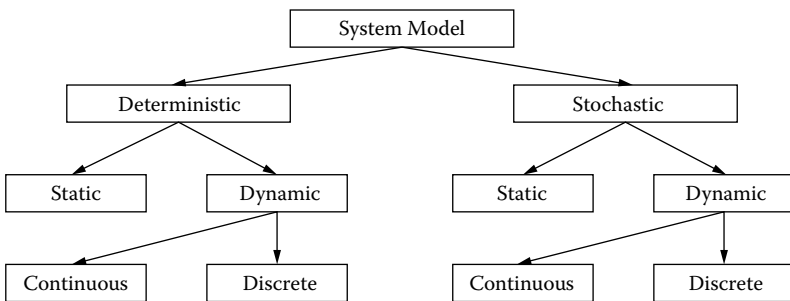


FIGURE 11.1 A taxonomy of model types.

in a dynamic model. Dynamic models often offer an explicit representation of the sequence in which events occur. Continuous dynamic models involve states that evolve continuously. They often rely on differential equations. In contrast, discrete dynamic models produce states that are a piecewise constant function of time. A discrete model may evolve a new state every 15 minutes, every day, or annually, whereas a continuous model is continuously evolving new states. The same kinds of models are found in the stochastic universe, where risk assessors deal with random components in the systems they model.

Simulation models, the focus of this chapter, are a subset of mathematical models that can exhibit any of the characteristics of the family tree of system models in [Figure 11.1](#). Monte Carlo simulation models built in the spreadsheet environment enable us to explore the stochastic branch of models and will occupy most of our attention, but there are many more complex system simulation models in use that are worth a brief discussion. Evans and Olson (2002) identify four such simulation modeling approaches.

Many of these system models involve the flow of some entity or object through a system. The entity might be an attribute (purity, resistance, strength), a condition (new, fresh, complete), a piece of information (message, order, profile), or a physical object (an egg, a towboat, a human being, a pathogen). System simulation models reproduce the most important activities and dependencies that control the flow of one or more entities through a system over time. These sorts of models tend to be too complex for a spreadsheet.

Activity-scanning simulations describe the activities that occur during fixed time intervals. The model is incremented by some fixed time period and it describes the activities of interest that occurred during that time period. For example, the model will describe what happens in the first time period and then advance to the next time period and continue the process. If we model the movement of towboats on a waterway, this would include all the activities that occur within a given time increment such as distances traveled and positions, traffic maneuvers, and dockside operations. If our model follows eggs from laying to consumption, it might represent what activities occur in the first 24 hours, followed by the activities in the second 24 hours, and so on. If we are monitoring bacteria in an egg, it might describe all the physical activities that occur within the egg at fixed time intervals that offset bacterial growth in an egg.

Process-driven simulation models focus on the process an entity must move through in a system. So, for example, if we're concerned about how an egg gets from the farm to a store, the process could be described and modeled as follows:

Egg forms→laid→transported to collection→collected→transported to processing→washed→graded→separated→transported to packaging→placed in carton→palletized→shipped to retail→received→stored

If we think in terms of discrete modules, this sort of model would use modules corresponding to the parts of the process rather than modules defined as increments of time. So, we could examine what happens in the washing process or the shipment to retail outlets.

Another type of simulation model is called event-driven. Events are occurrences in a system at which point changes in the system (or entity under consideration) occur. These events take place at a moment in time. Events are processed in chronological order, and time is advanced from one event to the next. These models focus on events that change the system, and so they are often computationally efficient. This kind of model describes changes in the system that occur at the instant an event occurs. For our egg example, contamination of the egg in utero, breakdown of the yolk membrane, and cooling on the pallet are events of potential interest that can change the egg entity from risk free to risky when assessing the risk of Salmonella in shell eggs. If we are modeling towboats, the risky events of interest might include traffic maneuvers when meeting, passing, or overtaking other vessels in the waterway or perhaps when navigating difficult turns.

When variables of interest change continuously over time, continuous simulation is appropriate. The amount of money moving through an economy, water in a stream, oil in a pipeline, or milk in a production run are all examples of continuous variables. These continuous variables are frequently called state variables. Continuous simulations rely on equations defining relationships among state variables that enable dynamic system behavior to be studied. System dynamics is a popular form of continuous simulation.

Simulation is a legitimate technique for solving problems when analytical solutions are not possible. Whereas analytical models represent reality, simulation models imitate it in a simplified manner. Simulation models allow us to conduct controlled experimentation that is otherwise impossible. Simulations can produce information that reveals new facts about the problems we work on. They are suitable for a broad range of applications and can be effective training tools.

Building models generates insight that enables us to make better decisions. Modeling improves our thinking about and understanding of a problem, and it enables us to experiment and learn about it as well. As this discussion suggests, a wide range of simulation modeling options is available. Spreadsheet models are an especially useful platform for building risk assessment models because they require no special programming language skills or abilities. These spreadsheet models are the focus of the remainder of this chapter.

11.3 A MODEL-BUILDING PROCESS

There is no one way to build a mathematical spreadsheet model for risk assessment. Modeling may be the most idiosyncratic part of the risk assessment process. Nonetheless, it can be useful to have a process in mind. The model-building process presented in this section has served me reasonably well over the years; feel free to adopt or adapt it. It assumes your data have already been collected or will be collected once step 4 is completed. Thus, data collection is not an explicit step in this process. The 13 steps in this process include:

1. Get the question right
2. Know the uses of your model
3. Build a conceptual model

4. Specify the model
5. Build a computational model
6. Verify the model
7. Validate the model
8. Design simulation experiments
9. Make production runs
10. Analyze simulation results
11. Organize and present results
12. Answer the question
13. Document the model and results

11.3.1 GET THE QUESTION RIGHT

Know what information the model needs to produce. If the risk management questions are not clear or if they are not the right questions, then nothing that follows in the model-building process will make any difference at all.

Different questions can lead to very different models. Consider the following questions that relate to a food-safety concern with *Vibrio parahaemolyticus* (*Vp*) and oysters. How many people get sick from *Vp* in oysters? What is the probability of getting sick from eating a raw oyster? How effective would refrigeration of oysters within 60 minutes of harvest be in reducing illness from *Vp* in oysters? What is the risk of eating raw oysters to people with liver disease?

Each of these questions will require different data and a different model structure. Get the right question, then get the question right. The first step in developing any model is understanding what question(s) the model needs to be able to answer. Be sure to discuss and clarify the meaning and intent of each and every question with the risk managers before you begin to build your model.

11.3.2 KNOW THE USES OF YOUR MODEL

Understand what the model is expected to do and how it will be used. Is the model identifying research needs, developing a baseline risk estimate, attributing risk to different hazards? Will it be used to evaluate risk management options? What kinds of options might they be? Is it a learning tool? Will it be shared with others or used again? Who will use it? Will it be added to over time, or is it to be completed once and for all? Is it the basis for a regulation?

Understand what the model cannot do. Risk managers, in particular, must be made aware of the limitations of the model and its outputs. The seemingly innocent request to evaluate an unanticipated RMO after a model is built may be impossible because the necessary data were not collected or the model structure does not support that analysis.

Anticipate as many potential uses of the model before you begin to build it as possible. This can only be done through close collaboration and clear communication between risk managers and risk assessors.

11.3.3 BUILD A CONCEPTUAL MODEL

This is where your model-building effort is most likely to succeed or fail. Models fail less often due to data and parameter value issues than they do for faulty conceptualization of the problem to be represented. This step proceeds from the abstraction of ideas and notions to the cold, hard reality of details. The best modelers will include the important processes and exclude unimportant ones. This step calls on both science and art.

You now have specific questions to answer. Work out your risk hypothesis for each question before you begin to build a model. Develop your risk narrative. That narrative should answer the four questions:

1. What can go wrong?
2. How can it happen?
3. What are the consequences?
4. How likely is it?

Use the qualitative generic process if it fits your problem better than the four questions do. Be practical, not bound to any one approach. This is the step where you work out the major ideas for your model. What are the stated variables? How are they related to one another? The conceptual model is a mental model. A sample for a pest outbreak associated with a fruit import is shown in [Figure 11.2](#).

11.3.4 SPECIFY THE MODEL

Once the conceptual model has been developed it is time to convert it into a specification model. This means moving from concepts to develop the relationships, equations, and algorithms that will describe the ways the various components of your conceptual model will work together. This is the model construction step that usually stops short of actually building the final computer program. It may help to think of it as the paper and pencil exercise of figuring out the calculations that will be needed in your model. It is more than this, but that provides a good mental image of the essence of this task.

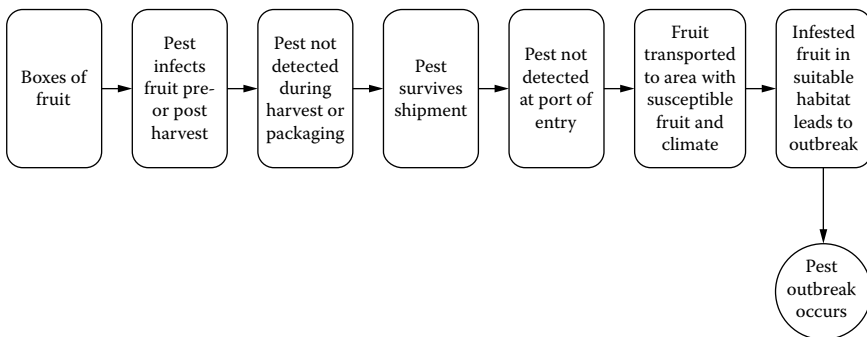


FIGURE 11.2 Conceptual model for fruit import pest infestation risk.

Parameter specification from minimal to maximal precision:

- Guesstimates (“hand waving”)
- Expert opinion
- Bounded estimate
- Survey-based data
- Data-based parameters (averages, etc.)
- Curve-fit parameters (trade-offs)
- Parameter sensitivity testing
- Entire parameter sets by optimization

Source: Risk Analysis 101 USDA, APHIS, PPQ.

The functional form of all relationships as well as the model logic are built in this step. Placeholders and dummy values can be used in lieu of data. The specification model defines the calculations, logic, and other inner workings that will make the model run. It often includes a detailed sketch of the spreadsheet model. In the current example of [Figure 11.2](#), this will concern such things as the mathematical process that determines how many boxes of fruit are imported, how we identify which are infected with pests, how we calculate the percentage of the pests that avoid detection and survive transit, and so on.

11.3.5 BUILD A COMPUTATIONAL MODEL

If we think of the specification model as the skeleton, then the computational model puts flesh on the bones. In this step you complete the computer program needed to run the model you have specified and analyzed and organized the data you will need to make the model operational. The output of this step is a fully functional spreadsheet model.

Placeholders are replaced with real data. Dummy values may be replaced by probability distributions. At this point you have a working risk assessment model. You will learn how to choose probability distributions to represent knowledge uncertainty and natural variability in [Chapter 13](#). For now, we focus on the steps required to build a model rather than on the details.

11.3.6 VERIFY THE MODEL

Verification is an extremely important separate and formal step in the model-building process. You want to get the equations, calculations, logic, cell references, and all the details just right. This is when you ensure that your computational model is consistent with the specification model and that the specification model is correct. You want to make certain that you have built your model correctly. So, you debug, review, and test your model to ensure that the conceptual model and its solution are implemented correctly and that the model works as it was intended to work.

Many model builders verify their own work. The obvious advantage of this approach is their intimate knowledge of the model's structure. The disadvantage is that they have often been working with the model for so long they can no longer see potential problems. Having a model verified by someone other than its builder(s) can be time consuming and more costly, but it is often more effective in finding flaws. It is certainly more effective in increasing the credibility of the model and confidence in its outputs.

11.3.7 VALIDATE THE MODEL

Once your model is verified to ensure that it does what you want it to do in the way you want it done, it is time to validate your model. Is it a good representation of reality? Have you built a model that represents reality closely enough to provide valid information to support decision making? The weakest form of model validation is a model that accurately describes the system being modeled. Next, we ask if the model produces plausible results by considering whether the model can reproduce independent results like statistics or real data.

There are basically three ways to validate your model. You can validate model outputs, model inputs, or your modeling process. Historical data validity uses historical inputs to see if your model reproduces historical outputs. If weather conditions that always produced rain in reality produce sunny days in your model, you have a problem. There are at least two practical issues with this form of validation in risk assessment.

The first, and most pressing for risk assessment, is the lack of historical data. You must hold back some of your data and not use it in the model-building process to use it to validate your model. A common technique is to divide the available data. Part of the data, say half, is used to build the model and develop all the requisite relationships in the model. The other half is used to test the model. If actual data are input into the model, we expect to get predictions that closely match the actual output data from a valid model. Risk analysis is a decision-making paradigm designed for conditions of uncertainty. Consequently, data gaps and insufficient information frequently make historical data validation impossible. Frequently there are not sufficient data for confidently building a model, much less enough to hold some back.

A second problem is how closely a model must replicate historical conditions. If you are fortunate enough to have the data, how many rainy days must your model replicate for us to declare it valid? The answer to that question is most often a pragmatic one rather than a statistically rigorous one, a matter of art more than of science.

A second validation approach is data validity. When the outputs cannot be validated, it may help to validate the inputs. Data validity means you have clean, correct, and useful data. Furthermore, it ensures that all input data and probability distributions are truly representative of the system modeled. When simulating situations that have never existed, it is often impossible to assure data validity.

When neither the inputs nor the outputs can be validated we have few options but to try to validate the reasonableness of the process. Face validity, the third option, asks experts to examine the model or its results to determine if they are reasonable. A model has face validity when it looks like it will do what it is supposed to do in a way

that accurately represents reality. One face validity test is to present knowledgeable experts with real-world data and model output data. If they cannot distinguish the two or find no significant divergence between the two, the model that produced the data may be considered valid on the face of its output data. However, a model that looks like it should work is quite different from a model that has been shown to work.

Validation can be checked at several levels. For instance, each module in a model should be validated. In a microbiological risk assessment, for example, it may be possible to validate a pathogen growth model or a dose-response curve even though the entire model cannot be validated. It may be advisable to validate components of some of the modules. A probability distribution chosen to represent a variable value within a module might be validated, for example. Of course, the whole-system level, that is, the entire model, should be validated as should any benchmark cases. Graphical comparisons, confidence intervals, statistical tests, and hypothesis tests can be useful validation tools to help determine whether model predictions are within an acceptable range of precision.

Verification and validation, together, provide the basis for the assessors' degree of confidence in the model. Risk managers should always inquire after the specific steps taken to verify and validate the model. Risk assessors should always inform risk managers about the verification and validation effort and its results. Some organizations use a model certification process to address questions of model verification and validity for models to be adopted for use throughout the organization.

11.3.8 DESIGN SIMULATION EXPERIMENTS

Characterizing the range of outcomes in an uncertain world is not a simple thing to do. There are often many scenarios to investigate. Assessors may be asked to explore historical conditions, existing conditions, a benchmarked baseline condition, future conditions, improved conditions, worst case, best case, different geographic locales, different seasons, and so on. Consequently, the assessor must carefully plan the simulation experiments that must be run to answer the risk manager's questions and to fulfill the intended uses of the model. This means deciding what parameters and inputs will vary, what assumptions will be used for which experiments, and so on.

If you sit down with your model and just start making runs, it is likely that, sooner or later, you will get what you need. It is also likely you'll waste a lot of time making runs you did not need. Carefully identifying the various conditions for the simulations you want to run is essential to an efficient risk assessment process. Arrange your series of experiments efficiently. It may make sense to do them in a specific order if significant adjustments must be made to your model for different conditions. Write down the runs you will do in the order you will do them. Take care to verify all alterations to a model and save significantly different versions of your model as separate files.

11.3.9 MAKE PRODUCTION RUNS

This could easily be an extension of the preceding step. Once you have identified the range of experiments you want to run, the next step is to run them. It is very easy to

fall prey to the excitement of running your model as soon as it is built. Many assessors skip over the verification, validation, and experiment design steps. You have likely spent a good bit of time and effort to get to the point of a computational model, and you want to use it. Unfortunately, few if any models are error free. If you make a slew of runs with your model and then find a decimal point error in the formula, everything must be repeated. Resist the temptation to jump directly to production runs.

One of the most frustrating, common, and avoidable problems is failure to document a production run. Every time you run your model you should carefully record the nature and purpose of the run (e.g., existing risk estimate to establish a baseline measure of the risk) and make note of your model's initial conditions, input parameters, outputs, date, the analysts, and so on. Enter this information into a log you keep on a separate worksheet in your model. Keep it up to date.

It can also help to be systematic in making your runs. For instance, using our current example, if we are investigating pest establishment risks for several fruits, several countries of origin, and several pests, it makes a lot of common sense to work smart. If setting up the model for a specific commodity takes time, it may make sense to do all the runs for avocados before moving to the peaches. On the other hand, if it takes more effort to set up the pest or country parameters, it may make sense to sequence the runs in another fashion. This is why you design your experiments so that you can run them efficiently.

It is especially important to take great care when making runs that reflect the presence of a new risk management option. These runs need to be carefully documented. It may also be important to record any fixed seeds* that were used to initiate your simulation process in case there is a desire to reproduce the simulation at a future date.

Take special care to save all outputs from a production run and to carefully identify them. Unless you are absolutely sure about the outputs you will and will not need to complete your risk assessment, save all of your simulation outputs if possible. It is far better to save outputs you will never need than to need outputs you never saved.

11.3.10 ANALYZE SIMULATION RESULTS

This is the all-important process of getting useful information from data. As the runs are completed, the assessors need to analyze the results and learn what the simulations have taught us about the problem. This analysis is statistical in nature, and it needs to account for the uncertainty in the inputs and to carefully convey that and the resulting uncertainty in the outputs to the risk manager. It is through the analysis of your simulation results that you will craft answers to the risk manager's questions, always taking care to characterize the remaining uncertainty in useful and informative ways.

11.3.11 ORGANIZE AND PRESENT RESULTS

The information assessors glean from the simulations needs to be organized and presented to decision makers in a form that is useful. At this stage of the modeling

* Seeds are explained in [Chapter 15](#) and [Appendix A](#).

process, useful information is information that supports decision making and carefully addresses the significant uncertainties encountered. Presenting useful information for decision making is the topic of [Chapter 18](#).

11.3.12 ANSWER THE QUESTION(S)

The entire reason for doing a risk assessment as well as for building an assessment model is to provide risk managers with the specific information they need to make a decision. Be sure you answer the questions. Do it in a question-and-answer format. Do not assume that your well-organized and well-presented report narrative and results will accomplish this purpose. Answer each question specifically. To the extent that lingering uncertainty affects those answers, this must be carefully portrayed as well. Once you have adequately answered the questions, feel free to summarize the insights you have gained, offer specific observations, and even to conjecture in a responsible way.

11.3.13 DOCUMENT MODEL AND RESULTS

Many risk assessments are going to be documented by some kind of report. Printed risk assessments are as common as crows. Careful documentation of your results is assumed to be an essential part of your model-building process. Few would disagree with that statement. However, there is more that needs to be done.

You need to document your model. That means explaining the structure of the model, including relevant descriptions of the preceding steps, your conceptual and specification models, the source and quality of your data, the results of the verification and validation efforts, as well as the history of production runs. And that is not all of it! You also need to provide the equivalent of a user's manual in your documentation.

You have likely spent so much time on this risk assessment model that your inbox is piled high with tasks that all had to be done yesterday. There may be no time to document your model, but you intend to do so the first chance you get. Alternatively, you are sick of living with the model; you know it inside and out; and you can't stand to spend another minute dealing with it. Both of these scenarios pretty much ensure that your model will never get documented. That could be a problem.

As familiar as you are with the model today, in six months' time there is a good chance it will look like someone else's work to you. Inevitably there will be questions you are asked to answer, and it will take 10 times longer than it would have had you documented your model.

Then consider what happens if the model builder gets hit by a bus or changes jobs? With the builder goes all of the organization's model expertise unless someone has carefully documented the model and how it works. As much of a pain that it is to document your model, you cannot afford not to.

11.4 SIMULATION MODELS

Simulation is the process of building a model of a system or a decision problem and experimenting with the model to obtain insight in to the system's behavior or to assist

in solving the decision problem. This can be done with physical models. Do you recall the coin-operated mechanical horse of your youth that sat outside the mall? That was a physical simulation model. Physical simulation models have grown increasingly sophisticated and are now used for all sorts of training and testing.

Simulation models are often used in training exercises. Food companies hold simulated recall exercises; first responders use simulated emergency exercises for training. Everyone has participated at one point in time in the fire drill, another simulation model exercise. These simulations are valuable training tools in situations where it is prohibitively expensive or too dangerous to allow trainees to use the real equipment in real situations. Tabletop exercises provide another form of simulation training that enables decision makers to learn valuable lessons in a safe virtual environment.

While risk analysis can make effective use of these kinds of simulation models, the most common simulation models and the focus of this chapter are computer simulation models. Computer simulations are used to model actual or hypothetical situations on a computer so that they can be studied to see how the system works. By changing variables and other model inputs, predictions may be made about how the system will behave under a wide variety of circumstances/scenarios.

Simulation models have been used for modeling the function of natural systems (flood, drought, hurricane tracking, ecosystems) and human systems (traffic flow, transportation systems, engineering, economics, the social sciences). They are used in all the natural sciences and have been used to model processes of all kinds. Clearly, analytical solutions to problems are preferred and should be sought when they exist. Computer simulations arose as an adjunct to, or substitute for, modeling systems for which closed-form analytic solutions do not exist. Simulation models are able to generate a number of representative scenarios describing the possible behavior of a system when it is either impossible or impractical to consider the entire range of possible scenarios.

Simulation models are most helpful when problems exhibit significant uncertainty, a situation commonly characterizing most risk assessment problems. Monte Carlo simulation tends to be used in static models, while systems simulation (described previously) are used more often in dynamic models. The Monte Carlo process, a sampling experiment designed to estimate the distributions of outcome variables that depend on one or more probabilistic input variables, is described in detail in [Chapter 15](#).

Simulation is a legitimate technique for solving problems when analytical solutions are not possible. They have a broad range of applications and, in risk assessment, are often constructed in a patchwork style, that is, a hazard module may be built first, followed by an exposure/likelihood module and a hazard characterization/consequence module. These may all be pulled together subsequently in a risk characterization module. Readily available commercial software makes simulation modeling easy to do.

Simulations are not without their downside. The larger models can be costly or time consuming to build and run. Powerful computers may be needed for the largest simulations. Model results are very sensitive to model formulation, and there is no guarantee of an optimal solution being identified from the results.

Perhaps the greatest disadvantage of simulation modeling is that it has become so easy to do. It is tempting, when faced with a problem, to sit before the computer

and start to build a simulation model. Too often this is easier than thinking the problem through and possibly finding an analytical solution to a problem. The ease of simulation modeling can encourage overlooking other techniques.

11.5 REQUIRED SKILL SETS

Building a good risk assessment model requires a special skill set. Powell and Baker (2007) have proposed breaking this skill set into technical skills and craft skills. Their distinction is a useful one and one I will build on in the remainder of this chapter. Technical skills are necessary for getting the right answer. Getting the right answer is important, in case you had not guessed that! Craft skills are extremely useful for simplifying complex problems and for modeling in new and poorly structured situations. Craft skills represent the creative side of modeling. Both skill sets are invaluable.

The discussion that follows is generally applicable, but there is a wide range in the formality with which risk analysis is conducted. In a regulatory setting, the risk analysis process and the risk assessment in particular may be quite formal. In a large organization where risk analysis has penetrated the culture, it may be practiced less formally in branches, sections, teams, and even by individuals. Some readers will find some of the ideas that follow useful; others may find them less so. For example, if you address the knowledge uncertainty and natural variability in a model used only by you because it makes sense to do so, you may not feel it necessary to design your model to communicate effectively with others. Feel free to take what is useful from the sections that follow and leave the rest. Modeling is an art, and ultimately each artist must develop their own style.

11.5.1 TECHNICAL SKILLS

Technical modeling skills comprise the knowledge and proficiencies required to build a specific risk assessment model. These are the skills that get you to a right answer. No one person may possess all the necessary technical skills for a complex risk assessment, but all those skills must be present on the assessment team.

First, technical skills require the modeler to know or to be able to understand the relevant science represented in the model. This does not mean the modeler must be a microbiologist to build a food-safety model or a civil engineer to build an engineering-reliability model. It does mean that discipline-specific knowledge must be present and available and that the modeler must be capable of translating that knowledge into a workable and reasonable model structure.

Second, there is the technology knowledge that is required. R, Unix, Linux, Java, C++, Perl, MySQL, Microsoft C, and other language skills may be required for some models. In this book, we will focus on spreadsheet models, so it is sufficient to have knowledge of Microsoft Excel or a similar spreadsheet program. If additional software tools, for example, Palisade's @RISK, used in this text, are used, the modeler must be proficient in their use as well. (An introduction to the use of several modules of Palisade's DecisionTools® Suite is found in Appendix A.)

Third, there is a wide variety of narrow, well-defined tasks the modeler must be able to carry out. There are techniques and methodologies for all sorts of calculations

that may not belong to any one discipline. These include basic math and language skills, for example, as well as more specialized skills. For economic and financial models, this could include handling present-value calculations. For engineering models, it might include working with a reliability beta index model, a hazard function, or a fragility curve. For food-safety models, this task might be constructing or programming a dose-response curve. These skills also tend to be discipline based.

A good risk assessment team will have all these technical skills available. It is not uncommon for a risk assessment model builder to come from a quantitative disciplinary background that may be quite different from that of the problem's context. The technical skills of risk assessment model building remain one of the scarcer resources in risk analysis. When the requisite skills are spread across many people, frequent team interaction and effective communication are essential.

11.5.2 CRAFT SKILLS

This discussion of craft skills has some general applicability, but it is intended primarily for those who work in the spreadsheet environment. Craft skills are separated into two topical areas for presentation here: the art of modeling and the practice of modeling, as this chapter title suggests. The discussion that follows attempts to flesh out the 13-step process presented previously with some art and practice tips.

11.5.2.1 The Art of Modeling

Powell and Baker (2007) offer eight modeling heuristics that are simply too good for anyone to ignore. They form the basis for this discussion of the art of modeling as supplemented by my own experiences. To see these heuristics in their original form, the work of Powell and Baker is not to be overlooked. The box introduces the example followed in the remainder of this section.

THE EXAMPLE

To illustrate the heuristics described here, we will use the U.S. FDA *Vibrio parahaemolyticus* Risk Assessment, July 19, 2005, Quantitative Risk Assessment on the Public Health Impact of Pathogenic *Vibrio parahaemolyticus* in Raw Oysters found at <https://www.fda.gov/downloads/Food/FoodScienceResearch/UCM196915.pdf> (accessed July 16, 2018).

The risk assessment model, Appendix 3, can be obtained from the following link <https://www.fda.gov/downloads/Food/FoodScienceResearch/UCM196915.pdf> (accessed July 16, 2018).

Vibrio in raw oysters represent a serious health risk. This risk assessment considered different geographic sources of oysters and different seasons of the year. To simplify the exposition, we'll use only the Gulf Coast of Louisiana in the summer as the single geographic region and season. In addition, we will consider only one of several questions posed to risk assessors, "What reductions in risk can be anticipated with different potential intervention strategies?"

11.5.2.1.1 *Identify the Question(s) and Simplify the Problem*

We will assume that the modeler begins with a well-defined decision context and a list of questions the risk managers would like to have answered. Let us also assume that the risk assessment team has considered these questions, answered those that could be answered with the available information and knowledge, and now seeks to build a model to predict answers to the remaining questions. This is where we would like the art of modeling to begin. The truth is that few risk assessment modelers ever find themselves in such a situation. So, let us back up and begin a bit more realistically with the risk manager who has never read [Chapter 3](#).

You, the modeler, simply must know what question(s) you are trying to answer with your risk assessment model. There is no way around this if you are to build a useful model. Ideally, you will be the beneficiary of a good risk management approach, such as the one described in [Chapter 3](#) of this book. If you do not know what the risk manager's questions are, sit down with your risk managers and ask them, "What do you need to know to solve the problem you are facing?" Write down their responses. Ask if there is more they need to know. Get them to understand what they have asked for and what you will provide and not provide.

Albert Einstein has been quoted as saying, "Any intelligent fool can make things bigger, more complex, and more violent. It takes a touch of genius—and a lot of courage—to move in the opposite direction." This brings us to the starting point for modeling: it is time to begin to simplify.

Build the simplest model you can. Power it with test-case data. Can it answer the question(s) risk managers have asked you? If yes, stop model building and go get real data. If not, revise the model and repeat the process. Make your model as simple as you can, so long as it meets the needs of your risk managers. It is always easier to add to a simple model than it is to simplify a complex one.

Sanchez (2007) formalizes this advice in four very concise suggestions for building a model:

1. Start small. Begin with the simplest possible model you can. It should cut away all the complexity that is not essential while still capturing the essence of the system. This can sometimes best be done by focusing on the questions you are trying to answer and the outcomes you'll need to provide those answers.

Simplifying anything requires us to make assumptions. Document your assumptions as you make them. Remember that you are most dangerous as a model builder when you begin making assumptions without recognizing that you are doing so. Peer review is one of the best ways to guard against this danger.

2. Improve your model incrementally. It is easy to add features to a basic working model. You can often improve a model by relaxing the assumptions with a more complete representation of reality. Even this should be done simply. Prioritize the changes you could make. Make one small change and see if it is adequate.
3. Test your model frequently. You want your model to conform to reality, not to duplicate it. How do you know when the model is adequate? If it answers

the questions you have been tasked with answering, it is quite likely to be adequate.

4. Backtrack if you must. In every model there comes a point when additional improvements are not worth it. When the latest change produces no measurable benefit to the answers to your questions, do not be afraid to go back to the earlier, simpler model when all you have added is complexity.

The question for this example (see preceding box) is, “What reductions in risk can be anticipated with different potential intervention strategies?” This question requires risk assessors to first estimate the annual number of illnesses before it can address the risk reductions. The simplest model that does this is:

Eat oysters → get sick

Clearly, this is not going to be sufficient, but it is a start. Perhaps there are things that happen before the oysters are eaten that are important or maybe there are alternative outcomes. Most importantly, we have begun to build our model.

11.5.2.1.2 Break Problem into Modules/Sections

One of the most effective ways to simplify a problem is to decompose it, that is, to break it down into simpler components or modules. This decomposition is the basis for the conceptual risk assessment model discussed in the 13-step procedure. We can always break any risk assessment into a hazard/opportunity identification, a likelihood assessment, a consequence assessment, and a unifying risk characterization. Likewise, each of these components can be further decomposed.

When working on a specific decision problem, it is usually simpler to decompose the problem into components. The reason for doing this is that it is easier to think about and work with the components of the problem than it is to work with the whole problem. The components, when well chosen, provide a natural structure for the assessment model.

The question then becomes: how many components do you need? Where do we draw the line? Powell and Baker (2007) suggest that a problem should be divided into components that are as independent of one another as possible. This number remains a subjective judgment. Each component of the model would then be specified and built separately, with the builder remaining cognizant of where each fits into the overall conceptual model. A model module would have its own worksheet(s) and would be physically separated from other modules.

In our example, as shown in [Figure 11.3](#), we might look at that simplistic model and decide it does not capture the key components of this decision problem. It might be useful to break that eating-oysters problem down into several components such as harvesting, handling, storage, consumption, and health outcome.

It is time for a brief caveat to the reader. The risk assessment chosen to illustrate the art of modeling is a real one that was actually used for public decision making. It is presented as a real example rather than an ideal one. Thus, you will find that it does not always conform to the practices described in this chapter.

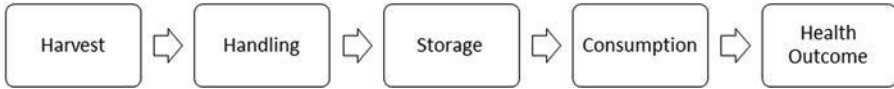


FIGURE 11.3 Key model components of *Vibrio* risk assessment model.

11.5.2.1.3 Rapid-Iteration Prototyping

Word-processing software did not spring from the womb the way it looks today. It began with someone figuring out how to get software that would type words neatly arranged on a page. It began with a prototype, and then features were added to that model until it evolved into the word-processing software we use today. Echoing the “keep it simple” message discussed previously, the way to approach modeling is to build and refine it in the same way. Build a prototype of your model; use it; examine the gaps between what it gives you and what you want; and then refine it.

PROTOTYPE

A prototype is a working model suitable for testing. It takes inputs from the user and produces outputs.

In practice, that means building a prototype of each module and testing it. Rapid-iteration prototyping means building a prototype as quickly as possible, testing it to see if it works as intended, and if it does not, moving on to the next prototype as quickly as possible. This is all done without worrying about finishing the model. The emphasis is on improving the model.

This is an especially useful approach for new model builders who struggle with wrapping their heads around a big problem. Simplify, break it into modules, and work quickly. Expect errors, insufficiencies, and problems, and this will free you to be more creative and crafty in your model building.

Risk assessment is often needed for ill-structured problems with lots of uncertainty. There are few things more satisfying in this situation than having a working model, no matter how crude. Beginning to bring order from chaos is psychologically very satisfying, even if the final model is many iterations off into the future. The most important thing is to begin. Add detail, refine your thinking, improve calculation efficiencies, and simplify the problem further as you go. Iterate, iterate, iterate your model.

Figure 11.4 shows a simple model that could estimate the number of people who get ill annually. Note that it is using test-case data. With a probability of illness, the number of eaters, and the assumption that this is a binomial process, we actually have a working prototype of the simple “eat oysters → get sick” model described previously. In the random iteration shown, 94 people become ill.

Does it give us everything we need? Probabilities could, conceptually, be estimated for different regions and seasons, but we’d have to be able to get the

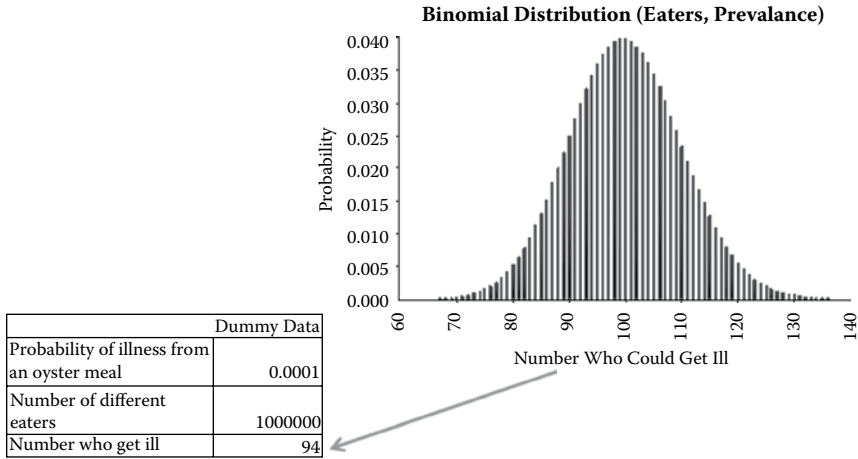


FIGURE 11.4 A simple *Vibrio* risk assessment model prototype.

data and estimate them. Keep in mind that our question requires us to be able to investigate the effectiveness of risk reductions associated with different RMOs. If they could be expressed as changed probabilities of illness, we might be onto something here.

As it turns out, all the data inputs in the binomial model are uncertain. To estimate the probability of illness from an oyster meal we have to decompose it into more pieces, ultimately, the pieces shown in Figure 11.3. In addition, there are other questions asked by the risk managers that this early iteration model does not answer. There is a desire to model watermen’s behavior and the other components identified in Figure 11.3. Nevertheless, the very first primitive model might look like this. We know we are not done because the model does not answer all the questions!

11.5.2.1.4 Graph Key Relationships in X–Y Plane

How do you begin to “complexify” a model? Express your intuition! Modeling is an abstract activity. You often begin with nothing but a weakly defined problem with no definitive structure and a crude conceptual model. From this you are to bring order and answers! It can be difficult to clarify your thoughts and to get started.

Powell and Baker (2007) point out that many people have a good intuition about the modeling challenge they face but lack the skills to represent those intuitions in a useful way. Experienced modelers often have a variety of ways to consider a problem. They may try to identify the parts of a risk assessment model. If working on a food safety problem, they may look for the hazard identification, hazard characterization, exposure assessment, and risk characterization pieces. Some may identify different components of these four steps. Still others will use analogies, draw influence diagrams, arrange objects on a table, perform experiments, develop risk hypotheses, or drink a beer. Figure 11.5 illustrates how the actual risk assessment represents the components of Figure 11.3.

Gulf Coast Louisiana Summer		Model Module	
	No mitigation		
Water parameters			Harvest
mean m	28.650722		
mean s	1.3282188		
Water temperature	28.650722	degrees C	
	2.4080866		
Log Vp level in environment	2.408087	log counts/gram	
min time on water	5		
likely time on water	9		
max time on water	11		
Time on the water	8.6666667	hours	
Time unrefrigerated	4.8333333	hours	Handling
Air temperature parameters			
m	-1.66		
s	1.33		
Ambient air temp	26.990722	degree C	
sqrt(max growth rate)	0.1901383		
Estimate growth rate in oysters	0.2007189	log counts/hr	
outgrowth1	0.9701415		
Predicted counts at 1st refrigeration	3.378228	log counts/gram	
Duration of cooldown	5	hours	
outgrowth2	0.6021568		Storage
Predicted counts after cooldown	3.980385		
Length of refrigeration time	7.7	days	
Predicted level after die off	3.483585	log counts/gram	
Grams oysters consumed	383.227	grams	Consumption
Total Vp exposure in one meal	1166919.8	log counts	
Pathogenic Vp consumed	2929		Health Outcome
probability of illness	3.4667194	log counts	
Log(risk)	0.0001033		
ill? 1=yes 0=no	-3.9857685		
	0		

FIGURE 11.5 Key model components of actual FDA *Vibrio* risk assessment model.

Some will draw a picture of the problem as they understand it. Mind maps, introduced in Chapter 7, are great for fleshing out model components. Visual representations of problems can make the abstract tangible, and a problem we can look at is often easier to deal with than a mathematical or conceptual one that is stuck in our minds. Few of us are blessed with the artistic skills or confidence to think we can sketch a problem or a model. But we can all graph a freehand relationship between two variables, and that is a good place to begin.

So, assuming that we have identified the components of a conceptual model, as shown in Figure 11.3, and we have identified some critical variables in each component, we begin to ask some simple questions. What is the relationship between water temperature and the number of *Vibrio* in the water? How about the number of *Vibrio* and time on the water or the length of refrigeration? What about the probability of getting sick and the number of *Vibrio*? Even if you have no background in microbiology you may have some intuition about the nature of these relationships, and visualizing them is a good way to start.

Even simple visualizations are powerful. Consider the simple model that follows:

RMOs → Risk assessment model → Public health outcomes

It focuses our attention on three ideas. There are risk management options to consider. Ultimately, they have public health outcomes, being more or less effective in lowering *Vibrio* illnesses due to oyster consumption. The model in the middle step suggests we must identify relationships that connect risk management options to public health outcomes.

Research suggests these visualization techniques help us by externalizing the analysis. They move ideas from inside our minds to the external universe, where we and others can more readily consider them. This is especially important for risk assessment because it is usually a team effort, and externalizing ideas is essential for group work. Debate, progress, and revision are not possible until ideas are externalized and made more concrete.

Sketching the relationships between pairs of variables is also appealing because there are a limited number of relationships that are possible. A few examples are shown in Figure 11.6. As a practical matter, the linear relationship is most commonly considered. In the prototyping spirit, it makes a lot of sense to begin by ascertaining whether a relationship between two variables is positive or negative. A linear relationship assumption can always be amended as theory or increasing intuition suggests a more complex relationship.

Some relationships cannot be expressed as a simple positive or negative one. The relationship between health and a specific nutrient, for example, may look like the relationship shown in Figure 11.7. At very low levels of the nutrient, health may decline due to insufficient levels of the nutrient for peak bodily function. Across a range of levels of the same nutrient, health may increase. Once excessive amounts of

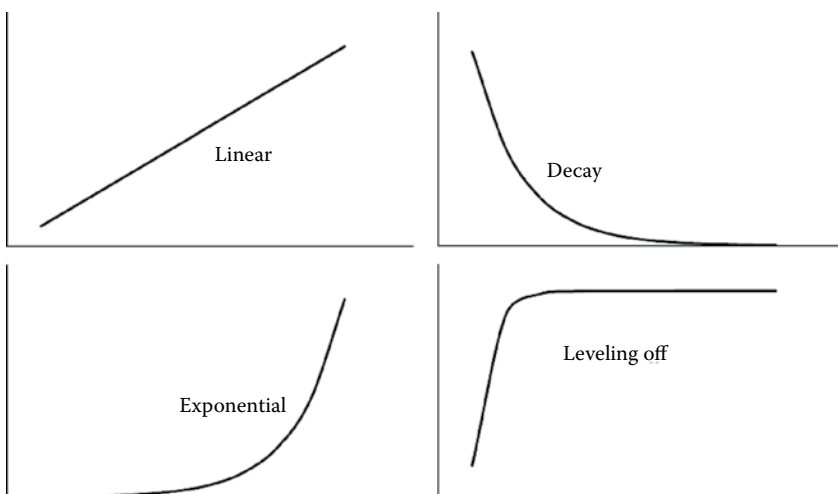


FIGURE 11.6 Sample relationships between pairs of variables.

the nutrient are consumed, health may once again be adversely affected, resulting in the odd negative/positive/negative slopes seen in [Figure 11.7](#).

The point, not to be lost, is that once these ideas are reduced to paper they become clearer. This makes them easier to understand or to challenge should others disagree. Visually representing key relationships can be an effective heuristic for beginning to build a risk assessment model. Choose the most important pairs of variables in your model and sketch the relationship you think is possible. You need not be correct in the beginning. You only need to begin. So, pick up a pencil and sketch.

The *Vibrio*-in-oysters model offers many possible relationships of interest. A few were mentioned previously. The rough hand-drawn sketches of [Figure 11.8](#) could

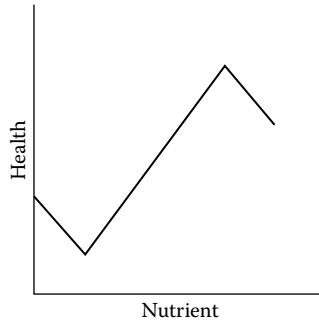


FIGURE 11.7 A nonmonotonic relationship between variables.

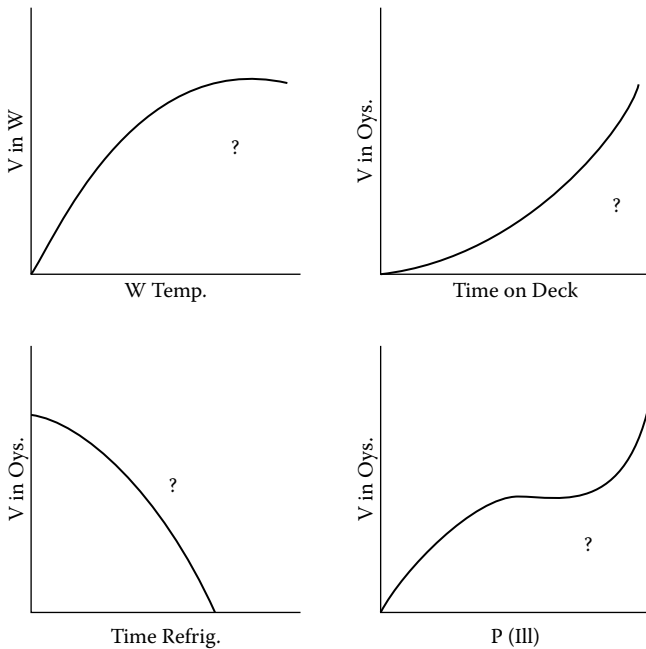


FIGURE 11.8 Hand-sketched relationship hypotheses for key assessment model variables.

represent initial ideas about the potential natures of those relationships. *V* stands for the number of *Vibrio*. The first thing to capture in a relationship is the nature or direction of the relationship. Is it positive or negative? Then it may be useful to represent ideas you may have about that relationship, whether they are right or wrong at this point. Presenting them visually gives others a chance to review and critique your ideas.

The upper-left sketch of [Figure 11.8](#) shows the number of *Vibrio* present in a given volume of water over a range of temperatures. This sketch suggests the number of *Vibrio* increases up to some maximum and then levels off. As the modeler is an economist, it is useful to commit these ideas to paper so that those trained in predictive microbiology might either point out the shortcomings or confirm the wisdom of the modeler's intuition. The other sketches suggest hypotheses about how other variables are related to the number of *Vibrio*. They can be vetted with others before relationships are specified.

FAMILIES OF CURVES

It is useful to know the functional forms of different families of curves in order to produce sketches of them. The function, its basic behavior, and its mathematical form are shown here:

Linear functions—constant returns, $y = ax + b$

Power functions—increasing returns, $y = ax^b$ for $b > 1$, for diminishing returns $b < 1$

Exponential functions—decay, $y = ae^{-bx}$; leveling off at asymptote $y = a(1 - e^{-bx})$

S-shaped curve—rapid then slowing growth, $y = b + (a - b)(x^2/(d + x^c))$

Source: Powell, S. G., and K. R. Baker. 2007. *Management Science: The Art of Modeling with Spreadsheets*. 2nd ed. Hoboken, NJ: John Wiley and Sons.

11.5.2.1.5 Identify Parameters

At some point we must move from intuition to functions and logical formulas. This is a necessary step to get from a visual representation to a mathematical formulation. In the model-building process presented earlier, this is the specification step on the way to building a computational model.

Several components or modules have been identified for the *Vibrio*-in-oysters model. Example relationships of interest were introduced in the previous section. Parameterization of a model is the step where we get specific about the model's structure and form. This heuristic may be most effectively developed and illustrated with our example.

Consider the health outcome component, specifically the relationship between the number of pathogenic *Vibrio* ingested and the probability of illness. This relationship between exposure to a hazard and probability of illness is called a dose-response relationship. A sample schematic is shown in [Figure 11.9](#).

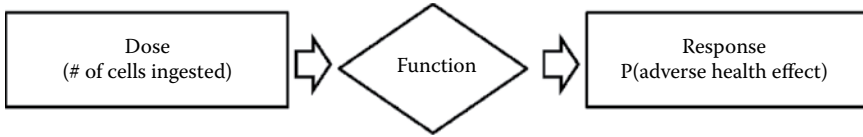


FIGURE 11.9 Dose-response links input (dose) to output (response).

Dose-response data tend to have a sigmoid shape. When available data are fit to a function, it is common practice to use any one of a number of mathematical functions that exhibit this shape. One such function is the Beta-Poisson, which is of the form:

$$P_{\text{ill}} = 1 - \left(1 - \frac{\text{Dose}}{\beta} \right)^{-\alpha} \tag{11.1}$$

where P_{ill} is the probability of illness, Dose is the number of pathogenic cells ingested, and α and β are parameters to be determined based on the available data. Such a function specifies the nature of the relationship between the dose and the health response. The function in this general form represents a family of curves. Sometimes, as in the case of the current example, it is the modeler’s job to select one from among this family by choosing specific values for α and β . Identifying these parameters takes the conceptual relationship to the specified level.

FDA risk assessors determined the values for the parameters α and β to be 18,912,766 and 536,058,368, respectively. These values were determined fitting the Beta-Poisson function to the available data. The resulting dose-response curve is shown in [Figure 11.10](#).

Probabilities of illness reach about 10% when the eater has ingested about 5.5 log of pathogenic *Vibrio* cells (about 350,000 cells). The probability of illness rises rather steadily to a 100% probability of illness at log 8.8 cells (about 630 million cells). This

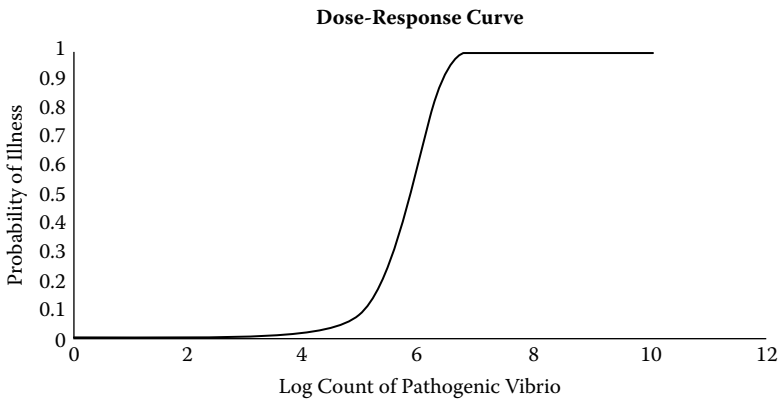


FIGURE 11.10 Dose-response curve.

is just one of an infinite number of possible relationships, however. Each pair of α and β values yields a different curve. Identifying parameters, with or without uncertainty, is a critical step in the art of model building that is often well served by statistical techniques and judgment. When point estimates of parameters are not possible, they can be estimated by distributions.

Once you have parameterized your model it is time to consider protecting those parts of your model that should not be changed. This is especially important if users will include people not familiar with the structure and details of the model. It is a simple matter to format selected cells with protection. This can avoid accidental changes to parameters that should not change. The protection can be removed if changes become necessary at some point in the future.

11.5.2.1.6 Generate Ideas and Scenarios but Do Not Evaluate Them Too Soon
Best-practice modeling is a creative activity. It is not easy to be creative. The rewards for creativity are rarely obvious, while the sanctions for being wrong are often quite evident. We are often biased by our education, training, and experience to be logical and to seek the right answer. But life is often ambiguous and even maddeningly illogical. The wicked problems of risk analysis rarely have right answers; there are only answers that are better or worse than others.

Following the rules and being practical are lessons we learn at home, at play, and at work. While these are wonderful attributes, they do little to aid creativity. One of the more persistent blocks to creativity is our tendency to judge an idea prematurely. Many of our education systems do a better job teaching us how to criticize ideas than they do teaching us how to create ideas. Consequently, many of us have a strong preference for judging ideas rather than generating them, and we are quick to turn it loose against ourselves.

Model building, like much of life, requires a period of divergent thinking, followed by some intensive convergent thinking. It is terribly easy to rely on our biases, mindsets, and belief systems when we approach tasks that cry out for creativity. When trying to model a problem, begin with divergent thinking. Generate as many alternative ideas as possible. Don't evaluate. Be creative.

Brainstorming, the topic of [Chapter 8](#), is a creative thinking technique that is both effective and easy. The only real difficulty is getting a group to commit to use the technique and to have fun with it. One of the tenets of the best brainstorming techniques is a "no evaluation/no criticism" rule. A second valuable rule is "the wilder the better." Use them both early in the model-building process.

Do not fall in love with your first idea. When starting to build a model, it is important to consider as many different approaches to the problem and to answering the risk manager's questions as possible. That cannot happen in an environment where ideas are criticized and defeated before they have had a chance to fully develop. The harshest critic of most ideas is the self. We are very quick to censor our own thoughts and only slightly less quick to criticize the ideas of others.

When the critical self is in charge, the open-ended job of developing a model can seem overwhelming. The downside of every approach, the considerable problems we can anticipate, the hurdles that seem insurmountable are all very evident from the start. Modelers must learn how to quiet the critic in themselves and in others. When

building a model you will make mistakes. There will be blind alleys. You may get halfway through a model and realize there is no way out. It is okay to begin again.

Begin by generating as many ideas and approaches as possible. Think of as many ways to model *Vibrio parahaemolyticus* and oysters as you can. Let them ferment for a while. Refine them, explore them, flirt with them, and get to know them. Only then is it time to systematically evaluate them.

11.5.2.1.7 *Work Backwards from the Desired Form of the Answer*

If you have done a good job at divergent thinking, you may have many possible approaches to take with your model. Your problem now is to choose one. To do so it is often helpful to begin at the end of your model.

What do you want your answer to the risk manager's question(s) to look like? Imagine the specific form the best answer will take. Pay attention to the units of measurement your answer(s) may require. Then work backwards from that point to the best approach or the most logical starting point for your model.

Powell and Baker (2007) propose the "PowerPoint heuristic." Imagine that your answer must be summarized in a single slide. What is the essential message for that slide? Is it a figure, a graph, a table, a procedure, a number, a distribution, a recommendation? Working through this exercise helps you recognize what your critical outputs are and what the essential message of your model must be.

In the model for *Vibrio* in oysters, we want to know how many people get sick annually the way things are done now. We also want to know how those numbers of people might be reduced by a heat treatment, a freeze treatment, a rapid cooling treatment, and regulation of the harvest.* Let us stay with the estimate of the existing risk for now. What do we need to get the annual number of people who get sick? First, a rate of illness or probability of illness per eating occasion is needed along with the number of eaters. It is a simple matter to understand how these two outputs get to the essential message for us.

What do we need to get the rate of illness? We need to know how many eaters out of, say, 100,000 get sick. What do we need to get this? We are going to need a dose-response relationship and a dose. This approach suggests that we might want a model that provides the dose for a given eater at a given meal. If that is the case, we will need a way to estimate the eater's exposure to pathogenic *Vibrio*. This is an input to the dose-response relationship.

Continuing to work backwards, to get the number of pathogenic *Vibrio* in a meal, we need to know the size of the meal and the *Vibrio* load per gram of oyster flesh. Then the *Vibrio* per gram times the number of grams will give us a log count of the pathogenic *Vibrio* the eater ingests.

Preliminary risk assessment work may have provided insight into the nature of the available data. For example, if data on pathogen loads at the time of consumption are available, our model may have reached its beginning point. Get the data on pathogen loads and meal size and work through to the number of annual cases of illness.

* These details on the nature of the risk interventions under consideration are found in the risk assessment.

In the *Vibrio* example, these data were not available, so it was necessary to use predictive microbiology to estimate it. Using the available science, the model estimates the amount of *Vibrio* present in a gram of oyster flesh at the time of harvest. That number is then allowed to grow as the oysters remain on the deck of the workboat and during the period when the oysters are being cooled down. This produces a maximum number of *Vibrio* per gram of oyster flesh. The model estimates the amount of die-off during refrigeration and uses this value to estimate the total *Vibrio* load in a meal. Along the way, the modeler learned it was easier to work with all *Vibrio* and to estimate the percentage of them that were pathogenic later in the model. Working backward from the form of the answer you want often provides the focus you need to begin an open-ended process like model building.

11.5.2.1.8 *Focus on Model Structure, Not on Available Data or Data Collection Issues*

“Models before data” would be a great bumper sticker for modelers. A good modeler focuses on the structure of the model and getting it to represent reality in a way that meets the information and decision-making needs of risk managers. One of the most common, most appealing, and most limiting approaches to model building is building to the data. Consequently, many modelers begin by searching for, collecting, and analyzing the data. They then build a model that uses the data they have instead of the model that should have been built.

It is tempting for a modeler to build a model that makes use of the existing data. Likewise, it is tempting to avoid including model components for which data do not yet exist. This approach is flawed from the outset. There is no automatic reason to assume the available data are accurate for your purposes. At the other extreme, if we avoid model structures that require new data, we may be failing in an opportunity to “grow the science.” Research can be as integral a part of risk assessment as is addressing uncertainty in our analysis.

Build the model that will solve the problem and answer the risk manager’s question(s). Do not worry about the data. A good model improves the risk assessment process and often expands the body of knowledge because of new data that must be collected and organized.

The existing data are often flawed and need to be carefully screened. All our data describe the past, and all our risk management decisions are about the future. There is always good reason to suspect the temporal relevance of our data. Some of the more common sources of bias and errors in the data are sampling error, data collected for different purposes, masking, inappropriateness, definitional differences, geographic or cultural irrelevance, flawed experimental design, and so on. See others in the accompanying box.

The best-practice method is to build the model you need. Let it tell you what data you need rather than letting the data tell you what model to build. Once the appropriate specification model is built, you can then use the available data to refine the model. This sequence may also avoid unnecessary collection of additional data. If necessary, your better data-free model can be revised to accommodate the available data, but you will know what you are sacrificing in the process. Getting new data and getting better data are not always obligatory activities.

TYPES OF BIAS

Selection bias
 Volunteer or referral bias
 Nonresponse bias
 Measurement biases
 Instrument bias
 Insensitive measure bias
 Expectation bias
 Recall or memory bias
 Attention bias
 Verification or work-up bias
 Intervention (exposure) biases
 Contamination bias
 Co-intervention bias
 Timing bias(es)
 Compliance bias
 Withdrawal bias
 Proficiency bias

Source: Hartman, J. M. et al. 2002. Tutorials in clinical research: Part IV: Recognizing and controlling bias. *Laryngoscope*, 112: 23–31.

Good data do matter. But good data in a flawed model are not necessarily better than imperfect data in a good model. Good decisions are frequently driven more by good models than the data that are in them. A well-structured model can often reveal valuable insights with a rough estimate of model parameters. Frequently, insights about the problem gained by building the model are sufficient for informing the decision-making process. Data are not always necessary for informed decision making.

11.5.2.2 The Practice of Modeling

Modelers have developed many handy and helpful ideas about how to build a model in a spreadsheet environment. These are the focus of the remainder of the chapter. You will notice a bit of overlap with the art of modeling heuristics at times. The difference is that here we assume you have tackled and solved the conceptual problems and now look to practice the art of modeling.

11.5.2.2.1 Sketch the Model—Document the Logic Flow

Once you understand the model, after your initial visualization efforts and before you begin to build your spreadsheet, sketch the logic flow or the components of the model. The visual representation will help you decide how best to organize your efforts. [Figure 11.11](#) is taken from FDA's *Vibrio* risk assessment. It provides a very effective visual summary of the model's construction. This diagram makes it easier to identify component modules at a finer level of detail and more intuitively than does [Figure 11.3](#).

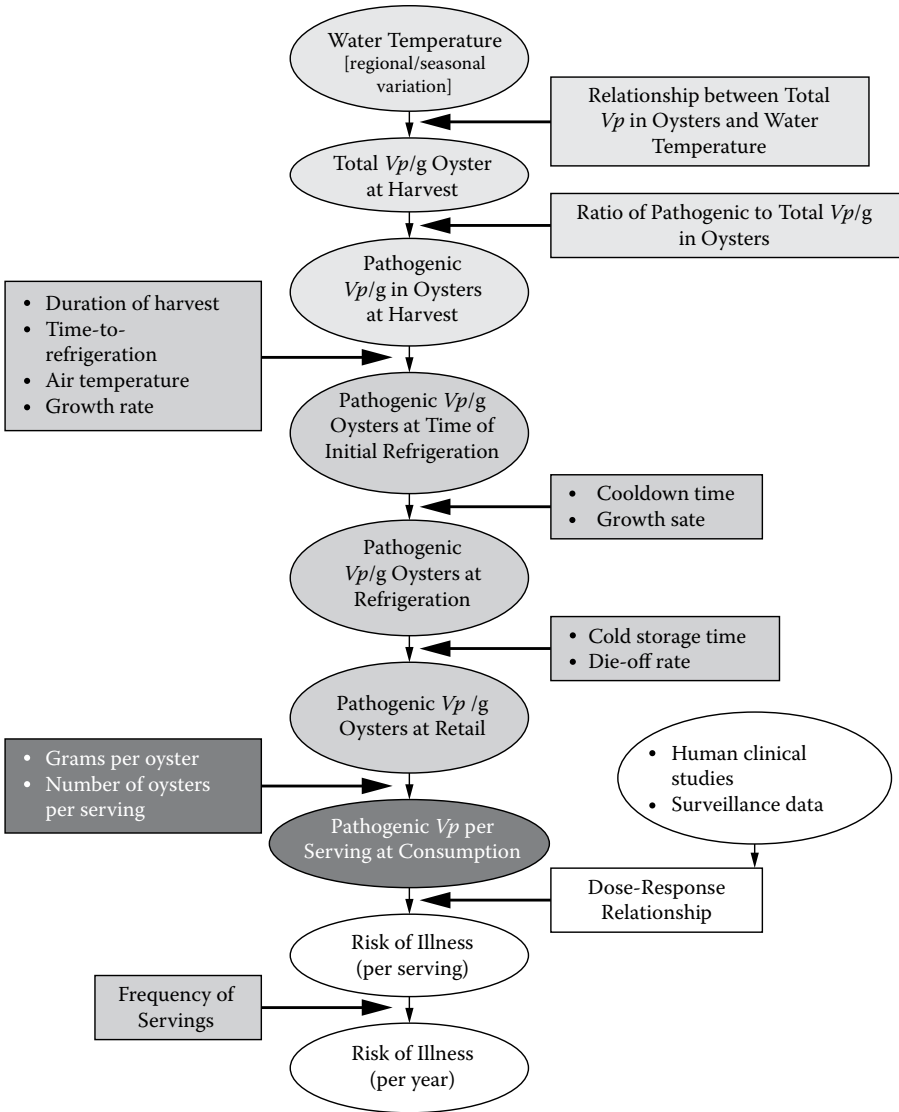


FIGURE 11.11 Schematic representation of the *Vibrio parahaemolyticus* risk assessment model. (From Food and Drug Administration. 2005. Center for Food Safety and Applied Nutrition. Quantitative risk assessment on the public health impact of pathogenic *Vibrio parahaemolyticus* in raw oysters. <http://www.fda.gov/Food/ScienceResearch/ResearchAreas/RiskAssessmentSafetyAssessment/ucm050421.htm>.)

Make the shapes in your sketch be meaningful. Influence diagrams are a common model-sketching tool that rely on the common convention of showing a chance event as a circle, a decision as a square, a calculation as a rounded square, and a payoff as a diamond. As long as the shape and color schemes in your model sketch have meaning, their information content is enhanced.

11.5.2.2.2 *Think Communication as You Design the Model*

Before you begin to build your computational model, think about how you can organize the model so that it aids the risk communication process. Spreadsheet models consist of tabbed worksheets. If you use these worksheets to give your model a logical structure, it can save you and others who may use it a great deal of time in the future. Following are some suggestions for organizing a spreadsheet model.

Overview sheet: The first sheet should provide an overview to the risk assessment model. Why was it prepared and what does it do? When was it developed and by whom? Using what software? The overview sheet should be brief, and it should at some point include the list of risk management questions the model was built to answer.

Instructions sheet: Documenting your model is a critically important part of the modeler's job. Spreadsheet models are not likely to be so complex as to require an actual user's manual. However, they should provide instructions sufficient to enable a future user of the model to understand how to update data and other model components as well as how to run the model and access the desired results. The second sheet should include these instructions. If the model has been verified and/or validated, the methods by which this was accomplished and the time frame should be documented here as well.

Log of use sheet: This feature is rarely included, but it can be extremely useful, especially when it is being used by a government agency for regulatory, stewardship, or other public purposes. The log of use sheet identifies who used or modified the model for what purposes and when. It can also be used to record the planned sequence of simulation experiments and the dates they were completed.

Guide to model sheets: A modular risk assessment is likely to consist of many separate worksheets. The organization of a worksheet can be difficult to discern from the short phrase on the tab. In a large model, all the tabs may not even be visible at the same time. This guide identifies the various sheets in the model and briefly describes the purpose or function of each sheet. The guide functions as a table of contents and is an indispensable aid for a large model.

Influence diagram/conceptual model: The sketch of the model needs to be presented somewhere in the model itself. It may be helpful to add a narrative to accompany the influence diagram or model layout. This may be combined with the guide to your model sheets.

Assumptions: Assumptions are critical to the construction of any risk assessment model. All explicit assumptions and as many implicit assumptions as possible should be identified and listed in an assumptions sheet. It may be helpful to organize the assumptions by model module.

Inputs: One of the most practical things you can do is create a sheet where all input variables and parameters can be entered. Separate the variables from the constants. This will make it easier for you to correct, change, revise, and update data throughout the model's lifetime.

Relationships: Adequately identifying and modeling dependencies among variables in your model is one of the modeler's greatest challenges. It is critically important to document and to convey to others the nature of these dependencies. Each

interrelationship between or among variables should be described here in a narrative form. Include the formulas used to capture these dependencies when possible and indicate where in the model they can be found. In the *Vibrio* model this would include the dose-response relationship and the growth and die-off equations, for example.

Performance measures: Many models will have performance measures. These are cell values that are of interest to the risk assessor or the risk manager. They tend to be intermediate calculations rather than outputs. The number of *Vibrio* cells per gram of oyster flesh is a performance measure in our example. A model that calculates a benefit-cost ratio would have costs and benefits as performance measures. A transportation model might have travel time as a performance measure. Identify all the performance measures and include the formula used to calculate them when possible. An example is presented in Table 11.1. In some instances, it may be useful to include a cell reference for the performance measure (not shown in the table) so it can be easily located in the risk assessment model and observed.

Outputs: Collecting all model output cell values in a single place is extremely helpful with complex models. Models constructed in a modular fashion may have outputs of interest spread over several worksheets. In an event tree, model outputs may be scattered over many cells in a worksheet. Consolidating all output cell values on a single page is not only convenient for observing outputs, but it can also be an effective editing and debugging aid. Note that these outputs are not detailed statistical and graphical outputs of simulations. They are only images of the output cells, similar to the model values shown for performance measures in Table 11.1.

Modules: Each model component should have its own module, and each module should have its own worksheet(s). The worksheets should be labeled descriptively, and each should include a brief narrative explaining the function of the module. If a model sketch is used, it is helpful to indicate what part of the model is being represented by the module. The module sheets are the guts of the model.

Historical data used to generate model inputs: Often, model inputs are derived from historical data. When this is the case, it is desirable to include these data in the risk assessment model itself if it is practical to do so. The size or proprietary nature of the data files may make it impractical. When the data cannot be included, its source and location should be noted.

Graphics page: Some models make use of dynamic graphics so that model effects and relationships can be more easily observed. If your model makes use of dynamic graphics, gather and present them all in a single worksheet when practical to do so.

TABLE 11.1
Performance Measure Examples for a Risk Assessment Model

Performance Measure	Model Value	Formula
Log V_p level in environment	2.0963456	$-1.03 + 0.12 * E10 + \text{RiskNormal}(0,0.886)$
Predicted counts at first refrigeration	2.8192952	$\text{IF}((E12 + E27) > 6,6,E12 + E27)$
Predicted level after die-off	2.6691434	$E31 - 0.0027 * 24 * E32$

11.5.2.2.3 Organize Your Model into Modules

My best advice to new and aspiring modelers is: do not attempt to work out the entire model in your head all at once. Put things on paper. Sketch the model's major parts. Practice the art of modeling. Once you have identified the components of your model, you have the framework for a modular model design. Build it simply first, then add to it.

Repeat the model-building process for each module. Treat the module like a mini-model. Build and work on one module at a time. Sketch it unless it is simple and obvious. Identify its subcomponents. Consider making subcomponents separate modules. Don't go overboard with the decomposition but make an effort to define modules that make sense to yourself and others.

If you are modeling a process, the modules are often easy to define. The egg production process in [Figure 11.12](#) provides an easy identification of modules. If there is no clear process, allocate specific tasks in the model (e.g., assessment and hazard characterization) to different sheets.

Use common sense. Some models are compact even though they have several discrete components. Though it is always wise to think in terms of modules and to build in terms of modules, it is not always necessary to separate the model physically along those lines. The FDA model we have been looking at, for example, does not use a modular approach.

11.5.2.2.4 Handling Inputs and Outputs

There are reasons beyond good communication for segregating your input and output values. Efficiency and accuracy are at the top of that list. A spreadsheet model should provide a single point of entry for the values of all model inputs, that is, variables and parameters. Isolate the data inputs to a single sheet of the model and it will be easier to input data, check for errors in inputs, avoid errors in formulas, and revise and update your inputs.

Formulas in your model should not include constants of numerical values nor distribution formulas for variables. Enter all such values into the cell of a single input

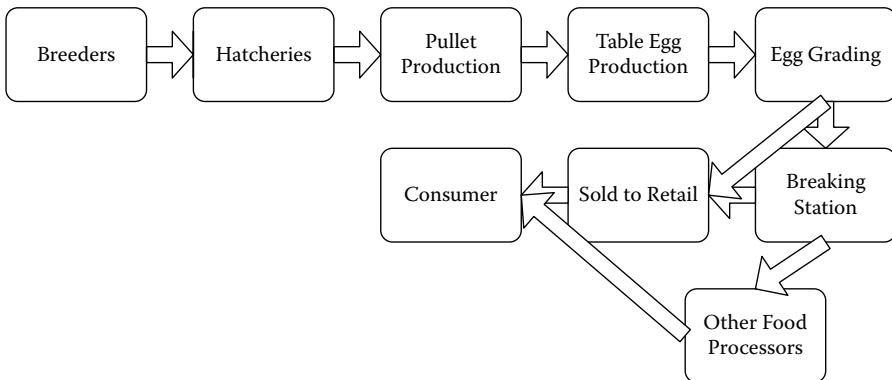


FIGURE 11.12 Process flow for shell eggs and egg products.

	A	B	C
1		Direct Entry Model	
		Weight	
		in	
2		pounds	Formula Syntax
3	Man 1	178	RiskNormal(182,16)
4	Man 2	194	RiskNormal(182,16)
5	Sum	371	
6			
7		Cell Reference Model	
		Weight	
		in	
8		pounds	Formula Syntax
9	Mean	182	182
10	SD	16	16
11	Man 1	188	RiskNormal(C9,C10)
12	Man 2	158	RiskNormal(C9,C10)
13	Sum	346	

FIGURE 11.13 Comparison of direct parameter and cell reference parameter entry.

sheet and then make sure all your formulas use the cell references of that cell in the input sheet in place of the actual values.

Consider a simple example of a model that calculates the combined weight of two men. Figure 11.13 shows two ways to enter the data. Notice that column and row identifiers are found in the figure’s margins. The direct entry model shows the formula using the actual numerical values as arguments in the distribution. The cell reference model shows arguments for the distributions using cell references.

The advantage to using cell references and a single point of entry for input data is that if new information shows the standard deviation to be 17 pounds instead of 16, then a single change in the cell reference model at cell B10 updates the model. Using direct entry, the modeler must be sure to make the changes in every instance where the standard deviation appears in the model.

In a more complex model, all input values like the mean and standard deviation would be entered on a separate input worksheet and then referenced there.

On that input sheet, separate your inputs into constants and variables. Constants are numerical values that do not change for a model run. Variables are numerical values that do change in a model run. There are two kinds of variables: deterministic and stochastic. Deterministic variables vary in a known pattern, as the hours of operation might reflect a systematic pattern of change from opened to closed over a week. These values may well change within a model run but they do so in a determined way. Decision variables and value variables are also deterministic variables, although we may be uncertain about what the most appropriate values for these variables are. In

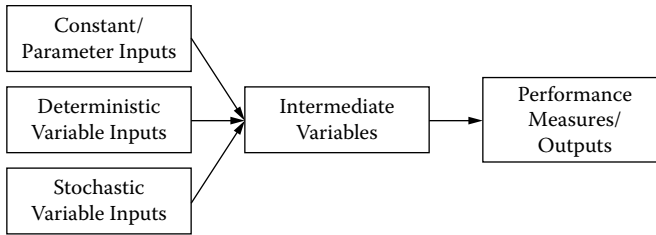


FIGURE 11.14 The role of intermediate variables in model input/output relationships.

that case, different values may be chosen for multiple simulations of an otherwise identical model, or we may simply want to do some sensitivity analysis of specific variables that have no true value. Stochastic variables have an element of randomness to them. They are usually represented by probability distributions. Segregate and identify constants, deterministic variables (including decision and value variables), and stochastic variables in your input sheet.

You may want to segregate the intermediate variable calculations of your model in their own worksheet as well, as represented in [Figure 11.14](#). These include the performance measures mentioned earlier. Intermediate variables link inputs and outputs through intermediate calculations. The ability to monitor intermediate values can be a valuable debugging feature of a model. When intermediate variables are performance measures, there may be intrinsic value in being able to observe them as one steps through a model. Consider gathering an image of all significant intermediate variables in a single place in your model.

Gathering an image of all model outputs in a single sheet provides a convenient way to find all the values of interest for answering the risk manager’s question(s) in a single place. Consider developing modeling conventions for your organization or at least for yourself. One of the simplest of these is to use color-coded fonts. Choose one color for any cell that includes an input value, another color for intermediate calculations, a third for outputs, and perhaps a fourth for data. This way the color patterns of your spreadsheet cells immediately convey useful information to anyone who knows the color code.

11.5.2.2.5 *Output Reports*

Each planned model run will produce outputs and performance measures of interest. These outputs should be documented in data arrays, tables, and graphics, that is, in output reports. There should be an output report for each run of the model. A large number of model runs may necessitate storing them in a separate spreadsheet file.

11.5.2.2.6 *Design for Use*

Design your model to be used. We have already said, “Build the simplest model possible but no simpler.” The corollary to that rule of thumb is to build your model as simply as possible. To make your model easier to use: calculate first, simulate second. Although there may be no closed-form analytical solution to your overall model, there may be analytical parts of the model. Whenever you have a choice between analyzing and simulating, choose analyzing. Keep your cell formulas simple. When you have a

complex formula, break it down into several intermediate calculations. This will help avoid difficult-to-find errors, and it may speed up your model calculations.

As you determine your model's structure and begin to quantify the variables and their interrelationships, one of the issues you must resolve is the level of detail or the resolution of your model. One way to frame this issue is as a trade-off between the realism of the model and its utility.

As the terms are used here, realism means the extent to which the model faithfully represents the details of the real-world process being modeled. Utility means the extent to which the model provides useful answers to the risk manager's questions. A simple model may be sufficient for answering the risk manager's questions, but it may not be a very realistic model. On the other hand, a realistic model is not guaranteed to produce useful answers.

Realistic models tend to be larger if only because they include more details. Greater detail is rarely worthless. However, greater detail also requires significantly more data to enliven those details, and data availability is always a real concern for realistic models. Realistic models do have the advantage of getting to a tangible level of understanding, a level of resolution that is easy to envision. In a large, detailed model, no one part of the model is likely to be "too" critical. Indeed, aggregating the results of many smaller components to get an output can be more accurate than directly estimating an output. If these are important concerns, you will want a more detailed, more realistic model. Expect such a model to require a lot of data.

On the other hand, a more abstract model with less detail can be a lot smaller. Sometimes a more abstract model is a necessity and not a choice, as it may not be possible or practical to include the additional detail in a model—although you know better than to build to your data! There may be too much knowledge uncertainty about the system being modeled, or it could simply be cost prohibitive to develop a realistic model. Oftentimes, capturing the key elements of a system in your model is sufficient to support decision making.

In general, when a model provides useful answers to the risk manager's questions, it is ready to use. Design your model for use. Then, if you decide that incremental additions to the model's realism are justified by the value of the information these enhancements produce, you can add as many as you like. But first, build a model you can use.

11.5.2.2.7 Minimize Stupid Mistakes

Take extra care with modeling dependencies and relationships among variables and parts of your model. We live in a complex universe, and many phenomena are treated as independent of one another, often because it is too difficult to deal with the more complex reality. Independence is not to be an assumption of convenience for the modeler. Things must truly be at least functionally independent to be so represented in your model.

Your model's structure should prevent the generation of any unrealistic scenarios. To ensure this, you must recognize and model any interdependencies among your model's variables, calculations, and components. Things that always happen together should happen together in your model. Things that can never happen together, things that move in the same direction, things that move in opposite directions—all must be accurately represented in the structure of your model. Dependencies can be built

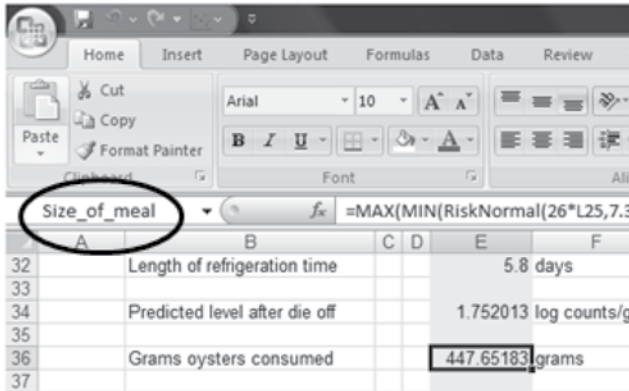


FIGURE 11.15 Use range names for key variables.

into a model using complex logic arguments, functions, correlations, linkages, and embedded arguments, among other means. Use whatever means necessary to ensure that you have carefully tended to important real-world dependencies and relationships, so they are reflected accurately in the workings of your model.

Copy and paste carefully. Remember that when you paste a cell formula your software is adjusting cell references for relative changes in their new location. This can result in unanticipated errors. Always make sure cell references are as desired after pasting copied material. Remember to use dollar signs (\$) when you want to preserve the absolute location of a cell when you copy and paste.

Use range names for key inputs and intermediate values. Using simple descriptive names for a cell or range of cells makes formulas that reference these cells much easier to read and understand. In [Figure 11.15](#), cell E36 has been named “Size_of_meal” in the example shown here. This is far more informative than using “E36.”

Compare the difference between the mathematically identical formulas in [Table 11.2](#). To understand the first formula, you would have to locate the cells referenced and see what the referenced values are before it is understood. The second formula uses range names and is far easier to understand. The more descriptive quality of the range names limits the likelihood of a stupid mistake like a cell reference typo where you type E35 instead of E36.

Use comments generously in your model to document assumptions and explain things. [Figure 11.16](#) presents an example to demonstrate the concept. This comment is not found in the original FDA model; it was created to illustrate the point made here about the value of comments. Comments can help eliminate stupid mistakes by

TABLE 11.2
Comparison of Cell Address and Range Name Formulas

=10^E34*\$E\$36
 =10^Log_vibrio_per_gram*Size of meal

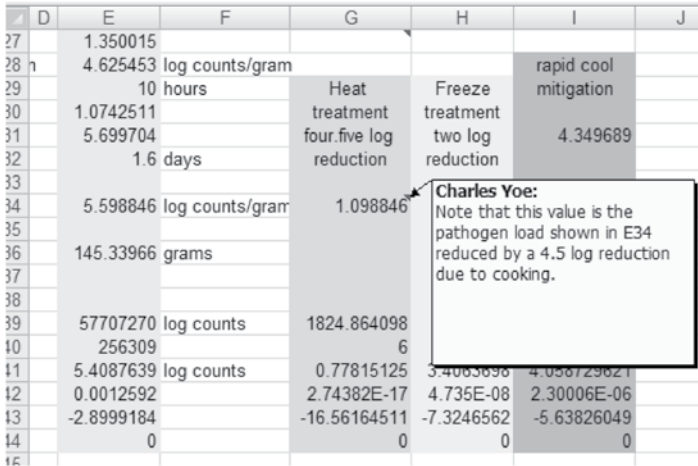


FIGURE 11.16 Use comments to document and explain the model.

reminding you and the naïve user of your model of things you might dangerously forget without the reminder. They are also excellent documentation aids.

Create generations of backup models. If you have ever saved changes in a file and then realized your changes were incorrect and mourned the loss of the correct file, you may already be doing this! When developing a model, each time you begin to revise it, save the revision as a new version, for example, MyModel01, MyModel02, etc. Then, when your work in progress veers off in a bad direction, you can simply return to an earlier generation of your model.

Be careful with external links. Minimize the number of links you have to other workbook files. Limit yourself to links with external databases if you must link at all. Once you link to another workbook, it may be linked to yet another workbook, and you may be entering a web of interconnections that you do not understand. While speaking of data, make sure your data are in a legitimate number format. Data can be formatted as text when imported carelessly. Text will not perform numerically!

Do not use cell formatting (see Figure 11.17) to round numbers. They are not truly rounded, they are simply displayed without trailing decimals. Figure 11.18 shows a

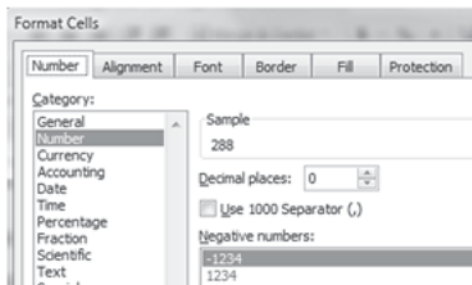


FIGURE 11.17 Truncating a value using cell format to mask decimals.

	K	L	M
15		Cell Format Formula	
16	Parameter	Value	Cell Formula in L
17	n	18	17.931
18	p	0.2	
19	Binomial	#NAME?	=riskbinomial(L16,L17)
20		Rounding the Value	
21	n	18	=ROUND(17.931,0)
22	p	0.2	
23	Binomial	4	=RiskBinomial(L21,L22)

FIGURE 11.18 Comparing the effect of cell format and rounding in a binomial distribution.

hypothetical binomial distribution. Values for n and p are given in column L. The exact syntax of the column L entry is given in column M. Thus, if you wanted to change the number 17.931 to the rounded-off integer, 18, use the ROUND function of your software. Cell formatting will display an 18 in the cell, but it will treat the cell value as 17.931. To illustrate this problem, imagine you want to use a number like 17.931 as an argument for the sample size, n , in a binomial distribution as shown in Figure 11.18. The binomial requires n to be an integer. In the top example, cell formatting is used for faux rounding. Notice it returns an error message (#NAME in cell L19) when entered into the binomial distribution. The second example uses the round function of Excel and enables the binomial function to work as expected.

Use the function wizard to minimize syntax errors. It can be found by clicking the f_x on the standard Excel toolbar. Figure 11.19 shows the function wizard listing all the @RISK probability distributions. Beneath the list is the Excel template that can be used to enter @RISK functions, as well as any of the Excel functions. Using the wizard will help minimize typos and inadvertent errors in formulas.

Be careful with parentheses in long formulas. It is common practice to use parentheses to establish the order of operations. It is easy to make mistakes with the placement of parentheses.

When you are building a model, it can be useful to “break your model” at times. To do this, you enter intentional error values into a cell. An example would be to enter a probability outside the acceptable range or to attempt to divide by zero. Once in a while error messages can be comforting. Your model should fail when it is supposed to. In a related fashion, it is useful to use simple values like 0.1, 1, 10, and other multiples of 10 to test your calculations. They need not be realistic values when you are building your model. Numbers like this make it easy to spot-check the accuracy of calculations.

11.5.2.2.8 Test and Audit the Model

Expect your spreadsheet model to contain errors. If you do, you’ll make a more serious effort to find and fix those errors. Few things are worse for a modeler than to discover an error well after you’ve begun to use your model for decision analysis.

This step was called verification earlier in the chapter. Its purpose is to verify and ensure the model is free from logical errors. If your spreadsheet model is a simulation model, your goal is to ensure that every iteration of the simulation is both accurately

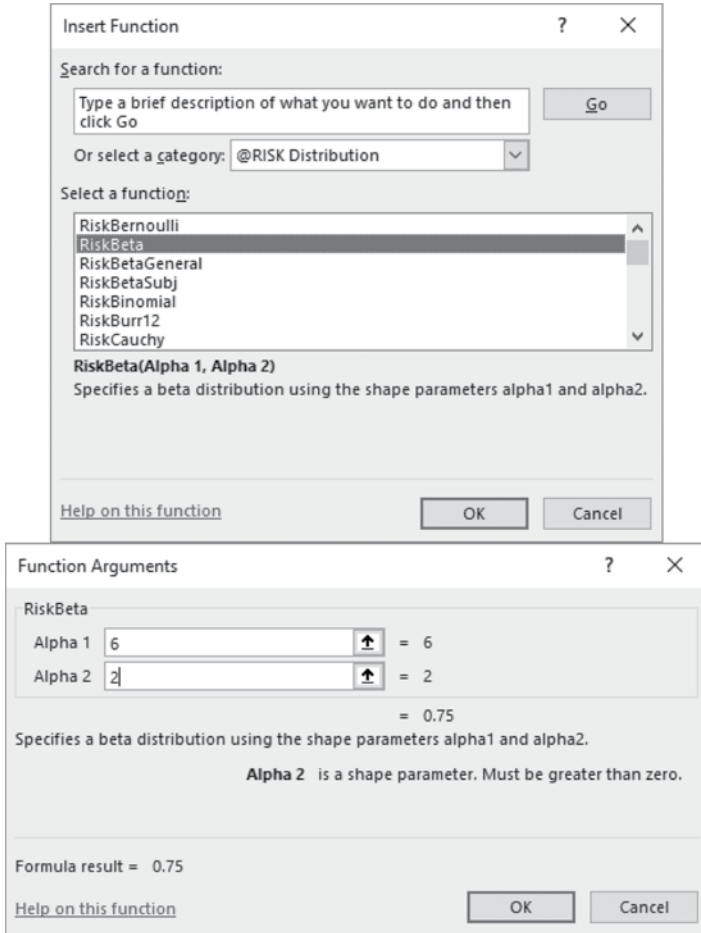


FIGURE 11.19 Excel’s function wizard helps minimize typographical and syntax errors.

calculated and possible. This is when the care taken in designing your model for use and communication will first pay off.

Testing and verifying your model can be laborious and monotonous. It is all the more difficult to catch errors when your focus wanders. One of the best ways to test your model is to have experts review the model. This is a luxury few risk management activities can afford. It is also difficult to find these experts. They usually need software, modeling, and subject-matter expertise. This is hard to find in a single person. So, assuming you will have to verify your model, how can you best do that? Approach your model with a skeptical attitude. Powell and Baker (2007), once again, offer the single best description of a plan for testing your spreadsheet model. In the following discussion, I have supplemented their suggestions with those of the Fuqua School of Business at Duke University (2006), Mather (1999), and a few of my own.

11.5.2.2.9 *Debugging*

Debugging is a methodical process for finding and correcting errors in your model's logic and data. There is a rich literature on debugging, but the truth is the method of that process is highly individualized and often idiosyncratic. There is no simple or foolproof way to debug a model. The simplest advice is to build your model in small modules and debug each module carefully before you link them together. The most basic form of debugging is to methodically check and verify every line of code in your model, or in the case of a spreadsheet model, the contents of every cell.

As you link your models, check carefully to ensure that interactions between the modules do not create new bugs. Debugging, as used here, is usually an ongoing process rather than a discrete event in the life of a model. You are always debugging your model right up to the time that it is verified.

11.5.2.2.10 *Make Sure Numerical Results Are Reasonable*

As your model takes shape and numerical results (either intermediate calculations or outputs) begin to appear, or when it is initially completed and you begin verification, check the reasonableness of your numbers. Prepare rough estimates of what the values should be before you complete the calculation. Probabilities must lie between zero and one. We usually have or can estimate a range of plausible outcomes for a calculation. If that reasonable range is exceeded, verify the formula.

Check your calculations with a calculator. You may have a formula that functions exactly the way you programmed it, but if you programmed it incorrectly you may never catch the errors. Calculators can catch errors in formulas.

Sound logic in your model should provide logical results for realistic sets of values. One way to test this logic is to use the zero test, where zero is regarded as an extreme value. Set one or more variables or groups of variables to zero and make sure outputs are as they should be if this value is zero. In our *Vibrio* model, zero *Vibrio* at the time of harvest should produce zero *Vibrio* at the time of consumption given the structure of the model, which does not permit cross-contamination. Likewise, zero *Vibrio* should never result in a positive probability of illness. Thus, the zero test often provides a quick check of the model logic at this extreme value. When zero is not a reasonable extreme value, set the variables to known or reasonable extremes and make sure the intermediate calculations and outputs are as they should be.

Logic tests can be used to debug your model. Increase and then decrease the values of each input value one at a time to ensure that the changes to the outputs are in the logical direction. For example, as water temperature or air temperature increase in the *Vibrio* model, the number of bacteria should increase as well. They should not only increase but be a reasonable magnitude as well.

Excel has some useful auditing capabilities. Two of them are the Trace Precedents and Trace Dependents commands. They can be used to graphically display or trace the relationships between precedent and dependent cells and formulas with tracer arrows. This enables you to ensure that the proper relationships are in place. An example of Trace Precedents is shown for the *Vibrio* model in [Figure 11.20](#). It shows all the cells that influence the probability of illness and the route of their influence. You need not understand the nature of those complex relationships from the figure,

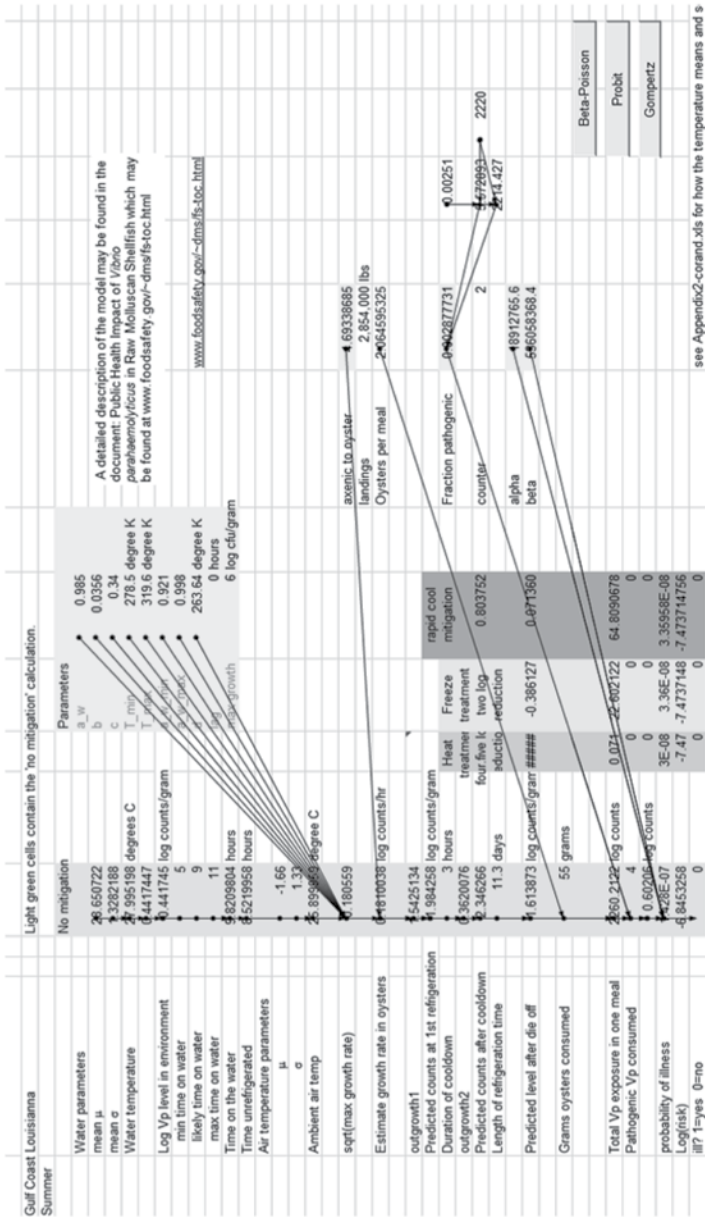


FIGURE 11.20 Trace precedents shows all the variables required to calculate the value in a single cell.

just appreciate the potential utility of the feature. Trace Dependents, as you might imagine, shows all the values that depend on a given cell. With a little practice, these tools can be very helpful in the verification process.

11.5.2.2.11 Check the Formulas

Perhaps this section should have been titled, “No Duh!” Formulas can be checked visually. This is the tedious and monotonous part of the verification. It is also the dangerous part, because if you built the model you may not be able to see your errors. Nonetheless, visual inspection of each cell formula is a minimal expectation for verification.

Excel has several nice features to aid this task. Putting your cursor in a model cell and pressing F2 or double-clicking in that cell will reveal the cell formula, and it will use a color-coded system to highlight every cell in the model that is referenced in that formula.

To reveal all the cell formulas at once, press Control ~. This is especially useful when cells in adjacent rows or columns have similar formulas. In that case, a break in the formula pattern may indicate an error.

Excel also offers an error-checking feature. If errors are found, each potential error is flagged by the appearance of a small triangle in the upper left corner of the cell. Excel’s error checking can find eight different errors. Excel has an error-tracing feature as well. This feature most often points to the source of the error.

The Simulation Settings of Palisade @RISK offer a Pause on Output Error option that is very useful. If a logical error is found in any cell, the simulation will stop on that iteration, enabling you to find the cell with the error message. Excel’s error-checking capabilities or your own trace back can then reveal the logical source of the error.

Excel offers a helpful Evaluate Formula option in the Formula Auditing group of the Formulas tab. To use it, position the cursor in the cell of interest and select Evaluate Formula. Evaluate, Step In, and Step Out options provide an excellent audit trail for checking formulas across a chain of cells. Using name ranges is a decided advantage for getting maximum value from this feature. If these built-in auditing features are not sufficient, there is a wide array of spreadsheet auditing software available on the Internet.

11.5.2.2.12 Test the Model Performance

If you cannot wait to begin to use your model before verifying your model—an ill-advised approach—examine your results as you would intend to do when using your model to answer the risk manager’s question(s). Simply using the model may reveal some logic flaws, and unusual results may help you find bugs in the calculations. If your model is logical and accurate, your results should be also. Doing some sensitivity analysis may help uncover problems in the model. Note that this is not considered an adequate method for verifying your model. It is, however, sometimes helpful for finding gross errors in a model.

If you build models, you will spend a lifetime developing and refining your craft skills. Like model building itself, these can tend to be rather idiosyncratic. The ideas offered here are but the tip of the craft skills iceberg. But, if you actually follow them,

they will advance you up the spreadsheet modeler's learning curve more quickly than your own trial-and-error methods will.

11.5.2.2.13 Documentation

Verification and validation are important steps in model development. They are often overlooked in the more casual application of risk analysis principles and in the less formal risk assessments. When a model has been verified and/or validated, the methods and time frame for accomplishing these tasks should be documented and appended to the model.

11.6 SUMMARY AND LOOK FORWARD

Not many risk assessors are trained as model builders. This is generally a skill that is picked up in practice by people with a quantitative orientation. As a result, the model builder is usually not the subject-matter expert. Model building is, consequently, often a group effort.

A 13-step modeling process is offered in this chapter to help those struggling with the notion of what it means to build a risk assessment model. Model building is iterative. It begins with a conceptual model, evolves to a specification model, and ends up as a computational model. Most model builders manage to muddle through those steps somehow, although it is rare to see the iterations as discrete and separate tasks. Verification, validation, and documentation are, in my experience, the most often overlooked tasks in model building.

The craft skills for model building are what experience teaches you. This chapter attempts to assist your development of craft skills by building on the eight heuristics offered by Powell and Baker (2007). [Chapter 12](#) addresses one of the technical skills quantitative risk assessors must have: a basic understanding and command of the essentials of probability. That is followed by two more chapters on probability topics that will expand your technical skills while, hopefully, helping you to develop your craft skills. These are “Choosing Probability Distribution” ([Chapter 13](#)) and “Characterizing Uncertainty Through Expert Elicitation” ([Chapter 14](#)).

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12 Probability Review

12.1 INTRODUCTION

Risk analysis is decision making under uncertainty. Resolving and addressing that uncertainty is a primary reason for risk assessment. Probability is the language we use to express our uncertainty. One has to understand probability if risk assessment is going to address the knowledge uncertainty and natural variability in our decision problems. Quantitative risk assessment uses the language of probability, and it is essential to know the structure of any language, so we do not misuse it. Learning that basic structure is the purpose of this chapter.

Risk has been described as the product of a consequence and its probability. Assessors need to understand probabilities to assess them honestly. Managers need to understand probability to manage risks effectively. Risk communicators have to understand probability to explain it to others. Not everyone needs to know how to do good probabilistic risk assessment, but everyone does have to be conversant and knowledgeable about some very basic facts about probability.

One problem with probability is that it does not lend itself well to intuition. If there is a 10% chance of rain and we get caught in a downpour, we are more inclined to think the forecast was wrong than we are to think the rain was an event that had only a 10% chance.

To further illustrate the nonintuitive nature of probability, consider the so-called Monty Hall problem, which I have used in risk assessment training for years. A letter writer to *Parade Magazine* (Whitaker 1990) posed the following question. “Suppose you’re on a game show, and you’re given the choice of three doors: Behind one door is a car; behind the others, goats. You pick a door, say No. 1, and the host, who knows what is behind the doors, opens another door, say No. 3, which has a goat. He then says to you, “Do you want to pick door No. 2?” Is it to your advantage to switch your choice?”

The answer is yes. You win twice as often if you switch. This just does not make sense to most people. The usual logic goes something like this. When presented with the original choice of one door from among three, we have a $1/3$ chance of winning the car. Once there are only two doors left, most people tend to believe each one now has a $1/2$ chance of hiding the car, and so one perceives that each door has a $1/2$ chance of winning. This is not so.

There was a $1/3$ chance the car was behind the contestant’s door and a $2/3$ chance it was behind one of the other two. When the host opens one of these other two doors he is providing the contestant with new information, the car is not behind door 3. The observant contestant now knows that $2/3$ chance of winning all resides in door 2. Given a choice between a $1/3$ chance of winning and a $2/3$ chance of winning, who would not prefer the better odds? So, you should always switch in such a game.

Here is how it works. Monty Hall, the game show host, always knows where the car is, and this is critical. Let the car be behind door 1. If you correctly chose the door with the car (door 1), he can open either of the other doors to reveal a goat. If you decide to switch when you pick door 1 you will give up the car and end up with a goat. Switching is a losing strategy in this case. The score is switch 0 and stay 1.

Suppose, now, you choose door 2, which is hiding a goat. Monty, knowing the car is behind door 1, opens the third door to show you a goat. This time switching doors wins for you. The score is now switch 1 and stay 1. Now imagine you choose door 3. Monty now opens door 2 to show you the goat. Once again, switching doors means you trade a goat for a car and win. The score is now switch 2 and stay 1. No matter which door the car is behind, the logic here always leads to a score of switch winning twice and stay winning once. If you switch, you will win $2/3$ of the time; if you stay with your original choice you win $1/3$ of the time. You are not guaranteed a win if you switch, but you will win twice as often as you lose in the long run, and that is not intuitively obvious to many people.

This chapter provides a review of probability concepts that you'll need to understand to do basic quantitative risk assessment. It is also a good review for managers and communicators as well. The chapter does not attempt a rigorous theoretical development or treatment of probability. What it does do is offer a survey review of the kinds of concepts anyone working in risk analysis is likely to need.

12.2 TWO SCHOOLS OF THOUGHT

Probability is the chance that something will or will not happen. There are two schools of thought on the nature of probability. They go by many names, but we'll call them the *frequentist* and *subjectivist* schools. The frequentist approach to probability is based loosely on the notion that true probability values are "out there" and that we can discover them through data. Specifically, we can calculate the long-run expected frequency of occurrence. The probability of an event A, $P(A)$, is equal to n/N , where n is the number of times event A occurs in N opportunities. It is the frequency with which A occurs out of the number of times it could occur. So, the annual probability of a hurricane hitting your community is estimated by the number of years a hurricane strikes out of the number of years observed. The probability of an accident per vehicle mile is the number of accidents divided by the number of vehicle miles. The frequentist view of probability works quite well with repeatable events.

There is also a subjective or degree-of-belief view of probability. This is based loosely on the notion that probability is an intrinsic phenomenon, that is, it is a device humans use to explain and deal with natural variability and knowledge uncertainty. Probability is not out there; it is in us. Probability is a measure of the plausibility of an event given our incomplete knowledge.

Some events have a uniqueness about them that denies the use of frequency. There are many things that have never happened before or things that may only happen once, so we cannot estimate their probabilities with frequencies of occurrence. A subjectivist view of probability is especially useful for these unique events. Bayesians favor this view of probability.

What is the probability I will obtain heads before I toss a fair coin? It is 0.5; this is a frequency. We can verify this probability by observing a great many flips and counting the proportion of heads. Once I flip the coin, what is the probability it is heads? The true probability is now either 0 if it is tails or 1 if it is heads. The true probability is uncertain, and now a degree-of-belief view of probability applies. With this simple example we have natural variation in the large, and this is amenable to the relative frequency view. We also have knowledge uncertainty in the small (a single completed toss). Thus, there is room for both schools of thought in my own approach to risk assessment. You will have to make your own choice.

Two people can have different degrees of belief about the probability of the same uncertain event and both can be right. If I believe there is an 80% chance of rain today and you believe there is a 50% chance of rain, we are both right if it rains. In fact, we are both right if it does not rain. If reading that hurts your head, it may be because you are beginning to understand. Probability is not easily intuited.

The mathematics of probability are well settled. The two schools of thought pretty much agree on these mathematical matters. It is the philosophy of probability that causes the problems. Discussions of this philosophy can bring out an intensity of emotions unrivaled by any other topic in mathematics, an intensity often reserved for politics and religion. If you want to be a good risk manager, never seat a frequentist next to a subjectivist at a dinner party.

FREQUENTIST AND BAYESIAN MEANS

A frequentist believes a population mean is real but unknown and often unknowable. It can only be *estimated* from the data using confidence intervals. A Bayesian believes the population mean is an abstraction. Only the data are real.

12.3 PROBABILITY ESSENTIALS

Probability is measured as a number between zero and one. Zero means there is no chance the event will occur, that is, it is impossible. Numbers close to zero are, therefore describing events that are close to impossible. One means the event has happened or is sure to happen. Numbers close to one describe events that are almost certain to occur.

What then is the most uncertain number of all? Is it your chance of winning the Powerball grand prize, which is 1 in 195,249,054 (the equivalent of 5×10^{-9})? Surely not, as that probability is fairly definitive; winning that prize is as close to impossible as you are likely to get! Small probabilities mean unlikely events; they do not convey great uncertainty, however. The most uncertain probability of all is 0.5. If the probability of rain is 50%, it is as likely to rain as to not rain. Once the probability shades a little one way, 0.500001, or the other, 0.499999, we can see it is slightly more likely to rain than not rain or to not rain than rain, and the uncertainty slowly begins to resolve as probabilities move toward zero or one.

The “sample space” is one probability theory concept it would be unwise to overlook. Let us start with something simple like tossing two dice, one red and one white. There are exactly 36 possible outcomes, no more and no less. Table 12.1 enumerates the possibilities. The sample space is the set of all the possible outcomes. The sum of the probabilities of all the possible outcomes must equal one. This is equivalent to saying that one and only one of these dice rolls must happen if we roll the dice. A sample space must be mutually exclusive (only one of them can happen at a time) and collectively exhaustive (there is no result, i.e., not included in the sample space).

There are 36 possibilities. Each outcome in the space has an equal chance, $1/n$, where n is the number of possible outcomes. In this case the probability of any one outcome is $1/36$. We can define an event as rolling a six, and, using a frequentist approach, we can see five different ways of doing this, each with a probability of $1/36$. So, the probability of this event is $5/36$.

Now let us use an event tree to identify a sample space. Figure 12.1 shows an example for tossing three coins in sequence. The figure shows how the sample space (circled) is derived through the various pathways. All possible outcomes are shown; there are no other possibilities. The probability of each triplet outcome is equally likely, $1/n$. This time, n is 8, and the probability of three heads (HHH) is 12.5% or $1/8$. We can again count up different outcomes to define events such as getting two heads. There are three ways to do that, each with a probability of 12.5%, so the probability of the event two heads and one tails is 37.5% or $3/8$.

Event trees are handy risk models for a wide variety of problems. The endpoints of such a model define the sample space for the risk problem. The endpoints need not be equally likely in a risk problem, but the sum of the probabilities of all endpoints must sum to one, just as they do here.

Note that Figure 12.1 shows a sample space constructed of numerous pathways comprising nodes and branches. When we arrive at a node, something has to happen. That is, we move forward on one branch or another. Thus, all branches must be mutually exclusive and collectively exhaustive. The probabilities of all the branches coming out of a single node must also sum to one, because something has to happen at each node, and the branches define all the possibilities. So, an event tree, in this sense, has sample spaces within sample spaces. The endpoints of each sample space must have probabilities that sum to one.

TABLE 12.1
Sample Space of Outcomes for Tosses of One Red and One White Die

Red	White	Red	White	Red	White	Red	White	Red	White	Red	White
1	1	2	1	3	1	4	1	5	1	6	1
1	2	2	2	3	2	4	2	5	2	6	2
1	3	2	3	3	3	4	3	5	3	6	3
1	4	2	4	3	4	4	4	5	4	6	4
1	5	2	5	3	5	4	5	5	5	6	5
1	6	2	6	3	6	4	6	5	6	6	6

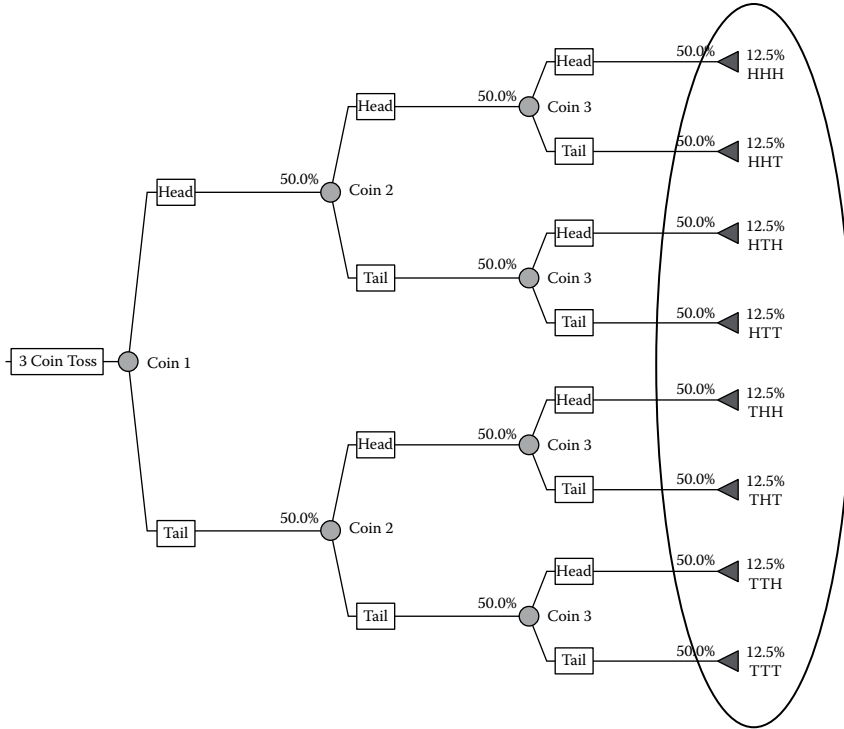


FIGURE 12.1 Event-tree sample space for a three-coin toss experiment.

When using tree models to represent risks, the same simple probability rules hold. Identifying the mutually exclusive and collectively exhaustive set of endpoints that will define the sample space is not often a simple exercise in counting as it is with dice and coins. Nonetheless, it is important to understand that such models are just defining a sample space of outcomes of interest to risk managers. These models must obey the mathematical laws that order probability. It is not okay to simply build a model and start filling in numbers. The numbers must behave properly and follow the laws of probability.

Figure 12.2 shows a simplified and hypothetical earthquake risk for a structure. There are four possible endpoints for this simple risk model. The probabilities of these four endpoints must sum to one.

Each node in an event tree identifies a new event, and each has its own unique probability, as seen in Figure 12.2. The first event is that the soil does (30%) or does not (70%) liquefy as the result of an earthquake. If it does, the second event is that the structure does (80%) or does not (20%) crack. If the result of the first event is no liquefied soil, then the probability of cracking (60%) and not cracking (40%) change because of different precedent conditions. Unlike the coin example, where each event is independent of every other event and probabilities are constant, the world of risk is full of dependencies. Preceding events and conditions usually influence the

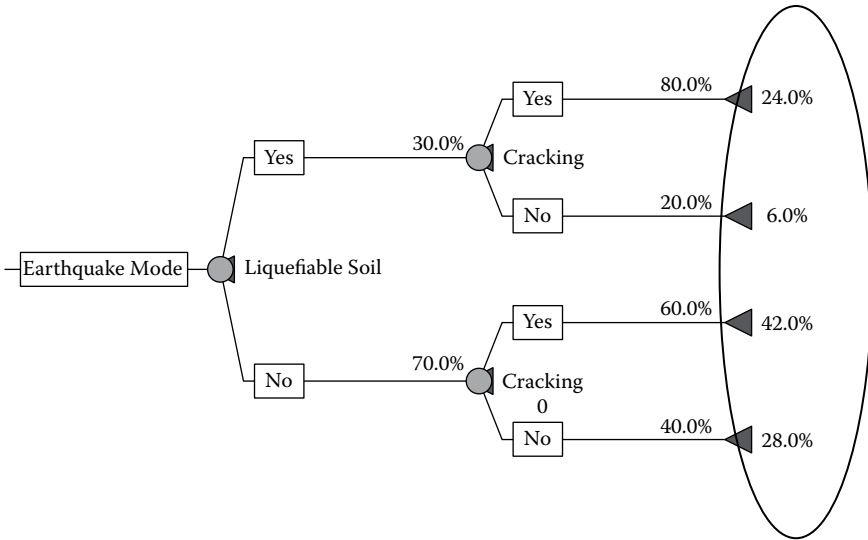


FIGURE 12.2 Event-tree sample space for structure cracking after an earthquake.

probability and nature of antecedent events. This leads to a sample space where the outcomes are not all equally likely.

The most likely outcome in the sample space is structure cracking with no liquefiable soil. The least likely outcome is no cracking when the soil does liquefy. There are principles and facts that underlie the probability values in a risk model like the event tree of [Figure 12.2](#).

Probabilities can be expressed as a decimal, percentage, fraction, or odds. Using the model in [Figure 12.2](#), the probability that the soil will liquefy and the structure will crack can be expressed as follows:

- Decimal = 0.24
- Percentage = 24%
- Fraction = $24/100 = 6/25$
- Odds = 6:19 (x:y based on $x/[x + y]$)

In the United States, the most common way of expressing probabilities may be odds. Games of chance and gambling are at the root of much of our knowledge about probability, and gamblers understand odds. In risk analysis the other three forms are more commonly used.

Decimals are sometimes preferred when speaking about the probability of a single event, for example, the probability of a single egg containing *Salmonella* Enteritidis is about 5×10^{-5} (FSIS 1998). Percentages are sometimes preferred to convey information about a population, for example, 0.005% of all eggs contain *Salmonella* Enteritidis. Fractions are another popular alternative for conveying risk information to the public, for example, about 1 in 20,000 eggs contain *Salmonella* Enteritidis.

12.4 HOW DO WE GET PROBABILITIES?

How do we manage to identify these numbers between zero and one? Where do they come from? There are three basic ways to estimate probabilities, although these three ways really just reflect the two schools of thought on probability mentioned earlier.

RANK AND ODDS OF POKER HANDS

Royal flush	1:649,739
Straight flush	1:64,973
4 of a kind	1:4,164
Full house	1:693
Flush	1:508
Straight	1:254
3 of a kind	1:46
2 pair	1:20
1 pair	1:1.37
High card	1:1

Classical or analytical probabilities are mathematical calculations that are used by both schools. I like to describe analytical probabilities as the kinds of probabilities that “smart people” can do with pencil and paper or a calculator. When you open a new deck of cards and find the odds of being dealt different poker hands (see box) before the draw, these probabilities have been calculated analytically.

Analytical probabilities rely on identifying sample spaces and taking subsets of them. Combinatorics like the factorial rule of counting, permutations ($n!/r!(n-r)!$), combinations ($n!/r!(n-r)!$), and other counting techniques are used to estimate probabilities of specific events, like a full house.

Unfortunately, risk assessors do not too often get the opportunity to work with analytical probabilities, although phenomena that are subject to random processes like the binomial, Poisson, and hypergeometric processes do provide opportunities to calculate these analytical probabilities at times. So, although analytical probabilities occupy a great deal of our higher education exposure to probabilities, they do not come up as often as we would like when doing risk assessment.

A second source of probabilities is empirical or frequentist probabilities. These are based on observation. How many times did the event of interest happen out of the number of times it could have happened? Think of a traffic light near your home. What is the probability you will catch it red the next time you encounter it? All we need to do is keep a little pad of paper on the seat of the car. Make a strike mark under “red” each time it is red and under “not red” when it is not. After a hundred or so observations, we can calculate the relative frequency of a red light. This is now our approximation of the true probability of catching the light red. As we record more observations over the years, our estimate gets better. A relative frequency is nothing but an estimate of the true probability for a frequentist. It is but data to a Bayesian.

Empirical probabilities are especially useful when the process of interest is repeated many times under the same circumstances. Empirical probabilities are good for estimating the reliability of electrical components, stream flows, causes of death, probabilities of cancer from animal toxicity studies, and the like. This makes relative frequencies or frequencies one of the most common sources of probabilistic information for risk assessment.

The third source of probability estimates is subjective probabilities. Subjective probability is based on evidence and the experience of the estimator. It relies heavily on expert opinion. It is most useful when we deal with the uncertainty that surrounds events that will occur once or that have not yet occurred.

Subjective probability estimates are especially useful for filling in data gaps and supplementing data with experience and judgment. Risk assessors must deal with different kinds of events as well as different levels of data and information about these events. Subjective probabilities are most useful for those unique events for which there are no relative frequency data and for which analytical calculations are not possible.

Suppose we want to estimate the probability that the channel bottom is 30% or more rock, or that there will be structural damage to a building if an earthquake less than 6.2 on the Richter scale occurs? We might want to estimate the probability of a fatal accident on a dangerous curve if the curve is redesigned and eased. We might need to estimate the probability of illness from a low-dose exposure to pathogenic bacteria, and so on. These examples lend themselves well to subjective probability estimates.

12.5 WORKING WITH PROBABILITIES

If it was as simple as the previous material might suggest, anyone could work with probabilities. It is not that simple. There are rules and theories that govern our use of probabilities. Estimating probabilities of real situations requires us to think about complex events and to apply these rules carefully. Most of us do not naturally assess probabilities well. Hence, it is critical to good quantitative risk assessment that you have people who can work effectively with probabilities. Some of the fundamental axioms and rules of probabilities are described in the following sections.

12.5.1 AXIOMS

Probability density functions and cumulative probability distribution functions (these ideas are discussed at length in [Chapter 13](#)) and their properties are all essentially developed from three fundamental axioms of probability. An event, E_i , is anything for which you want to know the probability. S is the sample space that includes all events of interest. The probability of an event, $P(E_i)$, is defined such that:

1. $0 \leq P(E_i) \leq 1$
2. $P(S) = 1$
3. If A and B are mutually exclusive events, then $P(A \text{ or } B) = P(A) + P(B)$

The first axiom means the probability of an event is a nonnegative real number between 0 and 1. The second axiom means the probability that some event in the sample space will occur is 1, and there are no events that can occur that are outside the sample space. The third axiom says the probability of two mutually exclusive events occurring together is the sum of their individual event probabilities.

12.5.2 PROPOSITIONS AND RULES

In addition to these axioms, there are some consequences of these axioms that prove to be essential for quantitative risk assessment.

12.5.2.1 Marginal Probability

A marginal probability is the probability of a single event, $P(A)$ (read, the probability of A), where A stands for any event whose probability we want to know. To illustrate this and the following concepts, we'll use the data in [Table 12.2](#). The hypothetical data show ownership of the levees in a region in the rows and the maintenance condition of those levees in the columns.

Two examples of marginal probabilities are shown as follows:

$$\begin{aligned} P(\text{Private}) &= 100/300 = 0.333 \\ P(\text{Adequate}) &= 160/300 = 0.533 \end{aligned}$$

12.5.2.2 Complementarity

The rule of complementarity ensures that the probability of an event and its complement in the sample space sum to one. The probability that event A does not happen ($\sim A$ means not A) is:

$$P(\sim A) = 1 - P(A) \tag{12.1}$$

Two examples follow:

$$\begin{aligned} P(\sim \text{Private}) &= 1 - 0.333 = 0.667 \\ P(\sim \text{Adequate}) &= 1 - 0.533 = 0.467 \end{aligned}$$

TABLE 12.2
Levee Ownership and Maintenance Condition

	Inadequate Maintenance	Adequate Maintenance	Total
Private	80	20	100
Locally constructed	50	50	100
Federal construction	10	90	100
Total	140	160	300

12.5.2.3 Addition Rules

There are many times when assessors will be interested in more than one event occurring. For two different events, A and B, the probability that A or B or both occur is defined by the addition rule. The form of the rule depends on whether A and B are mutually exclusive or not. When events are mutually exclusive they cannot occur simultaneously. When they are not they may both occur.

The addition rule for mutually exclusive events is:

$$P(A \text{ or } B) = P(A) + P(B) \quad (12.2)$$

An example is:

$$P(\text{Private and Local}) = 100/300 + 100/300 = 200/300 = 0.667$$

The rule works the same for N mutually exclusive events.

$$P(A_1 \text{ or } A_2 \text{ or } \dots A_N) = P(A_1) + P(A_2) + \dots + P(A_N) \quad (12.3)$$

The addition rule for nonmutually exclusive events is:

$$P(A \text{ or } B) = P(A) + P(B) - P(A \text{ and } B) \quad (12.4)$$

Because the events can occur at the same time we must avoid double counting outcomes. For example, consider the probability a levee is both private and inadequately maintained. There are 100 private levees and 140 inadequately maintained levees. There are eighty levees that are both, so they are counted twice, and we must subtract out these joint events.

The calculation is:

$$P(\text{Private and Inadequate}) = 100/300 + 140/300 - 80/300 = 160/300 = 0.533$$

The rule works for N nonmutually exclusive events, but all multiple counts of the same elements must be accounted for.

12.5.2.4 Multiplication Rules

Multiplication rules apply when we are interested in the probability that two things occur together. The proper formula depends on whether the events A and B are independent or dependent events.

Two events, A and B, are independent if the fact that A occurs does not affect the probability of B occurring. When we have independent events, the probability of both occurring, that is, the multiplication rule, is:

$$P(A \text{ and } B) = P(A)P(B) \quad (12.5)$$

The probabilities in [Table 12.2](#) are dependent, so we must vary the example for a moment, and then we will return to the table. In [Figure 12.3](#), let heads for coin 1 be

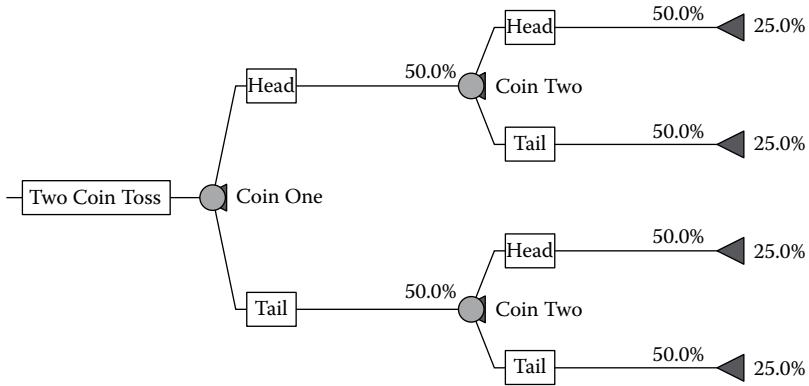


FIGURE 12.3 Probability tree for a two-coin toss experiment.

event A and heads for coin 2 be event B. They are independent events. The result of the first coin toss has no effect on the probability of the outcome of the second coin toss. Note that the probability of heads is the same regardless of what the result of the first coin toss was. In this example of independent events:

$$P(A \text{ and } B) = P(\text{coin 1 is heads and coin 2 is heads}) = (0.5)(0.5) = 0.25 \text{ or } 25\%.$$

Two events, A and B, are dependent if the outcome or occurrence of A affects the outcome or occurrence of B so that the probability of B is changed. The earthquake event tree of [Figure 12.2](#) is an example of dependent events. We saw that liquefiable soil made structure cracking more likely.

If A and B are dependent events, then the probability of both occurring is:

$$P(A \text{ and } B) = P(A)P(B \text{ after } A) \tag{12.6}$$

$P(B \text{ after } A)$ can also be written as $P(B|A)$ (read, the probability of B given that A has happened), and then the multiplication rule for dependent events is rewritten as:

$$P(A \text{ and } B) = P(A)P(B|A) \tag{12.7}$$

We can now return to our example using [Table 12.2](#). However, let us display it as the probability tree in [Figure 12.4](#). Note that the probability of inadequate maintenance varies depending on ownership. If ownership and maintenance were independent, the probability of inadequate maintenance would be the same for each kind of ownership and it would equal the marginal probability $P(\text{Inadequate}) = 0.467$.

The $P(\text{Private and Inadequate})$ can be read directly from the tree: it is 0.267. If we look at the table, it is even easier to find. There are 80 levees that are both private and inadequate out of a total of 300 levees, $80/300 = 0.267$.

Unfortunately, most probability problems do not come with a neatly worked out table or probability tree. That is when the formula becomes important. The term

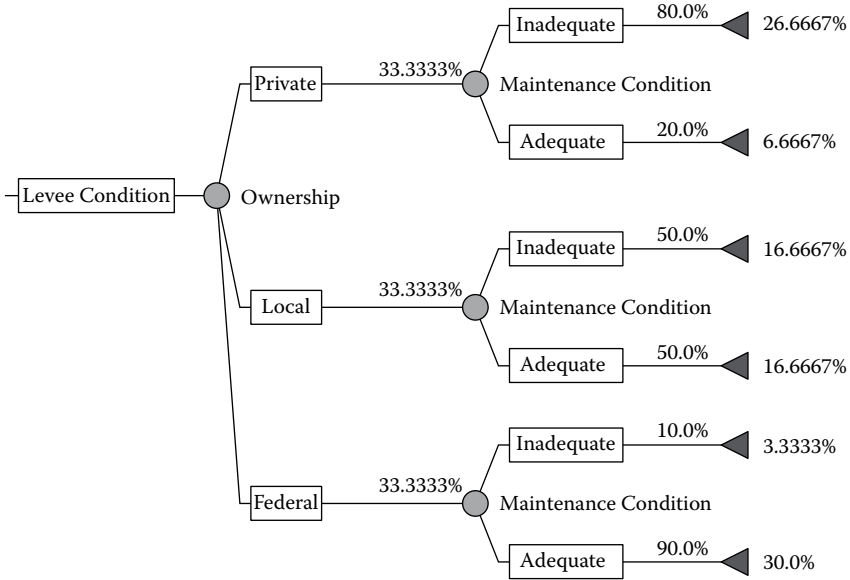


FIGURE 12.4 Probability tree for levee ownership and maintenance condition.

$P(B|A)$ in Equation 12.7 is called a conditional probability. It is the subject of the next section.

12.5.2.5 Conditional Probability

Information changes probabilities. We see that from the previous discussion. The $P(\text{Inadequate}) = 0.467$, but when provided with information about ownership, the probability that a levee is inadequate changes. To reflect this fact, we use conditional probability.

The probability that event A happens, given the condition that event B happens, is written $P(A|B)$. In our prior examples we could say:

$$\begin{aligned}
 P(\text{Inadequate}|\text{Private}) &= 0.8 \\
 P(\text{Inadequate}|\text{Local}) &= 0.5 \\
 P(\text{Inadequate}|\text{Federal}) &= 0.1
 \end{aligned}$$

Let us revisit the multiplication rule for dependent events using the conditions of inadequate maintenance and private ownership.

$$\begin{aligned}
 P(\text{Inadequate and Private}) &= P(\text{Inadequate})P(\text{Private}|\text{Inadequate}) \\
 &= (140/300)(80/140) = 80/300 = 0.267
 \end{aligned}$$

$P(\text{Private}|\text{Inadequate})$ is a conditional probability, and it is a switch of the conditional probability $P(\text{Inadequate}|\text{Private})$ shown previously. Using Table 12.2, we can see the condition that the levee is inadequately maintained in the second

column. This tells us the levee of interest is one of the 140 levees in that column. We are no longer dealing with all 300 levees. Thus, the conditional information changed the probability of a private levee from $100/300$ to $80/140$. Information changes probabilities.

Conditional probabilities can also be defined with a formula. Starting from the multiplication rule for dependent events we have:

$$P(A \text{ and } B) = P(A)P(B|A)$$

Rearranging we obtain:

$$P(B|A) = \frac{P(A \text{ and } B)}{P(A)} \quad (12.8)$$

Thus, substituting into Equation 12.8, we get:

$$\begin{aligned} P(\text{Private}|\text{Inadequate}) &= P(\text{Inadequate and Private})/P(\text{Inadequate}) \\ &= (80/300)/(140/300) = 80/140 = 0.571 \end{aligned}$$

12.5.2.6 Bayes' Theorem

Building on the notion that information can change probabilities, we introduce Bayes' Theorem, which is useful for updating probabilities on the basis of newly obtained information. Often, we begin with an initial or prior probability that an event will occur. Then, as uncertainty is reduced or new information comes in, we revise the probability to what we call the posterior probability. This revision can be done using Bayes' Theorem.

Bayes' Theorem is:

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} = \frac{P(A \text{ and } B)}{P(B)} \quad (12.9)$$

To illustrate the theorem, let us vary the example and consider the hypothetical event that a randomly selected crate of imported produce has some form of pathogenic *E. coli* to be 0.001. Thus,

$$P(Ec) = 0.001 \text{ and } P(\sim Ec) = 0.999$$

Suppose a diagnostic test can accurately detect *E. coli* 99% of the time. Further assume that 5% of crates that do not have *E. coli* will test positive. That is,

$$P(+|Ec) = 0.99 \text{ and } P(+|\sim Ec) = 0.05$$

Now suppose the test is administered to a randomly selected crate of imported produce, which may or may not have pathogenic *E. coli* on it, and the test is positive.

What is the probability that the crate has pathogenic *E. coli*? Using the concepts we have developed, we are looking for the probability, $P(\text{Ec}|+)$.

This is sometimes called the Bayesian flip because it is the opposite of the known probability $P(+|\text{Ec})$. Note also that we know $P(\text{Ec})$, which is the prior probability that is being updated with new information, that is, that the crate tested positive. Substituting into Bayes' Theorem in Equation 12.9 we are calculating:

$$P(\text{Ec}|+) = \frac{P(+|\text{Ec})P(\text{Ec})}{P(+)} = \frac{P(\text{Ec and } +)}{P(+)} \quad (12.10)$$

Substituting the available values we get:

$$P(\text{Ec}|+) = \frac{(0.99)(0.001)}{P(+)}$$

So far, we do not know $P(+)$. There are two ways a crate can test positive: if it has *E. coli* and tests positive or if it has no *E. coli* and tests positive. These two possibilities are defined as:

$$P(+)= P(\text{Ec and } +) + P(\sim\text{Ec and } +) \quad (12.11)$$

Recall from Equation 12.7 that $P(A \text{ and } B) = P(A)P(B|A)$, enabling us to rewrite this as:

$$P(+)= P(\text{Ec})P(+|\text{Ec}) + P(\sim\text{Ec})P(+|\sim\text{Ec}) \quad (12.12)$$

Substituting, we have:

$$P(\text{Ec}|+) = \frac{(0.99)(0.001)}{P(\text{Ec})P(+|\text{Ec}) + P(\sim\text{Ec})P(+|\sim\text{Ec})}$$

$$P(\text{Ec}|+) = \frac{(0.99)(0.001)}{(0.001)(0.99) + (0.05)(0.999)} = 0.019$$

Although the prior $P(\text{Ec}) = 0.001$, we now have an updated probability, conditioned on the knowledge that this crate has tested positive, and we see the probability that it is actually contaminated is only 0.019. This is the posterior of Ec given the positive test result. This is essentially telling us that if all crates were tested, only 1.9% of those that tested positive would actually be contaminated. That means that 98.1% of all positive testing crates would actually be free of pathogenic Ec. This somewhat surprising result is because so few crates are actually contaminated. Most crates are free of the organism, and these yield false positives at a low rate but in rather large numbers.

To see this, suppose we import 1,000,000 crates. At a rate of 0.001, we have 1,000 that are contaminated, and our test picks up 99% of them. So, we have 990 true positives. But 999,000 are free of contamination and 5% of them show up positive: That is 49,950 false positives. There is a total of 50,940 positive tests, but only 990 or 1.9% of them are actually contaminated. This is a powerful argument against 100% inspection. We would be destroying a lot of good product.

There is an entire body of statistics based on Bayes' Theorem. It is sometimes controversial if the prior probability is based on subjective considerations. This example began with a probability imbued with some credibility. When there is little to no data to support a prior probability, some people become uncomfortable with this approach.

12.6 WHY YOU NEED TO KNOW THIS

You cannot build valid models unless you know and follow the axioms and propositions of probability. It is essential to understand and obey the rules of probability when building models. It is not acceptable to simply apply probabilities in an uninformed fashion. It is not possible to do credible probabilistic risk assessment without a careful knowledge of and adherence to the rules of probability.

Consider the levee ownership model once more, this time as seen in Figure 12.5. Every rule discussed here is employed to build this simple model. Complementarity must be observed on the branches from a node and in the model endpoints. Probabilities of endpoints are determined via multiplication. Probabilities of dependent events rely on conditional probabilities. Probabilities throughout the model, but especially for endpoints, can be added to obtain other probabilities of interest. And this is a simple model. A risk assessor cannot know too much about probability.

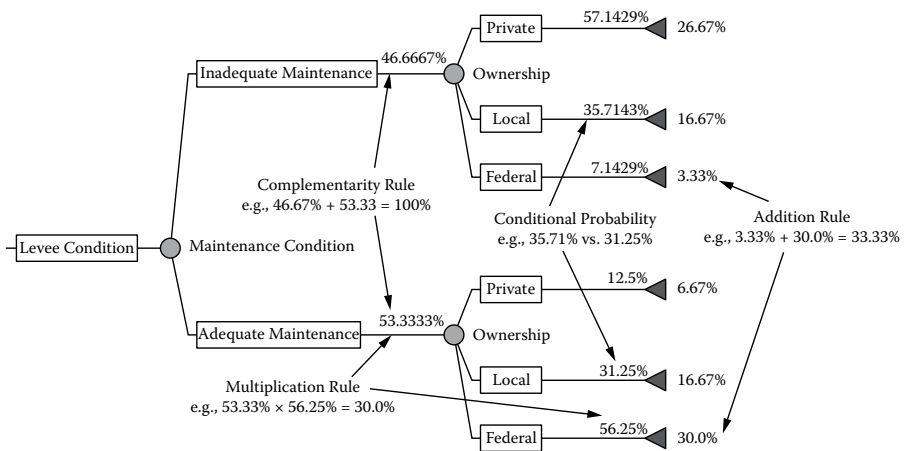


FIGURE 12.5 Levee-condition event tree showing application of rules of probability calculation.

12.7 SUMMARY AND LOOK FORWARD

Probability is the language of uncertainty. It is used to characterize our knowledge uncertainty and to describe the natural variability in the universe. Someone on the risk assessment team has to understand the basic laws, axioms, propositions, and rules of probability. A brief review of these essentials is presented here.

[Chapter 13](#) is devoted to helping the self-taught or trained-on-the-job risk assessor to accomplish one of the most challenging tasks in quantitative risk assessment: choosing the right probability distribution. This is a subject that is not treated very comprehensively in the literature. A nine-step process is offered and illustrated in [Chapter 13](#). [Chapter 14](#) follows with a discussion of subjective probability elicitation.

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13 Choosing a Probability Distribution

13.1 INTRODUCTION

Quantitative risk assessment requires probability estimation, either explicitly or implicitly. If you're going to be involved in risk analysis, you've got to be comfortable with probabilistic thinking. To do probabilistic risk assessment well, someone on the team has to be proficient in choosing the appropriate probability distributions to describe data, model natural variability, and represent knowledge uncertainty about model inputs for the problems you are addressing. One of the most confounding tasks, for new and experienced risk assessors alike, is learning how to choose the right probability distribution for a risk assessment.

Choosing a probability distribution is sometimes called choosing a probability model; this is not to be confused with building a probabilistic model. This chapter presents a strategy to help you to choose probability distributions when you have some information about the quantity you are modeling. Information may be recorded in the form of data; it could be general or specific knowledge; or it might be experiential wisdom or professional judgment. The strategy described in this chapter is primarily for situations where you have some data, but it should help you in any situation where you must choose a probability distribution.

The chapter begins by considering different graphs used to display probability information. This is followed by a nine-step strategy for selecting a probability distribution. It includes a simple method for developing an empirical distribution as well as steps to take when an empirical distribution will not do. Two example applications of the strategy are presented before the chapter ends by presenting and briefly describing several distributions that have proven useful to risk assessors.

13.2 GRAPHICAL REVIEW

Graphics are a principle means of conveying probabilistic risk information. Both risk assessors and managers need to be comfortable reading and interpreting probability graphs. So, we begin by reviewing the most common probability graphs, that is, the probability density function, cumulative distribution function, survival function, probability mass function, and the cumulative distribution function for a discrete random variable. These graphs give us more options for thinking about probability distributions and communicating the meaning of our risk assessment results, the topic of [Chapter 18](#).

13.2.1 PROBABILITY DENSITY FUNCTION

The probability density function (PDF) for a continuous random variable is represented by a curve such that the area under the curve between two numbers is

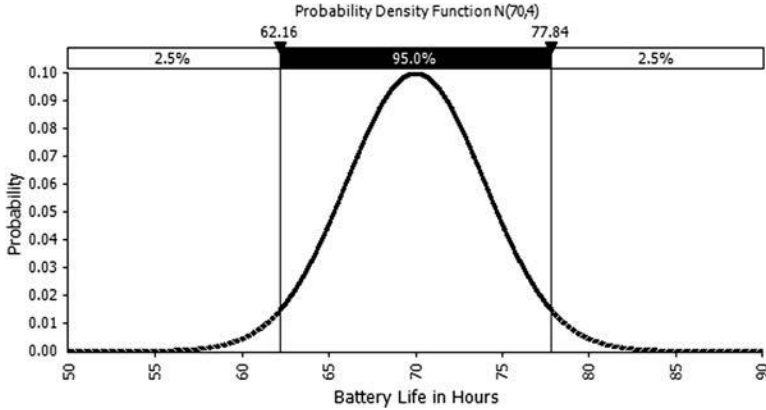


FIGURE 13.1 Probability density function of battery life in hours.

the probability that the random variable will take a value between those two numbers. Consider [Figure 13.1](#). The PDF shown represents the distribution of the population of battery lives measured in hours in a population that is normally distributed with a mean life of 70 hours and a standard deviation of 4 hours.

Note that lifetimes of 62.16 hours and 77.84 hours are identified by the delimiters and that 95% of all batteries have lifetimes between these two values. Because there is an infinite number of values for this continuous variable, the probability of any one specific value cannot be read directly from this graph. The probability of obtaining any one of an infinite number of possible values approaches zero. It is important, therefore, to understand that the numbers on the vertical scale of PDF curves have no useful probability meaning. The vertical numerical scales measure the density of the data and are not probabilities, despite the fact that the vertical axis is often labeled “probability” in such graphs.

Let us leave the battery life distribution for the moment so we can consider this vertical dimension more carefully. [Figure 13.2](#) shows two identical looking normal distributions. Both have a mean of 100. The function on the bottom has a standard deviation of one, the function on the top has a standard deviation of 10. Notice the vertical scale on the top graph shows a greater density of data. [Figure 13.3](#) shows the same two functions overlapping. The tall thin distribution (the top graph in [Figure 13.2](#)) has a greater density of data. As a heuristic device, imagine both distributions have an equal number of data points. The wide distribution distributes them over a greater portion of the number line than the thin distribution does, hence the thin distribution is denser. People are often confused by the numbers on the vertical axis of a density function, so, depending on the knowledge of your audience, it is sometimes less confusing to omit the vertical numerical scale.

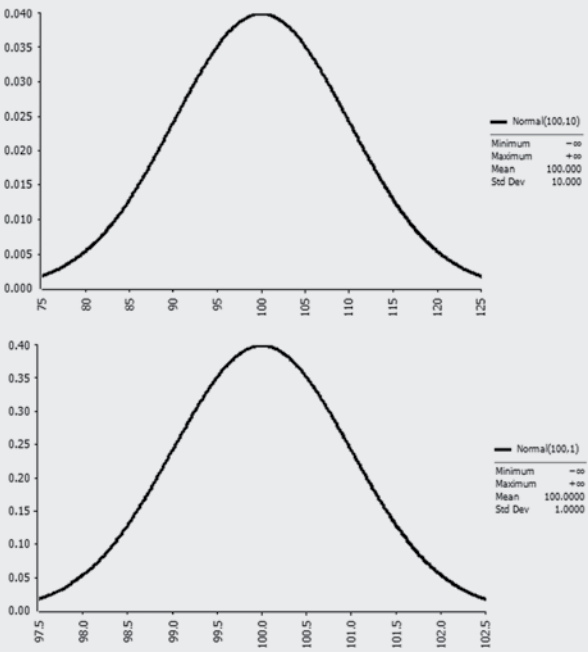


FIGURE 13.2 Similar looking normal distributions with different data densities.

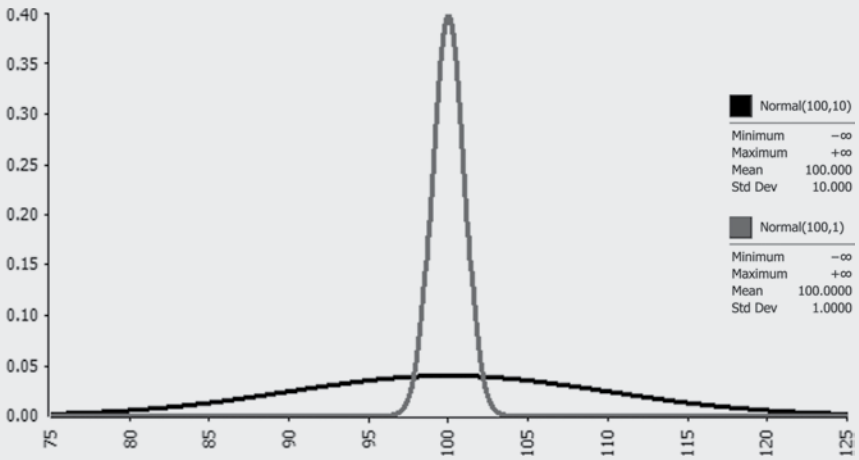


FIGURE 13.3 Normal(100,1) overlaid on normal(100,10) to demonstrate their different densities.

The total area under a density function equals 1. This is because the curve covers all the possible values, and one of them must occur. The sum of the probabilities of all possible values (i.e., the sample space) sums to 1, and this figure represents all those possibilities.

It is also possible to estimate probabilities of open-ended intervals. For example, there is a 2.5% probability a battery will last 62.16 hours or less and a 2.5% probability it will last 77.84 hours or longer. The shapes of a PDF can vary widely, depending on the mathematical form of the function that underlies it and the function's parameter values. The depiction of the distribution of a sample from a population is more appropriately called a histogram or relative frequency distribution.

Informally, you can think of a PDF as a picture of how a population is distributed. This is sometimes a helpful way to explain a distribution to those with little quantitative background. The distribution shows that the values of a variable fall along a specific segment of the number line. The height of the distribution shows the density of the values. The low or skinny parts of the graph indicate that these values occur less often. Figure 13.1 suggests that your battery will most likely last somewhere close to 70 hours. It also suggests it would be very unusual for your battery not to last at least 55 hours, and it would be just as unusual for it to last more than 85 hours.

13.2.2 CUMULATIVE DISTRIBUTION FUNCTION

The continuous data in the PDF can also be displayed as the cumulative distribution function (CDF), seen in Figure 13.4. It is mathematically equivalent to the PDF; the PDF is the derivative of the CDF and the CDF is the integral of the PDF. The horizontal axis remains unchanged. Unlike the PDF, the vertical axis has a meaningful scale. The vertical axis now represents a cumulative probability from 0 to 1. It may be easier for some to think of the vertical axis in terms of percentiles.

There are two ways to read this distribution. Beginning from the horizontal axis, choose a value of interest, say 62.16 hours (bottom horizontal arrow), and note its corresponding probability on the vertical axis. This value was conveniently chosen

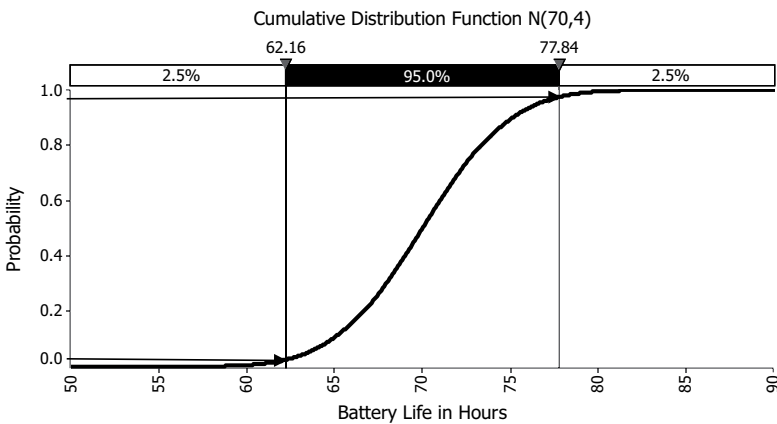


FIGURE 13.4 Cumulative distribution function of battery life in hours.

because its probability is also shown at the top of the graph, 0.025. The population interpretation of this value means that 2.5% of all batteries last 62.16 hours or less. The individual element interpretation is that the probability a random battery will last 62.16 hours or less is 2.5%. A third interpretation is that 62.16 hours is the 2.5 percentile value for the population.

The second way to read the curve is to choose a probability value on the vertical axis, find its intersection on the curve (top horizontal arrow), and read the corresponding variable value from the horizontal axis. In this case, the 97.5 percentile, that is, the cumulative probability of 0.975, value is 77.84 hours. Many CDFs have a more or less exaggerated S shape to them. Because the vertical axis has a meaningful scale, some people find this curve easier to work with to obtain probability estimates. It does not, however, reveal much about the shape of the distribution to the untrained eye.

13.2.3 SURVIVAL FUNCTION

The CDF curve in Figure 13.4 is sometimes called an ascending cumulative distribution. The same data can be plotted in reverse order as a descending cumulative distribution function, which is also called the survival function. An example is presented in Figure 13.5. The interpretation of the graph of continuous data changes in a nuanced way now. Look at the delimited value of 62.16 hours. The curve now says 97.5% of all batteries survive at least 62.16 hours. By contrast, only 2.5% of all batteries survive up to 77.84 hours. You can see batteries “dying off” as battery life is extended. Thus, this curve reveals the likelihood of surviving to a certain age.

The interpretation of the vertical axis has changed. In the CDF it is a cumulative probability, whereas the survival function is $1 - \text{CDF}$. Choosing the value 62.16 hours, the CDF of Figure 13.4 says 2.5% last 62.16 hours or less. With the survival curve, the vertical axis is no longer a cumulative probability; it is now a survival rate. At a value of 62.16 hours, we now see that 97.5% of all batteries survive at least this long. The survival function is often preferred for issues that involve failures.

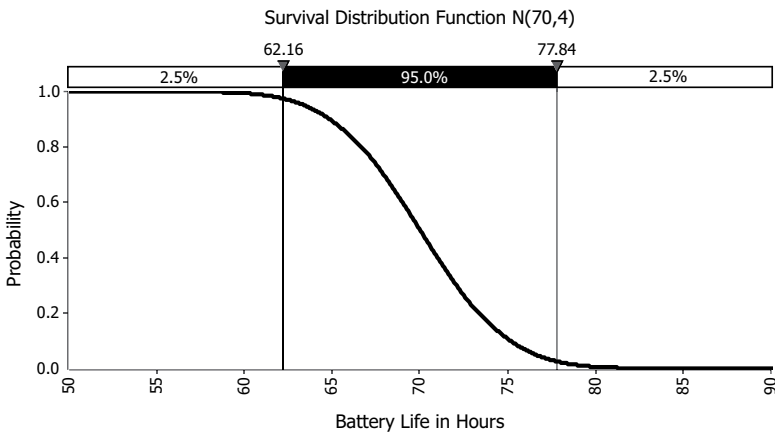


FIGURE 13.5 Survival function of battery life in hours.

13.2.4 PROBABILITY MASS FUNCTION

A discrete random variable does not have a probability density function; it has a probability mass function (PMF). There are two major differences between a PDF and a PMF, the first being that a discrete random variable has a finite number of variable values. As a result, the second difference is that the vertical dimension of a PMF is a meaningful measure of probability. It shows the probability a specific value will occur.

The example in Figure 13.6 shows a Poisson distribution with a mean (λ) of 25 water-going vessels that pass beneath a bridge in an hour. The probability that exactly 15 vessels will pass beneath the bridge can be read directly from the vertical axis; it has a probability of 0.01. A population interpretation means 1% of all hours have exactly 15 vessels passing. Alternatively, a randomly chosen hour has a 1% chance of having exactly 15 vessels pass under the bridge. It is also possible to calculate ranges of values as with the PDF. We can say 2.5% of all hours have fewer than 16 vessels. This is the sum of the individual probabilities of all counts of 15 or less. A sample from the population of a discrete random variable when graphed in this fashion is also called a histogram or relative frequency distribution.

13.2.5 CUMULATIVE DISTRIBUTION FUNCTION FOR A DISCRETE RANDOM VARIABLE

Cumulative ascending (shown in Figure 13.7) and descending (not shown) distribution functions can also be generated for discrete random variables. They are read and interpreted as described previously for the continuous random variable. The shape of the step function is typical for a discrete random variable. As the number of discrete values rises, the steps get smaller and the curve will smooth out and begin to look as smooth as a CDF for a continuous variable.

Armed with this review information, it is time to turn our attention to how to choose a probability distribution to represent a quantity in a probabilistic risk assessment.

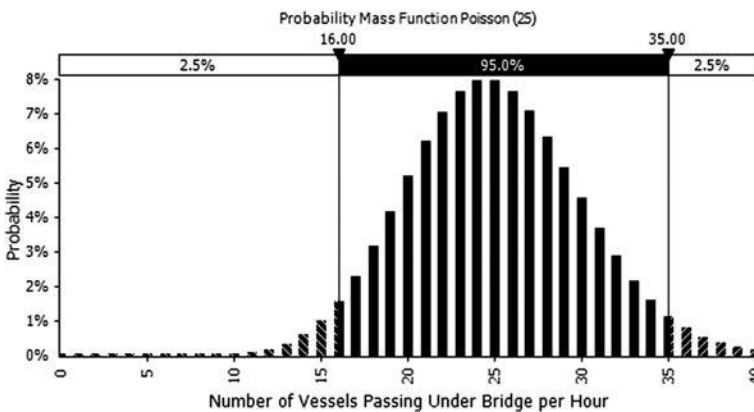


FIGURE 13.6 Probability mass function of number of vessels passing under bridge per hour.

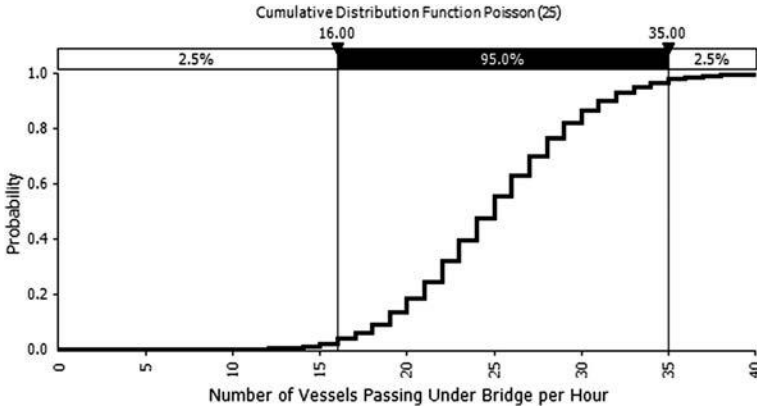


FIGURE 13.7 Discrete cumulative distribution function of number of vessels passing under bridge per hour.

A distribution can be displayed in any of the ways described previously. The shape is most revealing in the PDF and PMF view. The data, especially probabilities, are easier to read in the CDF and survivor function views.

13.3 STRATEGY FOR SELECTING A PROBABILITY DISTRIBUTION

When I began to do risk assessment I was not sure how to choose the proper probability distribution to represent the quantities in my models. I searched high and low for that definitive procedure that would guarantee I had not made a mistake. Guess what? It does not exist, and you will not find it here, either. I have managed, however, to develop a checklist for selecting a distribution. It was compiled over a number of years from a variety of sources, including my own imagination. It offers a sound basic strategy for choosing a probability distribution. Whether you use all, some, or none of this checklist for your own work it is essential that you document your rationale for selecting the probability distributions you do use.

Let us begin with the situation where you have some data to help you represent the natural variability or knowledge uncertainty in a quantity. Now you want to define a probability distribution to use in your risk assessment model. First, you should think critically about your quantity’s uncertainty along the lines presented in [Chapter 2](#). If you have some data, you are most likely modeling natural variability in your variable, although you could be representing your beliefs about the remaining knowledge uncertainty about your value, or possibly some combination of the two. With this as our starting premise, here are a series of steps to follow in order to select a probability distribution to use in your model. Each step is discussed in more detail in the pages that follow.

1. Use your data if possible.
2. Understand your variable and data.

- a. What is the source of your data?
 - b. Is your variable continuous or discrete?
 - c. Is your variable bounded or unbounded?
 - d. Do your data have a parametric or nonparametric distribution?
 - e. Do you know the parameters of your data (first or second order)?
 - f. Are your data univariate or multivariate?
3. Look at your data—plot it.
 4. Use theory.
 5. Calculate some statistics.
 6. Use previous experience.
 7. Try distribution fitting.
 8. Use expert opinion.
 9. Do a sensitivity analysis.

You may not have to apply a process like this often, much less for every uncertain quantity you encounter in a risk assessment. Selecting probability distributions in routine work can be a routine process. The uncertain quantities in a simple cost estimate, for example, may all be represented by pert, triangle, and uniform distributions based on the assessor's expert opinion. In other cases, the choice of distribution may be obvious. The process described herein for those times when you are identifying the distribution of an instrumental quantity's uncertainty, that is, one that could affect your model outputs, your decision choice, or the outcomes of your decision. When the uncertainty is significant you need a careful process to characterize the statistical nature of that uncertainty. This is such a process.

13.3.1 USE YOUR DATA

Many quantitative risk assessment models use simulation. Data can be used directly in a simulation or they can be used to define a probability distribution. Let us consider both these situations.

Some simulations use raw data values directly without any distribution. For example, if the data represent the time required to travel a certain distance or route in a model, then one of the data values is used each time a travel time is needed in the simulation model. In some cases, the data may be used in a very precise order, perhaps the order in which it was recorded. In other instances, the data may be used in a different or random order, but no values will be used that are not members of the data set. This is sometimes called a trace-driven simulation (Law and Kelton 1991). This is the most literal meaning of "use your data."

An alternative to a trace-driven simulation is to use your data to define an empirical distribution. If you have data that are reasonably extensive and representative of the population of interest, consider just using your data to define the distribution. You do not have to choose one of the standard probability distributions if you use your data to construct an empirical distribution. In such a case, each time you need a value for your simulation, a travel time value would be sampled from the empirical distribution you have defined. Some of these values may be identical to the values in your data set, and others will be interpolations or extrapolations of the actual values you have collected.

TABLE 13.1
Hypothetical Consumption Data for a Food Additive Measured in mg/kg bw/d/l

Sample Data					
33.3	44.2	33.4	0.9	16.2	11.7
22.2	40.2	16.5	24.5	24.9	6.0
25.8	34.7	3.6	5.0	22.7	23.2

Note: bw/d/l = body weight per day for a lifetime.

One common problem encountered in constructing an empirical distribution, even with extensive data sets, is bounding the data. It is not unusual to be unsure about the absolute maximum and minimum values for a population. Consider the problem of estimating the minimum and maximum possible weights for an adult (18 years or older) male. It is not always easy to bound your data, but it is always important to do so when you use an empirical distribution.

Any data set can be converted into an empirical distribution using the cumulative distribution. This is a valuable skill to have. Consider the data in Table 13.1. The data set is kept small for the convenience of the example. Let it measure consumption of a chemical food additive in mg/kg of body weight daily for a lifetime (bw/d/l) for eaters only. For the purposes of the sample calculation, let us assume they are representative of the population of interest to the risk assessor who wants to eventually estimate the following relationship:

$$\text{Consumption}_i \times \text{Body weight}_i = \text{Total intake}_i \tag{13.1}$$

Imagine this as a simple spreadsheet model, where there is uncertainty about both consumption and body weight. We want to create an empirical distribution for consumption that can be inserted into our risk assessment model by creating a cumulative distribution function. The first step is to decide whether your consumption data are representative of the population. The simplest way to think about this question is to consider whether the shape of a plot of your data would reasonably mimic the shape of the entire population distribution. Although 18 observations would never likely be considered representative of the population, let us suspend disbelief for the sake of keeping the data set small enough to demonstrate the technique compactly and assume that it is representative.

It is important to consider whether your data are extensive enough as well. Is it possible to observe values for your variable outside the range of your data? In other words, do your data likely represent the true minimum and maximum values for your variable? If they do not, you should enter a minimum and maximum bound, because extreme events are often of great interest in a simulation.

Suppose the example data do not contain the true minimum and maximum values. Then we must provide them. Let us estimate that a value very close to zero (because we restrict the sample to eaters only) consumption is a logical minimum, say 0.001, and 60 mg/kg/bw/d is a reasonable maximum value. Using Excel or any similar tool,

TABLE 13.2
Empirical Distribution Derived from
Consumption Data

Index	Data Value	Cumulative Probability $F(x) = i/19$
0	0.001	0
1	0.9	0.053
2	3.6	0.105
3	5.0	0.158
4	6.0	0.211
5	11.7	0.263
6	16.2	0.316
7	16.5	0.368
8	22.2	0.421
9	22.7	0.474
10	23.2	0.526
11	24.5	0.579
12	24.9	0.632
13	25.8	0.684
14	33.3	0.737
15	33.4	0.789
16	34.7	0.842
17	40.2	0.895
18	44.2	0.947
19	60.0	1.000

we add the minimum and maximum values to the data set, then sort and number the data starting at the minimum, as seen in [Table 13.2](#). This index number (i) is then used to calculate the cumulative distribution probabilities using the formula “ $i/\text{maximum index number}$.”

This procedure works for a data set of any size. Note that the third column shows the cumulative probability percentile value for the corresponding data value. Thus, $x = 16.5$ is the 36.8 percentile value. In other words, 36.8% of all values in the empirical data set are 16.5 or less.

All that remains is to graph the curve as seen in [Figure 13.8](#).^{*} As an empirical distribution, it tends to lack the S shape seen previously. Real-world data do not always follow the neat mathematical form of a well-defined function. Reality is splendidly messy.

The PDF can be easily generated from the CDF, as shown in [Figure 13.9](#). Note that this distribution does not resemble any of the familiar distribution shapes. If this is how the world behaves and how the real data look, then this is the distribution to use. Do not feel compelled to fit your data to a preexisting probability model. If you

^{*} This curve was created by entering the data in [Table 13.2](#) into the cumulative distribution function of Palisade Corporation’s @RISK software.

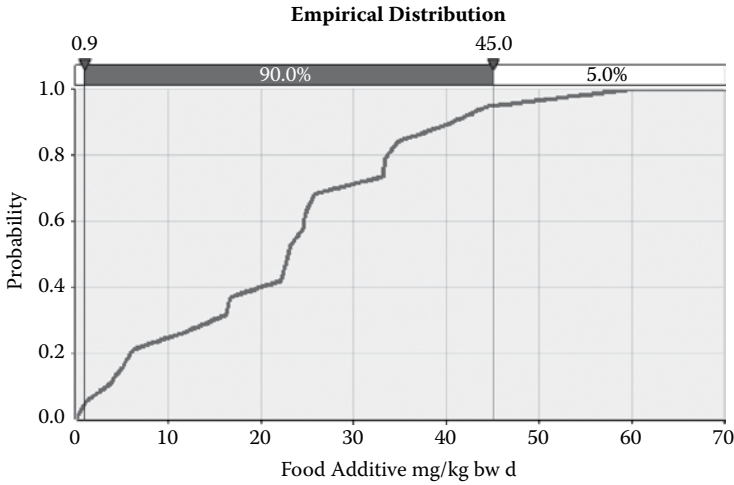


FIGURE 13.8 Empirical CDF of food-additive data.

have good, extensive data that represent the population reasonably, then just use it as an empirical distribution. If you use an empirical distribution, there is no reason to proceed to the subsequent steps.

13.3.2 UNDERSTAND YOUR DATA

Once you have decided it is not a good idea to use an empirical distribution, you will need to choose a probability distribution from among the bewildering list of candidate distributions. Figure 13.10 shows the probability distributions available with the

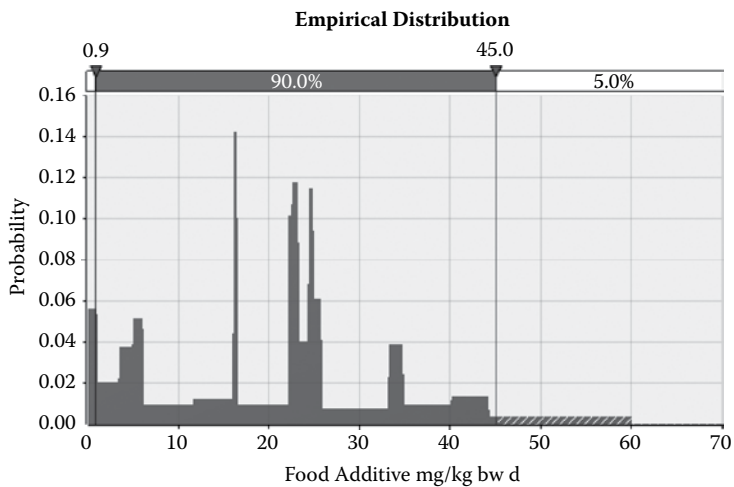


FIGURE 13.9 Empirical PDF of food-additive data.

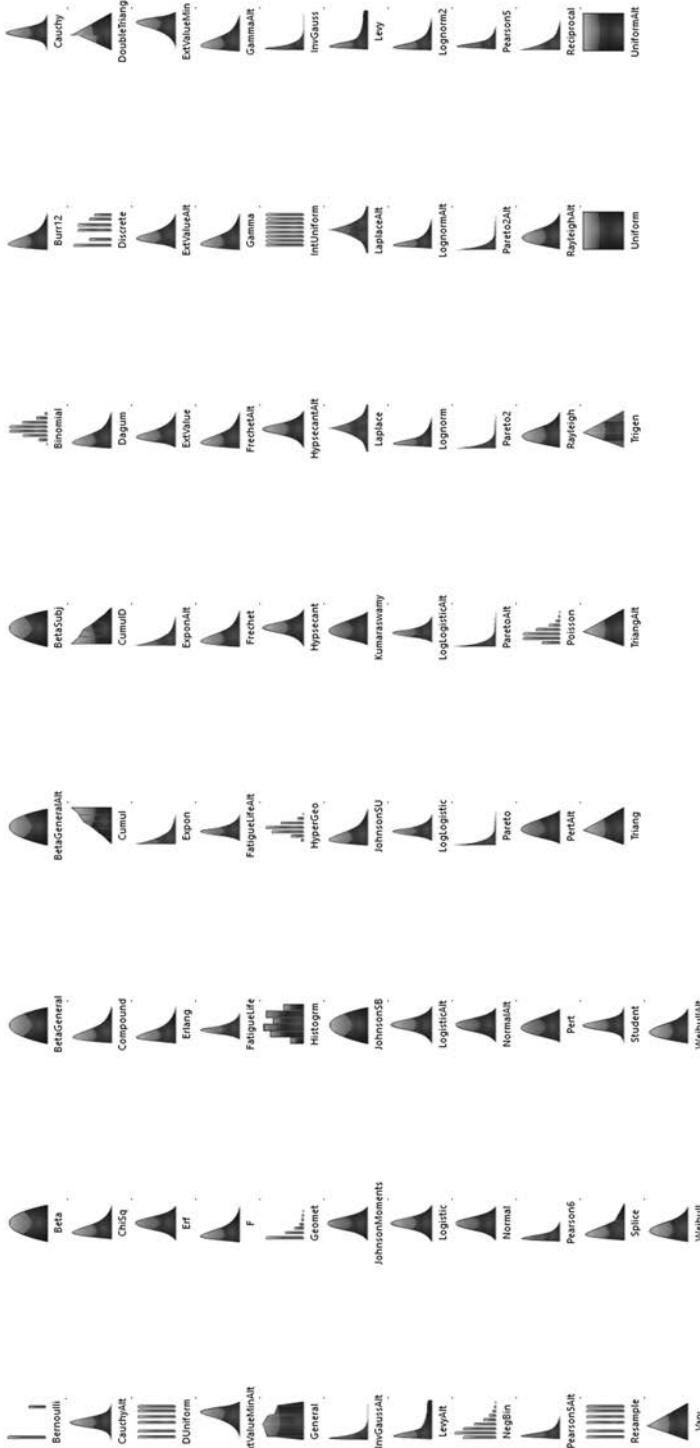


FIGURE 13.10 Palette of distributions available from Palisade's @RISK software.

popular Monte Carlo simulation software @RISK. A quick check of Wikipedia's "list of probability distributions" adds to this array of choices. Choosing a probability distribution from among this array that best suits your needs begins by understanding the data you do have.

13.3.2.1 What Is the Source of Your Data?

Where do your data come from? How were they collected? Under what conditions and when were they gathered? It should go without saying that data-gathering efforts should be designed to collect enough information to adequately define the tails of the distribution whenever it is feasible to do so. There is any number of data-quality issues you may concern yourself with, but the source of your data is far more basic. The source of your data will help you decide if you can and should use your data to help you define a probability model.

For example, are your data quantitative or qualitative? Do your data come from experiments, observation, surveys, computer databases, literature searches, simulations, or are they test-case data? The last three sources of data should be carefully scrutinized. The literature rarely presents entire data sets. If your data come from a literature search, it is quite likely you are dealing with something more accurately called information data. Data that are the result of a simulation must be used with care; this would rarely be a high-quality source of data. Test-case data are not real data. They are fine for developing prototype models, but they should not be used in a risk assessment. As long as your data have credible information content, they can be used to help you choose a probability distribution. If that content is missing because of your data's source, do not use them to define a distribution.

If your data were collected selectively for any reason, they may not represent the full distribution of values in the population of interest to you. When this is the case, it is important to identify and assess the differences between your survey or sample data and the population you wish to represent in your model.

13.3.2.2 Is Your Variable Discrete or Continuous?

Discrete random variables tend to be things that are counted, while continuous random variables tend to be things that are measured like distance, time, area, weight, qualities, and statistics. Think of a portion of the number line that is relevant for your variable. If there are values on that portion of the line that your variable cannot take, it is discrete. If every value is possible, you have an infinite number of possible values and a continuous random variable. See [Figure 13.11](#).

Discrete random variables are preferably represented by discrete probability distributions. Examples of discrete random variables include such things as barges in a tow, houses in the floodplain, people at a meeting, results of a diagnostic test (positive or negative), casualties per year, relocations and acquisitions, quarantine centers, animals per quarantine center, sperm per sample, illnesses per year, monthly sales, and the like.

Continuous random variables need to be represented by continuous probability distributions. Examples of continuous random variables include such things as the average number of barges per tow, weight of an adult striped bass, sensitivity or

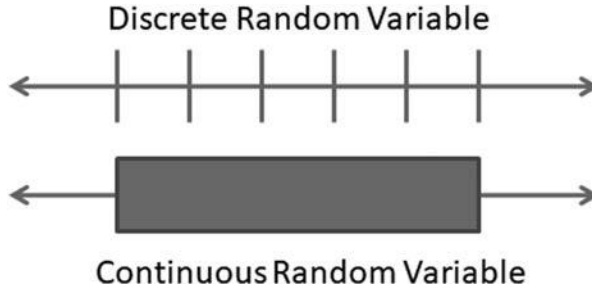


FIGURE 13.11 Discrete and continuous random variables' coverage of the number line.

specificity of a diagnostic test, transit time, expected annual damages, duration of a storm, area of shoreline eroded, sediment loads, average number of animals per quarantine center, weight of a sperm sample, amount of a food additive present in a 5-gram sample, prevalence of a pathogen or disease, a serving size, and the like.

This seemingly obvious step is frequently overlooked, but it is an important consideration in the choice of a probability distribution. Examples of some probability distributions were shown in [Figure 13.10](#). The discrete distributions are represented by vertical lines.

It is worth noting that although a random variable is clearly of one type or the other, a modeler may choose at times to treat it as if it was effectively its opposite type. For example, a dollar value is actually a discrete random variable. On the number line between \$5 and \$10, there are many values that cannot occur because dollars are only denominated in hundredths of a dollar. When dealing with large sums of dollar values, however, the number of possible values can grow very large and can be reasonably well approximated by a continuous distribution. As long as values obtained from a continuous distribution are appropriately converted to discrete values, via rounding for example, no harm is done by using a continuous distribution to represent a discrete variable. In fact, some discrete distributions (e.g., the binomial) approach a continuous distribution (e.g., the normal) as the sample size gets larger. Conversely, some continuous values like time may be sufficiently measured for some model purposes in whole hours or some other discrete time element. In such cases, it may be sufficient to represent a continuous variable with a discrete distribution. This is more a matter of art than science.

13.3.2.3 Is Your Variable Bounded or Unbounded?

Boundedness concerns the range of values your quantity can assume. What values are possible? A variable with a minimum value is left-bounded. If it has a maximum value, it is right-bounded. Variables with a minimum and a maximum are bounded, and variables with neither are unbounded. Stated somewhat differently, the values of a bounded variable are confined to lie between two determined values. Unbounded variable values theoretically extend from minus infinity to plus infinity. A partially bounded variable is constrained at one end, usually the left.

It is more important at the outset to ascertain whether your variable has bounds than it is to worry about what they are. Most physical and human phenomena are

bounded. Unbounded phenomena tend to be confined to conceptual contexts. Partially bounded phenomena may also be highly conceptual, for example an infinite number of tosses of a coin, annual stream flows into eternity, or servings of ground beef into infinity. When dealing with finite periods of time, most variables are bounded in some way. Choose a distribution with bounds that match your variable. Zero is a common minimum bound. Physical quantities, for example, do not ordinarily assume negative values.

If your variable is bounded, carefully consider and identify what those bounds are. Some bounds are easy. We know that the sensitivity of a test, the proportion of a population, or the probability of an event will be confined to the interval from zero to one. Other bounds are more difficult. We know that the travel time between two points has a nonzero minimum and some practical maximum, but we are unlikely to know exactly what they are. These are values worth sweating over. I wish I had more definitive guidance to offer, but I do not, although bounds can be estimated via an expert elicitation (see [Chapter 14](#)). Establishing a physical or plausible range of values for a variable is as much art as science. Generally, the range in a model's output depends more on the bounds of the model's inputs than it does on the actual shape of the input distributions (EPA 1997). Estimating the bounds for a variable is not a trivial matter and it should always be taken seriously.

It is rather common to use unbounded or partially bounded distributions to model bounded phenomena. This is reasonable when the probability that the chosen distribution will produce an unrealistic value is pragmatically nonexistent. Consider the battery life example presented earlier. In theory, a normal distribution could produce a negative battery life or a battery life of 100 hours or more. Although the probability of obtaining such values from a normal distribution with a mean of 70 and a standard deviation of 4 is nonzero, it is vanishingly small. There is a 7×10^{-69} chance of a negative value and a 3×10^{-14} chance of 100 or more hours. Thus, it can be reasonable to use an unbounded or partially bounded distribution for a bounded variable as long as the relevant range of values sampled from that distribution is realistic.

13.3.2.4 Parametric and Nonparametric Distributions

Parameters are numerical characteristics of populations. The most well-known parameters are measures of central tendency (mean, median, and mode) and measures of dispersion (range, standard deviation, and variance). In fact, any numerical characteristic at all—the minimum, the fifth largest, or the 37th percentile—could be a parameter. Population parameters are constants. The notion of a parameter is sometimes extended to any constant that appears in a model. Thus, in an equation that converts feet to inches, for example, $\text{feet} = 12 \times \text{inches}$, 12 is a parameter. The language can be confusing because the word *parameter* is often used without its contextual meaning being entirely clear to the reader.

When it comes to describing probability distributions, it is convenient to break them into parametric and nonparametric groupings (Vose 2008). A parametric distribution is defined by a mathematical model. A nonparametric distribution is defined by its shape.

The normal distribution, for example, follows a specific mathematical model that describes much of what happens in the biological universe. Many phenomena of interest in risk assessment involve measurement of the duration of time, x , between some initial point and the occurrence of the phenomenon of interest. Examples include how long between failures, between entering and leaving a store, between floods, between switch malfunctions, and so on. Such activities are described by the mathematics of the exponential function. Mathematical model-based, that is, parametric, distributions require greater knowledge of the underlying math and assumptions of the function if they are to be used properly. If the shape of the suspected distribution is driven by physical or biological properties or other mechanisms, you may well be dealing with a parametric distribution. You will, generally, require data to estimate the values of the relevant parameters.

Other times, there is no underlying mechanism or mathematical process guiding the distribution, and we simply use a shape, like a triangular distribution, a uniform distribution, or, more generally, a histogram. The shapes of the data define the distributions; thus, the empirical distribution described previously would be a nonparametric distribution. Nonparametric distributions are useful when the researcher knows nothing about the population parameters of the variable of interest. Their principle advantage may be that they require fewer and less stringent assumptions than their parametric counterparts. They are also intuitively easy to understand and are flexible.

Table 13.3 summarizes the type of variable, its boundedness, and its parametric nature for several common distributions. If you can identify these three attributes of your variable, you'll have a pretty good idea of the relevant distribution choices from the table. The shape column indicates whether the distribution assumes one basic shape or if the values used to define it can result in different shapes. Note that five nonparametric distributions can be used to define an empirical distribution.

In general, you would choose a parametric distribution if any of the following hold true:

1. You have theory that supports your choice.
2. The distribution has proven accurate for modeling your specific variable despite a lack of specific theory to support its choice.
3. The distribution matches the observed data well.
4. You need a distribution with a tail extending beyond the observed minimum or maximum.

Likewise, choose a nonparametric distribution if the following are true:

1. Theory is lacking.
2. There is no commonly used model.
3. Data are severely limited.
4. Knowledge is limited to general beliefs and some evidence.

Parameters are used to define most probability distributions. The normal distribution, for example, is defined by two parameters: the mean (μ) and the standard deviation (σ). Each distribution, other than empirical ones, has its own set

TABLE 13.3
Summary of the Characteristics of Random Variables and Their Selected Probability Distributions

Distribution	Type	No Bounds	Bounded		Left Bound Only	Category	Shape	Empirical Distribution
			Left and Right	Right				
Beta	Continuous	No	Yes	No	Nonparametric	Shape shifter	No	
Binomial	Discrete	No	Yes	No	Parametric	Some flexibility	No	
Chi-square	Continuous	No	No	Yes	Parametric	Basic shape	No	
Cumulative ascending	Continuous	No	Yes	No	Nonparametric	Shape shifter	Yes	
Cumulative descending	Continuous	No	Yes	No	Nonparametric	Shape shifter	Yes	
Discrete	Discrete	No	Yes	No	Nonparametric	Shape shifter	Yes	
Discrete uniform	Discrete	No	Yes	No	Nonparametric	Basic shape	No	
Erlang	Continuous	No	No	Yes	Parametric	Basic shape	No	
Error	Continuous	Yes	No	No	Parametric	Some flexibility	No	
Exponential	Continuous	No	No	Yes	Parametric	Basic shape	No	
Extreme value	Continuous	No	No	Yes	Parametric	Basic shape	No	
Gamma	Continuous	No	No	Yes	Parametric	Shape shifter	No	
General	Continuous	No	Yes	No	Nonparametric	Shape shifter	Yes	
Geometric	Discrete	No	No	Yes	Parametric	Some flexibility	No	
Histogram	Continuous	No	Yes	No	Nonparametric	Shape shifter	Yes	
Hypergeometric	Discrete	No	Yes	No	Parametric	Some flexibility	No	
Integer uniform	Discrete	No	Yes	No	Parametric	Basic shape	No	
Inverse Gaussian	Continuous	No	No	Yes	Parametric	Basic shape	No	
Logarithmic	Discrete	No	No	Yes	Parametric	Some flexibility	No	
Logistic	Continuous	Yes	No	No	Parametric	Basic shape	No	

(Continued)

TABLE 13.3 (Continued)
Summary of the Characteristics of Random Variables and Their Selected Probability Distributions

Distribution	Type	No Bounds	Bounded		Category	Shape	Empirical Distribution
			Left and Right	Left Bound Only			
Lognormal	Continuous	No	No	Yes	Parametric	Basic shape	No
Lognormal 2	Continuous	No	No	Yes	Parametric	Basic shape	No
Negative binomial	Discrete	No	No	Yes	Parametric	Some flexibility	No
Normal	Continuous	Yes	No	No	Parametric	Basic shape	No
Pareto	Continuous	No	No	Yes	Parametric	Basic shape	No
Pareto 2	Continuous	No	No	Yes	Parametric	Basic shape	No
Pearson V	Continuous	No	No	Yes	Parametric	Some flexibility	No
Pearson VI	Continuous	No	No	Yes	Parametric	Some flexibility	No
PERT	Continuous	No	Yes	No	Nonparametric	Shape shifter	No
Poisson	Discrete	No	No	Yes	Parametric	Basic shape	No
Rayleigh	Continuous	No	No	Yes	Parametric	Basic shape	No
Student	Continuous	Yes	No	No	Parametric	Basic shape	No
Triangle (various)	Continuous	No	Yes	No	Nonparametric	Some flexibility	No
Uniform	Continuous	No	Yes	No	Nonparametric	Basic shape	No
Weibull	Continuous	No	No	Yes	Parametric	Shape shifter	No

of defining parameters. These are entered as constants except in the case of second-order distributions, where the parameter itself is uncertain (see box).

A NOTE ON PARAMETERS

Words are used in varying contexts. You may find that you have chosen a nonparametric distribution like a triangular distribution only to be surprised to see its parameters defined as the minimum, most likely (mode), and maximum value. All distributions are defined by constants/parameters. Only parametric distributions are driven by an underlying mathematical process.

When the parameters of the chosen distribution are known it is sometimes called a first order distribution. When the parameters are subject to knowledge uncertainty and are themselves represented by a distribution this is called a second order distribution.

A normal distribution with a mean of 100 and a standard deviation of 10 is abbreviated $N(100,10)$ and is a first order distribution. If the mean and standard deviation are uncertain and represented by uniform distributions, for example, it would be abbreviated $N(U(80,105),U(8,11))$ and it is a second order distribution.

It is useful to recognize that although these parameters have different definitions and names that are not always revealing, they tend to play one of three basic functions in defining a distribution. They either identify the location, the scale (i.e., the range or extent), or the shape of the distribution.

The location parameter identifies the central location of the variable on the x -axis. It tells you where on the number line your data tend to concentrate. For the normal distribution, the mean is the location parameter. [Figure 13.12](#) shows three identical distributions, each with a different location parameter (mean). A change in the location parameter shifts the distribution left or right without changing it. A shift parameter is a second location parameter that is sometimes used to locate data. For example, a distribution with a left bound of zero might be shifted to the right by the amount of a shift parameter to indicate when observed values actually begin at some positive value.

The scale parameter controls the spread of the data on the x -axis. A change in this parameter compresses or expands the distribution without altering its basic form. Think of it as telling you how much of the x -axis your data cover. The standard deviation is the scale parameter for the normal distribution. All three distributions in [Figure 13.13](#) center over the same location parameter (mean = 0), but the majority of the data are distributed over different portions of the number line because they have different scale parameters.

The shape parameter, if there is one, governs the shape or basic form of the distribution. Think of it as indicating which values on the number line are most likely to occur. The normal always has the familiar symmetrical bell shape. The normal distribution does not have a shape parameter, nor does the exponential or several other distributions. Their shapes are governed by the mathematical model (function) that defines the distribution. A change in the shape parameter alters the form of the distribution, for example, its skewness. Some distributions, like the beta, have more than one shape parameter.

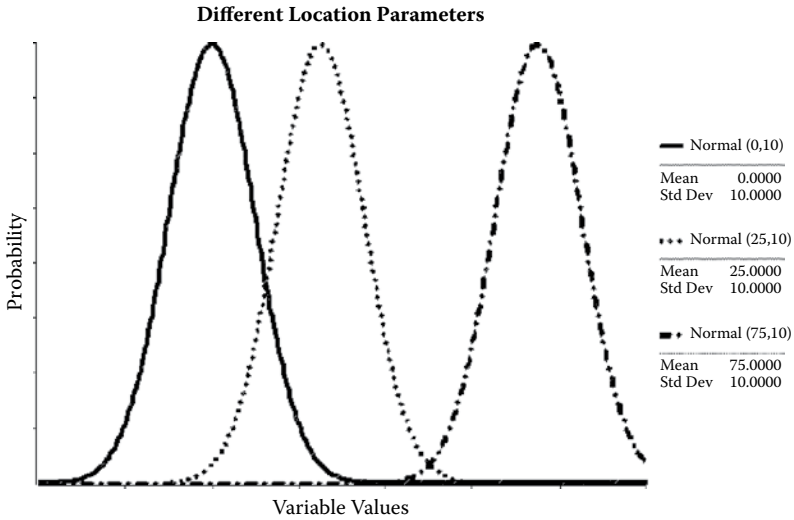


FIGURE 13.12 Plot of three PDFs with different location parameters.

All of the distributions in [Table 13.3](#) that are identified as shape shifters in the second-to-last column will have a parameter that serves as a shape parameter. The Weibull distribution shown in [Figure 13.14](#) demonstrates the effect of a shape parameter.

The first parameter identified in the legend is alpha; the second one is beta. These are not nominally very meaningful to anyone unfamiliar with the Weibull distribution, and in fact they have somewhat involved functional definitions. However, note that changing the alpha parameter, holding beta constant, changes the shape of

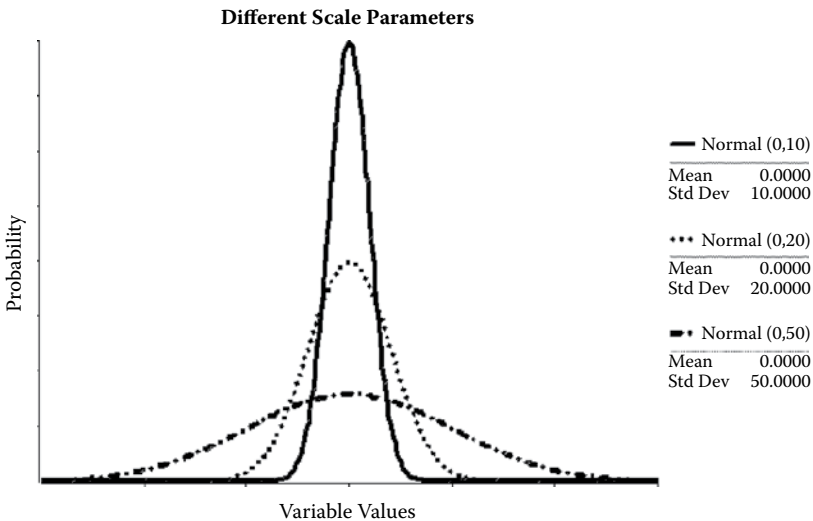


FIGURE 13.13 Plot of three PDFs with different scale parameters.

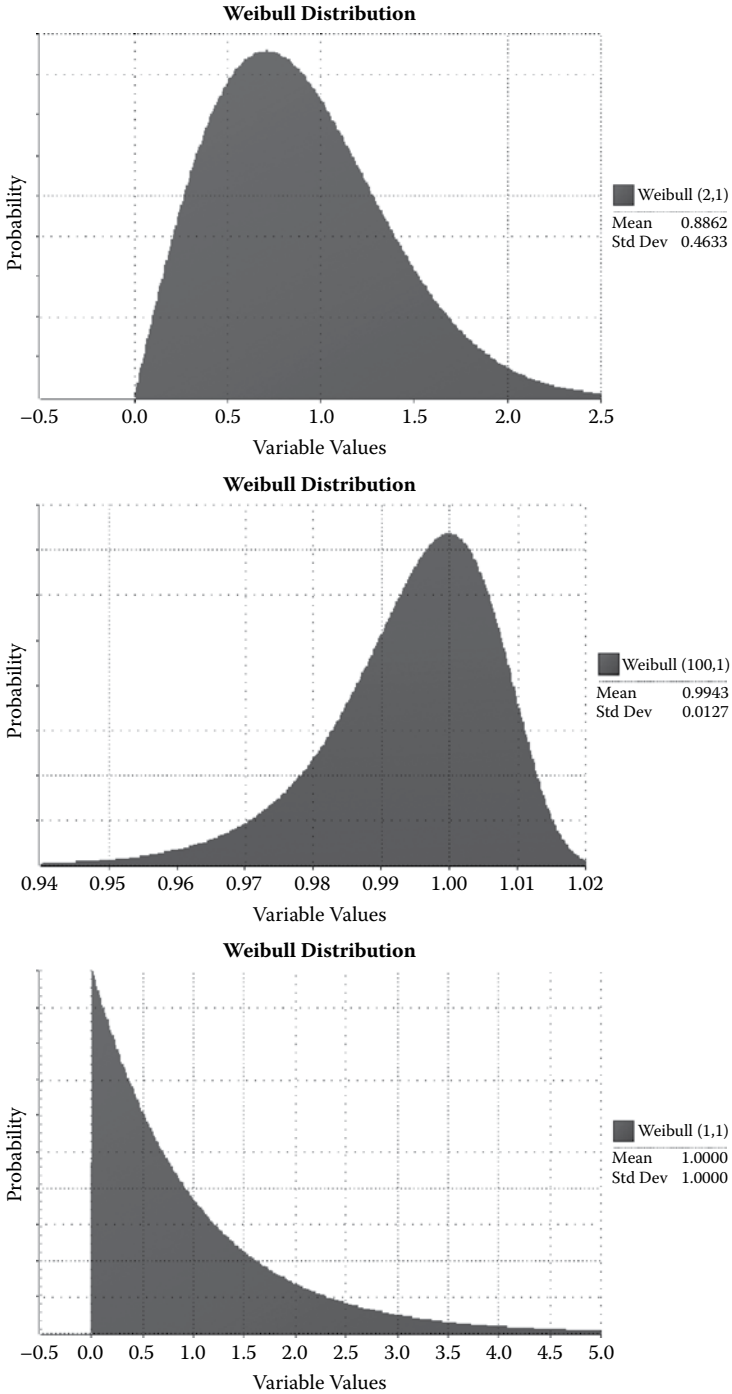


FIGURE 13.14 Plot of three shape-shifting Weibull PDFs.

the function appreciably. It also alters the scale of the distribution as well. Parameters may have roles more complex than fixing simple location, scale, and shape. This is governed by the mathematics of the different functions.

13.3.2.5 Univariate or Multivariate Distributions

Can you consider the distribution of your variable or your uncertainty about the value of an unknown parameter by themselves, or must you consider the values of other variables? A univariate distribution describes a single variable or parameter that is not probabilistically linked to any other variable or parameter in your model. Multivariate distributions are needed to address interrelationships with other variables. Many of the most important questions in science and technology concern how the values of one quantity can be used to control, explain, or predict another. Engineers are interested in how environmental factors affect tensile strength. Biologists are interested in how organisms react to changes in their environment. Sometimes it is not possible to properly consider variables in isolation. Take the time to identify and consider the presence or absence of significant correlations or interdependencies between input variables. If such relationships cannot be properly addressed by multivariate distributions, be sure to address them in the structure of the model.

Mechanistic models express relationships between variables in terms of exact mathematical formulas (force = mass \times acceleration) or in terms of the logic of causation (a causes b). Stochastic models express such relationships in terms of statistical tendencies of joint occurrence (e.g., high values of x tend to be associated with low values of y). Expressed in the more formal language of probability, the probabilistic framework for these stochastic situations involves the notion of composite events. These events give rise to two or more random variables.* The resulting probability model is a joint or multivariate distribution (Derman et al. 1973).

Multivariate distributions include the multivariate normal distribution, Dirichlet distribution, multinomial distribution, multivariate hypergeometric, and the negative multinomial distribution, with new distributions being identified regularly. They tend to be more difficult for most people to work with, so there is a bias toward handling such interrelationships mechanistically whenever possible. Thus, many modelers would use mass \times acceleration rather than a multivariate distribution for force.

If you are interested in the intersection of two or more events, or the outcome of two or more random variables at the same time, you may build your model with the appropriate dependencies reflected in the model structure. Alternatively, you may use a multivariate distribution.

13.3.3 PLOT YOUR DATA

Lest the point be lost, as you address the previously discussed data issues, you are converging on a smaller set of candidate distributions for your variable and your

* The simplest examples might be tossing two six-sided die. Each die has its own simple probability distribution, but in the game of craps we would be inclined to treat the situation as a single joint probability experiment. In this bivariate case we are, in effect, finding a volume under two curves in three-dimensional space, as opposed to finding the area under a single curve in the univariate case.

data. As you better understand your data from having considered the identified characteristics, it is time to take a look at the data. You may already have some notion about how your data ought to be shaped before you do so. Are your data known or thought to be symmetric or skewed? If skewed, in which direction? What else do you know or suspect about the shape of the distribution? It is useful to consider these things before you actually plot your data. You will be more likely to scrutinize surprises more carefully if you do.

Always plot your data to see what they look like. Data for the time between eruptions at the Old Faithful geyser in Yellowstone National Park (Howell 1998) are plotted in Figure 13.15. The mean time between eruptions for a sample of 222 data points was 71 minutes, with a standard deviation of 13.8 minutes. With these two parameter estimates and an assumption of a normal distribution, one could end up pretty embarrassed, as the data plot shows.

The actual data are bimodal and closer to two separate distributions of eruption times. One is centered around 55 minutes and the other is centered around 80 minutes. A normal distribution, $N(71,13.8)$, is superimposed for dramatic effect. Always make sure to plot your data and look at it. Also, remember that the number of bins used in a histogram plot can influence or even mislead your judgment with too much jaggedness or too much smoothness. It is wise to vary the number of bins before reaching any conclusions about the shape of your data. A wide variety of techniques are available to help you understand the shape of your data. The histogram is likely to be the most useful, but consider stem and leaf plots, dot plots, box and whisker plots, scatter plots, and other graphical techniques when

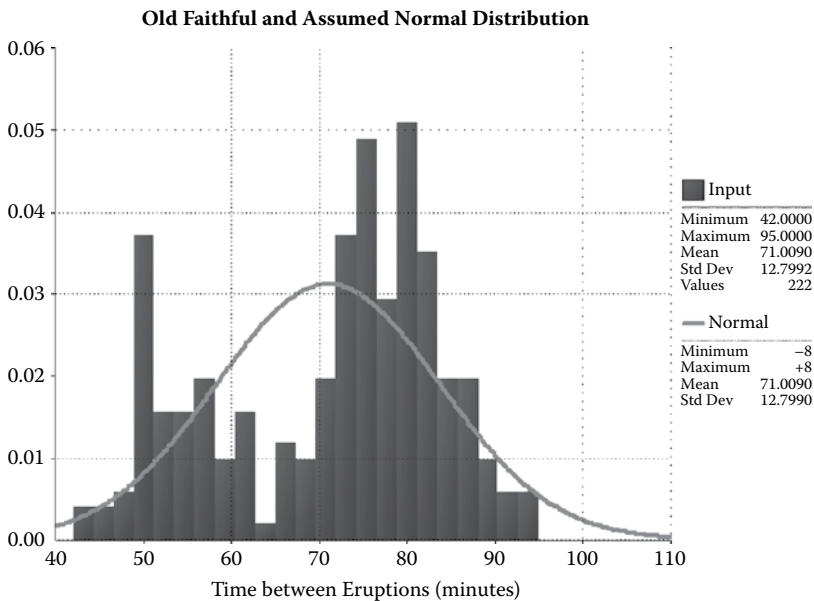


FIGURE 13.15 Time between eruptions for Old Faithful geyser in Yellowstone Park compared to a normal distribution of time.

the histogram is not revealing enough. Several of these plots are demonstrated in [Chapter 18](#).

What do your data look like? Are they single-peaked? Symmetrical? Skewed in one direction or another? Look for distinctive shapes for your data and use that information to eliminate potential distributions. Clearly the Old Faithful data will not be described by any single-peaked or symmetric distributions. In fact, there are no familiar shapes that match the Old Faithful data. Comparing the shape of these data to the distributions in [Figure 13.10](#) would steer us toward a cumulative or general distribution, which can be used to define an empirical distribution.

Using the information about your variable to narrow the candidate list of distributions, shape can then be used to further refine the candidate distributions. Be aware of the fact that some distributions are shape shifters, and a simple graphic like [Figure 13.10](#) will not indicate all the possible shapes a shape-shifting distribution can assume. The Gamma, Weibull, and beta distributions are sometimes useful and flexible forms because of their shape-shifting properties.

13.3.4 THEORY-BASED CHOICE

This is usually going to be the most compelling reason for choosing one distribution over another when it is available to you. On rare occasions there may be very formal theory about a variable. For example, the results of the central limit theorem posit conditions under which a sampling distribution is a normal distribution. This type of formal theory is a very powerful argument for a distribution choice, but it is rarely available in risk assessment.

More likely, and less formally, you may have theoretical knowledge of the variable. Each discipline has developed its own body of theory and knowledge of the behavior of different phenomena. Predictive microbiologists will have theoretical knowledge of the growth and attenuation of bacterial populations. Wildlife biologists and biostatisticians will have well-developed theories about population responses to habitat changes. Economists have knowledge of financial and others systems; engineers know the behaviors of materials and physical systems under a wide variety of conditions. And so it goes for most risk-relevant disciplines. This specialized knowledge can lead to working theories about the distributions of variables and uncertain parameters. These working theories lack formal proofs, but they are supported by the knowledge and theories of the disciplines from which they arise. Many parametric distribution choices could be based on these working theories.

In addition to formally proven theories and working theories, let us introduce the notion of informal/ad hoc theory and rules of thumb. It has been observed, for instance, that many biological phenomena tend to have normal distributions and many physical phenomena have lognormal distributions. Likewise, variables that are sums of other random variables often tend to have normal distributions. Variables that are products of other random variables tend to be lognormal. These sorts of observations and rules of thumb may be useful aids for thinking about the best choice of a distribution. Is the process that generates your data an additive one, as might describe risk consequences? Is it a multiplicative one, as suggested for some risk probabilities? Such insights may aid your distribution choice.

Informal theories tend to be study-specific. They are often ad hoc notions that may not even be suitable for experimental design and testing. They are also often expedient reasons for handling variables that are not among the critical uncertainties. For example, we might develop a simple ad hoc theory about the number of caffeine drinks consumed daily by members of the population. Common sense suggests that large numbers of drinks are not as likely as smaller numbers of drinks, so we expect a skewed distribution. Casual observation may also suggest that relatively few people drink just one caffeine drink per day, so we are not expecting the variable to fall from an initial peak, but to peak asymmetrically. Ad hoc theories like this might be more properly considered logic chains. Whatever they are called, they should be carefully documented when invoked as an additional piece of evidence for the choice of a distribution.

Take care to explicitly explore and develop the best reasonable theory for the shape of your data and the nature of your distribution. It may be the single most compelling piece of evidence for your choice.

13.3.5 CALCULATE STATISTICS

Summary statistics may sometimes provide clues about the probability distribution from which your data have come. A normal distribution has a low coefficient of variation and a mode, mean, and median that are identical. When these values are close to one another, it is an indication of single-peaked symmetry. An exponential distribution is positively skewed with an identical mean and standard deviation; thus, it has a coefficient of variation equal to 1. Positive skewness measures indicate data skewed to the right; negative measures indicate data skewed left. So, when the sample statistics from your data come close to meeting these conditions, that can be helpful information.

If only you could read a long, handy list of such rules of thumb, the task of choosing a distribution would be easier. Alas, that list has not yet been compiled, largely because it does not exist. Nonetheless, examining measures of central tendency and dispersion may help the assessor get a better feel for the data that are available and the distribution that best describes them.

Outliers can be problematic at times. Extreme observations could drastically influence the choice of a probability model. An outlier is defined as an observation that “appears” to be inconsistent with other observations in the data set. It is usually left to the analysts to define what is unusual. An outlier has a low probability that it originates from the same statistical distribution as the other observations in the data set. On the other hand, outliers can provide useful information about the process that produced your data.

There is no prescriptive method for addressing outliers. What is the data point telling you? What about your worldview is inconsistent with this outlying result? Should you reconsider your perspective? What possible explanations have you not yet considered? An outlier can be created by a shift in the location (mean) or in the scale (variability) of the process. It can also be a gross recording or measurement error. If an observation is an error, remove it.

Sometimes choosing a different distribution can eliminate an outlier. Values that seem to be outliers may be tail values of a skewed distribution. Try choosing a

distribution with and without the outlier(s) to see if it makes a significant difference in your choice of distributions or the estimated parameters for the distribution. There are more-sophisticated statistical methods for dealing with outliers. See Iglewicz and Hoaglin (1993) and Aggarwal (2013) for examples.

Ultimately, the explanation for your outlier(s) must be correct, not merely plausible. If you cannot explain it and must keep it, use the conventional practices described in this chapter and live with the skewed consequences. Another alternative to consider is to choose distributions that are less sensitive to such extreme observations like the Gumbel or Weibull.

13.3.6 PREVIOUS EXPERIENCE

Have you dealt with this same situation successfully before? What distribution did other risk assessments use? What does the literature reveal? It is always a good idea to see how others have handled similar situations in choosing a distribution. As the number of risk assessments grows, there is a rich body of experience growing, and this can be a source of useful insight in the choice of a probability distribution. For example, the Beta-Poisson is a common choice for a dose-response curve largely because it has been successfully used in a number of risk assessments.

13.3.7 DISTRIBUTION FITTING

Distribution fitting has taken on two distinct uses. The traditional usage is to use goodness-of-fit (GOF) testing to provide statistical evidence to test hypotheses about the nature of the parent distribution for your data, that is, fit validation. This determines whether a fitted distribution is a “good” fit for the data. The other usage is to identify the distribution that best fits the data. Different statistics are available for these different purposes.

The so-called information criteria, the Akaike Information Criteria (AIC) and the Bayesian Information Criteria (BIC), are used for the latter purpose. These statistics identify the distribution that provides the best fit for your data. They do not provide any useful information about whether that best fit is a valid fit, however. Consequently, the actual values of the AIC and BIC statistic do not have meaning, except in relative terms. A lower statistic is indicative of a better fit. It is not, however, an indicator of a valid fit. The two statistics are very similar, the theoretical underpinnings of both rely on Bayesian analysis. They differ in their assumptions for the Bayesian “priors.” The remainder of this section focuses on the traditional usage of GOF testing.

Once you have worked your way through the preceding steps, you should have some ideas about the specific distributions from which your data may have come. At this point, and only at this point, it is time to use GOF to test the null hypothesis (H_0) that your data come from a specific kind of distribution.

Three tests are widely used for providing such evidence. They are the chi-square test, Kolmogorov–Smirnov test, and the Anderson–Darling test. All work in essentially the same way by comparing the distribution of your actual data to the theoretical distribution from which you think they may have come. Differences between these two distributions are examined to see if they are statistically significant; think of that

TABLE 13.4
Interarrival Times in Seconds of Passengers at an Airline Counter During Peak Demand

Interarrival Times of Passengers (s)									
10.4	40.5	95.6	0.0	27.0	11.9	7.3	15.5	31.8	37.9
156.8	168.8	6.7	3.0	14.0	157.9	7.8	41.0	237.6	57.1
58.0	40.8	86.7	17.2	157.9	2.1	83.3	40.5	61.4	11.3
88.3	28.4	87.0	135.0	1.4	104.0	337.3	103.4	24.7	116.8
16.6	121.0	258.8	28.2	88.4	8.2	44.6	179.4	26.1	25.5

as meaning the differences you see are too large to be the result of simple chance differences. It is important to note that a GOF test is at best another piece of evidence to consider in your strategy for choosing a distribution and never a determining factor. The available software is so easy to use that many people are tempted to make the mistake of running their data through a fitting routine and letting the software identify the best distribution fit. This is the worst possible way to identify a distribution and it should never be done in that manner.

Suppose the 50 data points shown in Table 13.4 are the times in seconds between arrivals of passengers at an airline ticket counter during peak demand. Further imagine that we have followed the above strategy and we are leaning toward an exponential distribution, but it could also be lognormal or loglogistic.

The top of Figure 13.16 shows the plot of the actual data (histogram bars) and an exponential distribution with a mean of 70.25, the mean of the data set. You may be the judge of how well the two curves match for the moment. Be advised that the number of bins used in your graph can have a substantial visual impact on the apparent quality of the fit, as seen in the middle of Figure 13.16. For this reason, it is often better to display the data in CDF format, the bottom graph in the figure, where the differences between the input data and the hypothetical distribution are not masked by the number of bins.

The chi-square test is the most common GOF test. It is valid for both discrete and continuous distributions. Like the other tests, it tests the H_0 that your sample data come from a specific distribution versus the alternative hypothesis, H_1 , that they do not. It is a nonparametric, one-sided test. A good chi-square test usually requires about 50 observations or more.

The $\alpha = 0.05$ critical value for our sample of $n = 50$ for the chi-square statistic is 14.1. Thus, a value greater than this would lead us to reject the hypothesis that our data come from a specific distribution. Selected GOF statistics are shown in Table 13.5.

The chi-square test results show our data could be from any one of these three distributions. From the table we see that the sample data have a chi-square statistic of 3.12 for the hypothesis that the data come from an exponential distribution. This is less than the critical value of 14.1, so we accept the H_0 . The p value can be interpreted to mean the probability of getting a chi-square statistic of 3.12 or greater

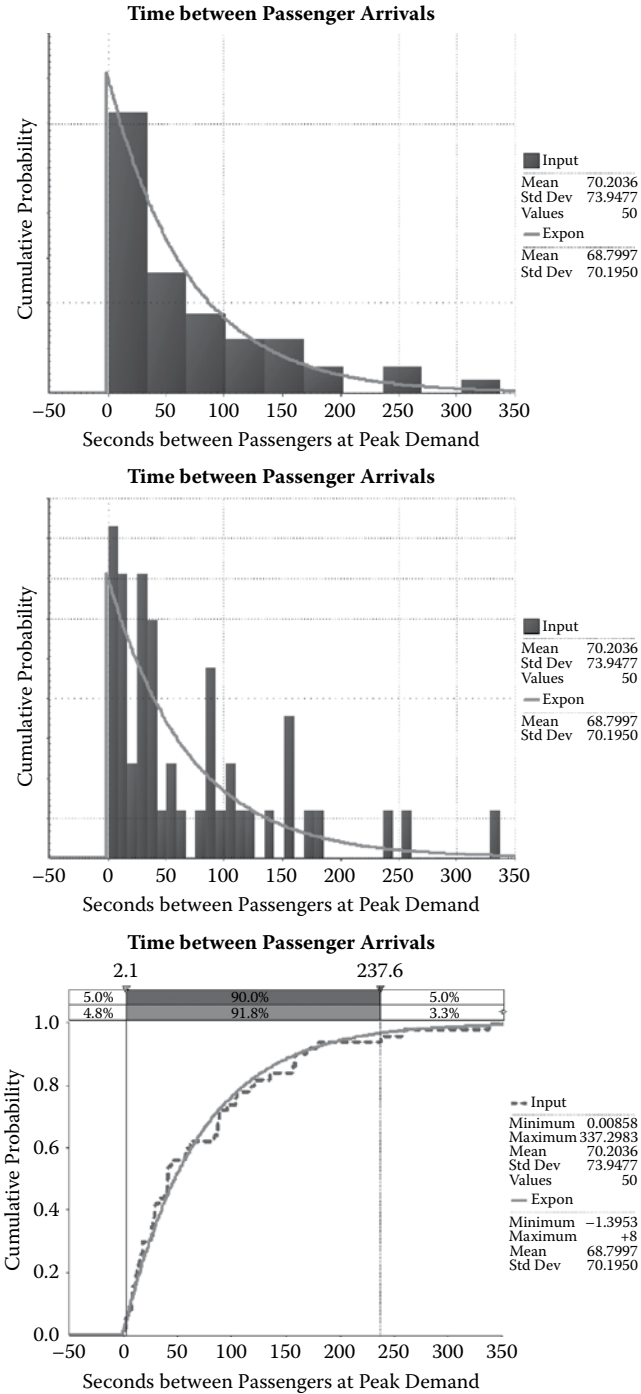


FIGURE 13.16 Three plots showing goodness of fit for passenger arrival data.

TABLE 13.5
Results of Three Different Goodness-of-Fit Tests for Three Parent Distributions

	Exponential	Loglogistic	Lognormal
Chi-square statistic	3.12	5.04	7.6
P value	0.874	0.655	0.369
K–S statistic	0.0977	0.0897	0.1354
P value	>0.15	NA	NA
A–D statistic	0.5433	NA	NA
P value	>0.25	NA	NA

(i.e., seeing the differences we see in the two curves) by chance is 0.874, and that is not at all unusual. Typically, we use a p value of 0.05 or less as our subjective definition of what would be too unusual to consider the result of chance. Note that the GOF test proves nothing with regard to our choice of distribution. The sample data could have come from any one of these three probability distributions based on the chi-square test. This is why it is so important to build a case for your choice based on the preceding steps. In general, a small test statistic and large p are “desirable” for accepting H_0 .

The Kolmogorov–Smirnov (K–S) test is for continuous sample data and is more suitable for small samples than the chi-square test. It works by sorting data in ascending order and finding the greatest difference between the theoretical value for each ranked observation and the actual corresponding data point. In other words, it plots two CDFs, as shown in the bottom graph of [Figure 13.16](#), and looks for the largest horizontal difference between the two. The test essentially examines the likelihood of finding a difference that large by chance in a sample of that size if the data are truly from the hypothesized distribution.

The K–S test provides a better fit for mean values than for tail values. The Anderson–Darling (A–D) test is a modification of the K–S test that weights differences between the theoretical and empirical distributions at their tails greater than at their midranges. It is the preferred test when a better fit at the extreme tails of a distribution are desired.

The K–S and A–D tests also show that our data could be from an exponential distribution. We would use the results of this GOF testing to add one more piece of evidence to the argument that our data come from an exponential distribution.

13.3.8 SEEK EXPERT OPINION

Hiring a qualified consultant is always an option for supplementing the risk assessment team’s knowledge of probability distributions. This, of course, could be done at any point in this process. In fact, it could obviate the need for a process. This step is not to be confused with expert elicitation of subjective probability information. That is the subject of the next chapter.

13.3.9 SENSITIVITY ANALYSIS

If you have reached this point in the strategy without arriving at a clear choice of a distribution, then use a sensitivity analysis. Run your model with each candidate distribution to see if the choice of distribution matters to the model outputs and, thus, the answers to the risk manager’s questions. If the choice does not matter, use the most conventional distribution. If the choice does matter and there is no reasonable option for further discerning the choice, then simply document the differences in results and highlight this result as a significant uncertainty.

13.4 EXAMPLE 1

Your final choice of a distribution for a specific quantity should be systematic, thoughtful, and documented. The strategy presented here enables you to choose in this way. Consider the situation where the assessor has the 110 data points for daily high water temperatures in July shown in Table 13.6 and is seeking a distribution to model the variability in high water temperatures for that month.

Let us suppose the assessor does not consider these data extensive enough to use as the basis for an empirical distribution. If they had thought otherwise, the method for developing an empirical distribution with the CDF for these data would be identical to that demonstrated earlier in the chapter.

13.4.1 UNDERSTAND YOUR VARIABLE AND DATA

What is the source of your data? These data were recorded via buoys on the waterway as part of routine data collection. They are a random sample of real data. I begin suspecting they may be normally distributed simply because the world often is.

Is your variable continuous or discrete? The data are continuous.

Is your variable bounded or unbounded? There are practical minimum and maximum temperatures for these coastal waters during the summer. Those bounds are, however, indefinite. Fuzzy bounds like that mean I could treat my quantity as

TABLE 13.6
A Sample of Daily High Water Temperatures in July (°C)

Summer Water Temperature in Degrees Celsius										
28.1	28.3	29.0	28.8	29.1	28.8	28.9	28.7	28.5	28.8	28.3
28.6	29.1	28.9	28.7	29.3	28.9	29.4	29.4	28.8	29.5	28.5
29.0	28.6	28.7	29.1	29.1	28.6	28.6	28.8	29.2	29.2	28.4
29.5	28.9	28.9	28.9	28.7	28.3	28.7	28.9	28.4	28.7	29.2
29.2	29.7	29.1	29.2	28.5	28.9	28.6	28.7	28.5	28.5	29.1
28.8	28.2	28.6	28.9	29.5	28.9	29.0	29.1	28.8	29.2	28.7
29.3	28.7	28.8	29.1	29.4	29.0	29.2	28.8	28.5	29.0	29.3
29.1	29.0	28.6	28.6	29.5	29.5	28.8	29.6	29.0	29.5	28.7
28.9	28.2	29.2	29.0	28.7	28.9	28.6	28.5	29.6	29.6	28.3
28.7	29.0	29.0	29.3	28.5	28.9	28.4	28.7	28.9	28.9	29.0

unbounded over a limited range of the number line. This is a finesse point that may be evident from earlier discussion in this chapter. It basically means a bounded distribution is more logical, but I do not yet have to eliminate the unbounded normal distribution I have begun to suspect.

Do your data have a parametric or nonparametric distribution? Although appearing early in the process, this question often cannot be answered until later in the process. I lean toward a parametric distribution because these data are produced by a natural process, which is often disciplined by a mathematical form. In addition, I note that I need a distribution with a tail extending beyond the observed minimum or maximum.

Do you know the parameters of your data (first or second order)? Parameter estimates can be obtained from these data, so it will be a first-order distribution.

Are your data univariate or multivariate? This quantity is univariate.

At this point, I am looking for a continuous bounded parametric distribution. I am also willing to consider an unbounded distribution like the normal.

13.4.2 LOOK AT YOUR DATA

The data are shown in the histogram in [Figure 13.17](#). The bins are 0.2 degrees wide. The data appear to be somewhat left-skewed. It is unclear if we have two peaks or just a random spike at 28.4–28.6 degrees. Plotting the data with more bins might help to resolve this issue. Based on the graph alone, it is difficult to call these data single-peaked and symmetrical.

The box plot in [Figure 13.18](#) confirms a slight skew to the left in the sample data and in the interquartile range. The skew does not look extreme in either view.

13.4.3 USE THEORY

My theory is quite informal for this data set. Quite simply, the “system” that produces a daily maximum temperature is complex enough and random enough that we believe deviations about the mean are likely to be symmetrical. A below-average temperature is as likely as an above-average temperature.

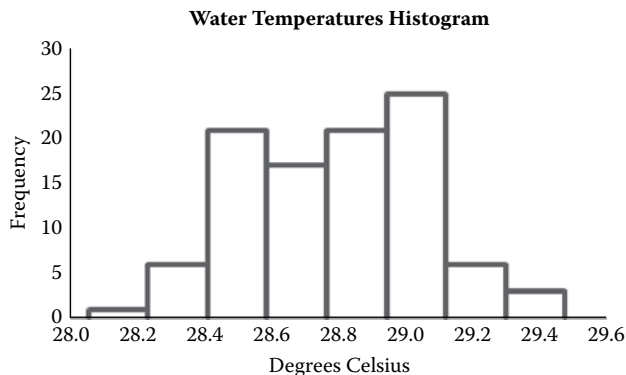


FIGURE 13.17 Histogram of maximum high daily water temperatures in degrees Celsius.

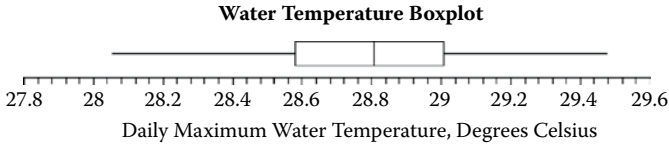


FIGURE 13.18 Box plot of maximum high daily water temperatures in degrees Celsius.

In addition, I think temperature is the cumulative effect of many environmental variables like cloud cover, ambient air temperature, currents, wind speed and direction, and so on. I believe these factors are likely to affect water temperature in a fashion more additive than amplifying, as a multiplicative relationship would be. This ad hoc theory or logic chain continues to nudge me toward a normal distribution.

13.4.4 CALCULATE SOME STATISTICS

Selected descriptive statistics are shown in [Table 13.7](#). The mean and median are approximately equal, and the coefficient of variation (0 to 100+ scale) is small. These indicate a potentially single-peaked and symmetric distribution like the normal. There are no outliers in this data set.

13.4.5 USE PREVIOUS EXPERIENCE

A U.S. FDA (2005) risk assessment of pathogenic *Vibrio parahaemolyticus* in raw oysters used a normal distribution to model water temperatures in the coastal waters of the United States. This is another piece of evidence for choosing a normal distribution.

13.4.6 DISTRIBUTION FITTING

At this point I have eliminated all discrete and nonparametric distributions. I have also eliminated anything with a right skew. I have shaky visual evidence of a normal distribution, but I also have my informal theory pulling me back in that direction. Some statistics and the prior experience of another risk assessment make me lean toward a normal distribution.

TABLE 13.7
Descriptive Statistics for Daily High Water Temperature in July (°C)

Count	110
Mean	28.8
Median	28.8
Sample standard deviation	0.3
Minimum	28.1
Maximum	29.5
Range	1.4
Standard error of the mean	0.03
Confidence interval 95% lower	28.7
Confidence interval 95% upper	28.9
Coefficient of variation	1%

A GOF test was run using several candidate distributions, including the normal, extreme value, gamma, inverse Gaussian, logistic, Pareto, and Weibull. The top of Figure 13.19 shows a theoretical normal distribution with the same mean and standard deviation as the data superimposed on the input data.

INFORMATION CRITERIA

Best fit rankings for the AIC and BIC are shown in the table below.

	AIC	BIC
Normal	24.1	29.2
Weibull	26.2	33.2
Lognormal	28.2	33.8
Extreme Value	39.2	44.3
Pareto	147.7	152.7

Note that the normal distribution provides the best fit as measured by both criteria.

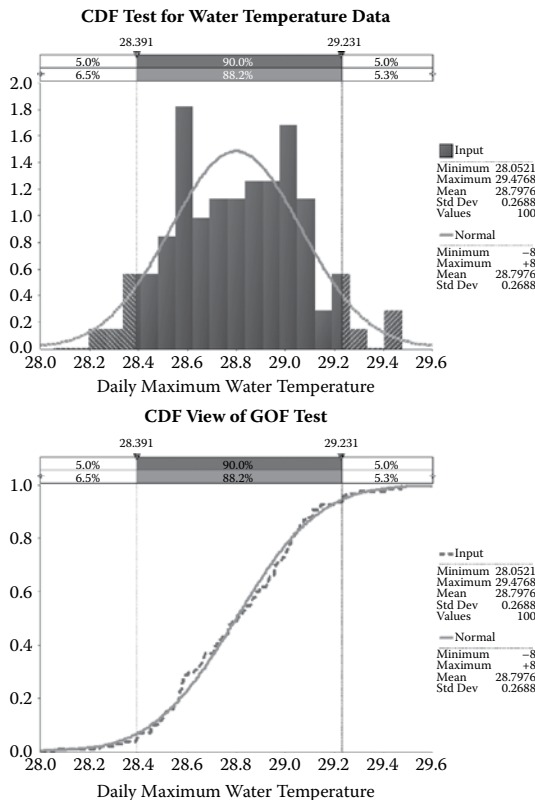


FIGURE 13.19 Two plots of the GOF test for the water temperature data coming from a normal distribution.

TABLE 13.8
Chi-Square Test Results for GOF Test for July Water Temperature Data and Five Selected Distributions

	Normal	Weibull	Logistic	ExtValue	Pareto
Chi-square test					
Chi-square statistic	7.14	8.02	11.98	17.26	121.89
P value	0.7122	0.6269	0.2864	0.0688	0
Crit. value @ 0.750	6.7372	6.7372	6.7372	6.7372	6.7372
Crit. value @ 0.500	9.3418	9.3418	9.3418	9.3418	9.3418
Crit. value @ 0.250	12.5489	12.5489	12.5489	12.5489	12.5489
Crit. value @ 0.150	14.5339	14.5339	14.5339	14.5339	14.5339
Crit. value @ 0.100	15.9872	15.9872	15.9872	15.9872	15.9872
Crit. value @ 0.050	18.307	18.307	18.307	18.307	18.307
Crit. value @ 0.025	20.4832	20.4832	20.4832	20.4832	20.4832
Crit. value @ 0.010	23.2093	23.2093	23.2093	23.2093	23.2093
Crit. value @ 0.005	25.1882	25.1882	25.1882	25.1882	25.1882
Crit. value @ 0.001	29.5883	29.5883	29.5883	29.5883	29.5883

There are a few places where we seem to have too many observations and a few where there are too few. This is to be expected from a random sample. What we want to know is if the differences we are seeing are statistically significant differences, that is, differences so big it is unlikely these data come from a normal distribution. Note the probabilities associated with the delimiters at 28.391 and 29.231 degrees: They give an indication of the fit in the tails of the distribution. My sample data have fewer observations below and above these values than the theoretical distribution would have. That also is not unusual in a sample the size of ours ($n = 110$). Always bear in mind that the number of bins in your graphic can have a powerful influence on the appearance of a fit. The CDF view, seen in the bottom of [Figure 13.19](#), provides a different perspective on the quality of the fit.

A statistical summary of the chi-square test is provided in [Table 13.8](#). The test statistic for the null hypothesis that my data come from a normal distribution is 7.13. Using a critical value of 0.05, I see that my test statistic is less than the critical value of 18.3, and so we cannot reject the null hypothesis. This is another piece of evidence to suggest my data could be from a normal distribution.

Note that the test statistics also suggest my data could come from a Weibull, logistic, or extreme value distribution as well. Only the Pareto distribution has a test statistic greater than the critical value of 18.3. This limits the utility of GOF testing as a primary piece of evidence for distribution choice. It is rarely, if ever, definitive evidence.

13.4.7 EXPERT OPINION

An expert is usually only consulted when we have been unable to identify a reasonable candidate distribution. I am satisfied with the body of evidence building toward a normal distribution. An expert opinion is not necessary.

13.4.8 SENSITIVITY ANALYSIS

Absent a set of viable alternative distributions, sensitivity analysis will not be necessary.

13.4.9 FINAL CHOICE

The normal distribution is continuous, parametric, consistent with my theory, successfully used in the past, and statistically consistent with my data. Therefore, I will use it. The differences and apparent skew in the plot of the data are considered mere random effects. The normal distribution describes the variability in water temperature. Because I am confident in the parameter estimates for this parametric distribution, there is no uncertainty reflected in the parameters of this distribution. I have a first-order distribution.

The normal distribution is an unbounded distribution. Its minimum and maximum values are minus and plus infinity, respectively. To ensure that I will not be causing any serious logic problems by using an unbounded distribution to model a bounded phenomenon, I must consider values that can result from a Monte Carlo process (the subject of [Chapter 15](#)).

The choice is to use a normal distribution with a mean of 28.8°C and a standard deviation of 0.3°C. If such a distribution can produce values that exceed the minimum and maximum bounds on the daily high water temperature in July, it cannot be used. Values within ± 5 standard deviations of the mean include virtually 100% of all possible values. This temperature range extends from about 27.3°C to 30.3°C. Values within that range are not outside the minimum and maximum bounds for a daily high water temperature in July. The mean ± 3 standard deviations accounts for all but about one-quarter of 1% of all possible temperature values. This smaller range (27.9°C–29.7°C) neatly matches the range of observed values. Thus, I am satisfied that using a normal distribution will not cause any boundedness problems in the model, and I am confident in the choice of a normal distribution.

13.5 EXAMPLE 2

We will not have data every time we need a distribution. Knowledge uncertainty and data gaps are common hurdles in risk assessment. Let us consider a quantity that varies, about which we have knowledge uncertainty. Imagine we are working on a risk assessment where we need to know how much time watermen spend on the water harvesting oysters on any given day. This is important in determining the potential outgrowth of pathogenic bacteria that may be on the oyster flesh when it is harvested.

Assume that the only information we have is what we gained from a couple of informal conversations with watermen. They have suggested they will not spend less than 5 hours on the water or more than 11, with 9 being the most common amount of time they spend harvesting oysters. Clearly, we lack the data for an empirical distribution, so we will choose a probability distribution from the universe of available distributions.

13.5.1 UNDERSTAND YOUR VARIABLE AND DATA

What is the source of your data? It is anecdotal information from watermen.

Is your variable continuous or discrete? It is continuous.

Is your variable bounded or unbounded? It is bounded.

Do your data have a parametric or nonparametric distribution? This is a nonparametric distribution. Our uncertainty is too great to consider anything more sophisticated.

Do you know the parameters of your data (first or second order)? Because we will use a nonparametric distribution, we will be working with a first-order nonparametric distribution.

Are your data univariate or multivariate? This is a univariate quantity.

13.5.2 LOOK AT YOUR DATA

There are no data to plot.

13.5.3 USE THEORY

There is no formal theory about watermen's behavior. There is a great deal of uncertainty here, and we will use the information provided. The only crude theory I can offer is that I expect relatively few watermen to spend the minimum time on the water. In relative terms, I expect fewer values from the low end and more from the high end of the distribution. The significance of this theory will become clearer in the sensitivity discussion. I base it on the fact that if watermen decide to go out onto the water, they are going to work for as long as possible barring bad weather, equipment failure, or personal emergencies. I expect these limitations to be relatively rare.

13.5.4 CALCULATE SOME STATISTICS

We have been able to anecdotally estimate a minimum, most likely (mode), and maximum value for time on the water. There is no other information currently available. Watermen have told us that if they go out onto the water, they will never be there for less than 5 hours. If conditions are not favorable, they will not go at all, and if they do go, travel time, setup, and a minimal harvesting would be no less than 5 hours. Visibility and sometimes regulations constrain the time they can leave or spend on the water. In addition, they must return in time to get their product to market the same day; this caps the maximum time at 11 hours. Most of the time a waterman spends 9 hours on the water and often several more hours at the dock or in other aspects of the business. Thus, we have a minimum of 5, a most likely value of 9, and a maximum of 11 hours spent on the waterway.

13.5.5 USE PREVIOUS EXPERIENCE

The previous experience of watermen was the basis for the input data but let us imagine there is no previous specification of such a distribution that we can find.

13.5.6 DISTRIBUTION FITTING

There are no data for distribution fitting.

13.5.7 EXPERT OPINION

The options for choosing a distribution are restricted to nonparametric distributions and parametric distributions that require little data. An expert is not required to make this choice. The candidate distributions include the uniform, triangle, pert, and beta. Because I have three bits of information, I will reject the uniform and beta, which require only two. My information is sparse, and I do not want to throw any of it away.

13.5.8 SENSITIVITY ANALYSIS

Sensitivity analysis can always be conducted by inserting different distributions into the model. Sometimes it is possible to do some sensitivity analysis outside the model. Figure 13.20 compares the two candidate distributions. Both use the same three parameters (5,9,11). The triangle shows that smaller values are more likely than in the pert and larger values are less likely than in the pert.

13.5.9 FINAL CHOICE

Based on the available information and my crude theory, the pert distribution will be used to express my beliefs about how much time watermen spend on the water in a given day. This distribution is representing natural variability in the time spent as well as knowledge uncertainty about that variability. The amount of time spent on the water is clearly a source of uncertainty that needs to be communicated to the

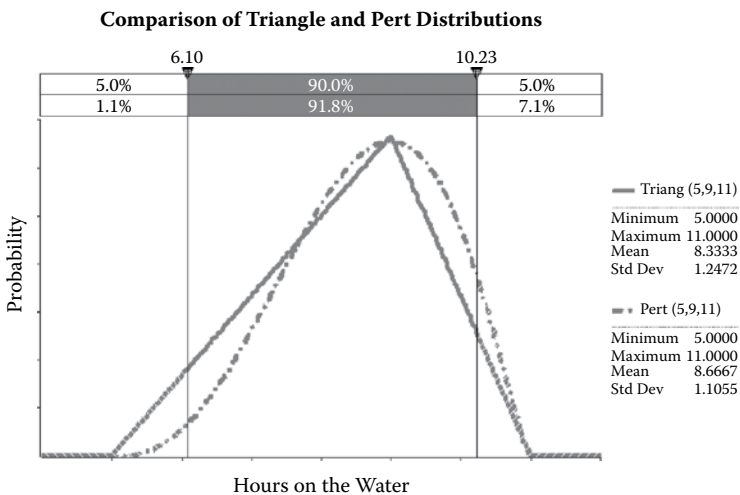


FIGURE 13.20 Comparison of triangle and pert PDFs for time on water data.

risk manager. With additional research we could reduce the uncertainty and better define the variability.

13.6 A DOZEN USEFUL PROBABILITY DISTRIBUTIONS FOR RISK ASSESSORS

Probabilistic risk assessment requires us to specify the distributions of random variable model inputs. The strategy just discussed describes a systematic approach to identifying an input distribution. This final section comments on some of the more common and useful distributions used for risk assessment. Four distributions are offered for those instances when there are relatively little data or information available for the variable of interest. Then, four discrete and four continuous distributions that are likely to be most useful to risk assessors are presented.

13.6.1 FOUR USEFUL DISTRIBUTIONS FOR SPARSE DATA

The uniform distribution (Figure 13.21) is used when data are sparse or absent. Note that the absence of data need not mean we lack information. The uniform describes a situation where a quantity is believed to vary between a minimum value and a maximum value (the distribution parameters) and little else is known about it. All values between the minimum and maximum occur with equal likelihood. In this sense it is a maximum ignorance distribution.

The triangular distribution (Figure 13.22) is also used in the absence of data and entails a little more knowledge about the quantity than the uniform does. It describes a situation where you know the minimum, maximum, and most likely values (the

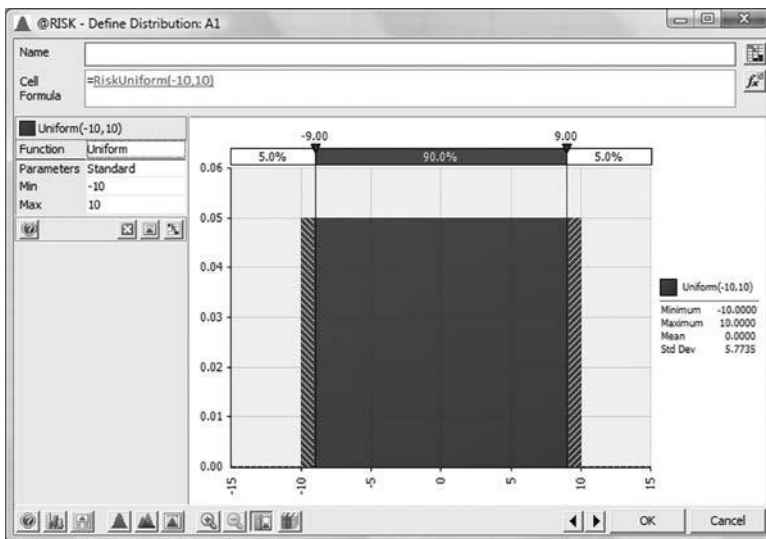


FIGURE 13.21 Uniform distribution.

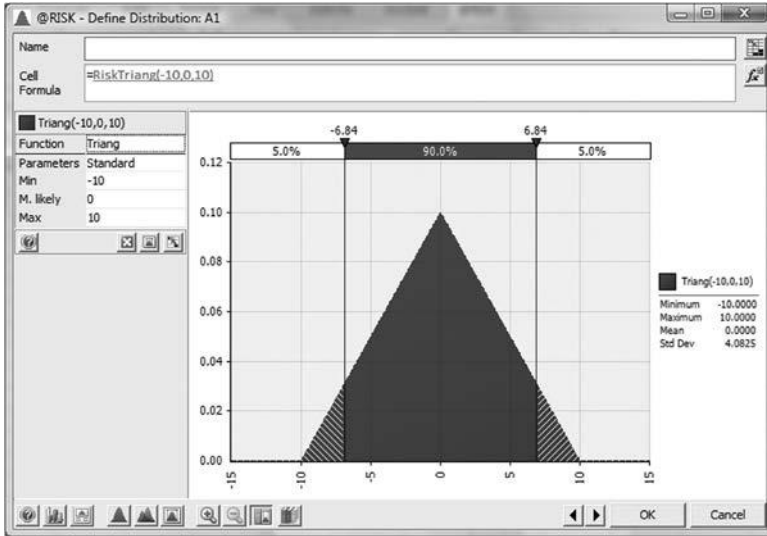


FIGURE 13.22 Triangular distribution.

parameters) to occur. The most likely value is the mode, not the mean. The mode value is elevated to form the peak of the triangle.

The beta (Figure 13.23) is a family of distributions that is also useful in the absence of data. It is a very flexible distribution commonly used to describe variability or uncertainty over a fixed (bounded) range. It is convenient for modeling uncertainty about the probability of the occurrence of an event, as it is naturally defined over

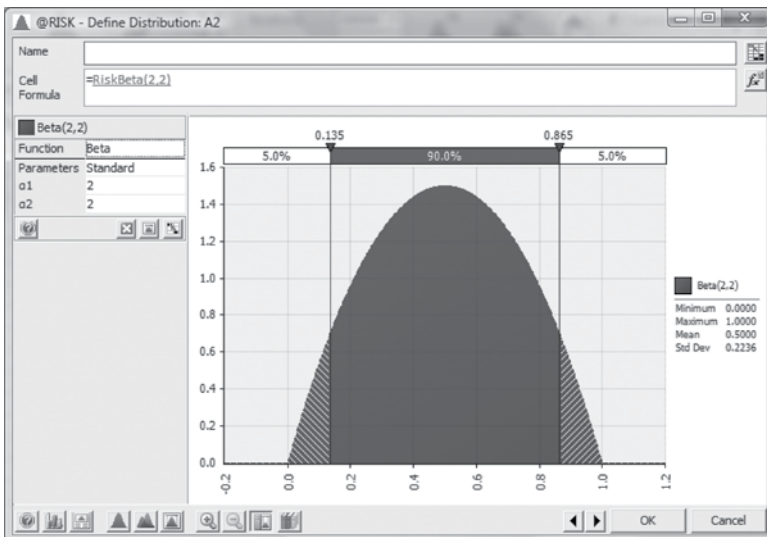


FIGURE 13.23 Beta distribution.

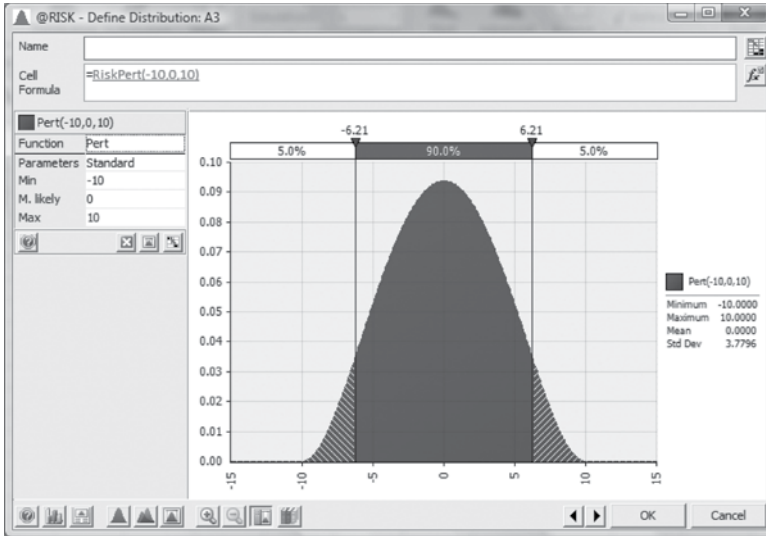


FIGURE 13.24 Pert distribution.

the 0 to 1 range. It is also useful for representing values expressed as fractions or percentages, such as incidence, sensitivity and specificity of tests, population proportions, and the like. Its parameters, α_1 and α_2 , are not intuitively obvious, but they function as shape and scale parameters.

The pert or betaPERT distribution (Figure 13.24) is based on the same information as the triangle distribution. It describes a situation where you know the minimum, maximum, and most likely values to occur. While the triangle “connects” these three points with straight lines, the pert uses the changing slope of a curve. As a result, the pert and triangle tend to differ in the percentage of values near the minimums and maximums.

These four distributions will meet a great deal of the risk assessor’s needs for representing knowledge uncertainty in a model when data are sparse.

13.6.2 FOUR USEFUL DISCRETE DISTRIBUTIONS

The yes-no distribution (Figure 13.25) describes observations that can have only one of two values, such as yes or no, success or failure, true or false, gets ill or does not get ill. It is a special case of the binomial distribution where the sample size, n , equals 1. It is often called a Bernoulli distribution. Its parameters are the probability of a yes and the probability of a no.

The discrete distribution (Figure 13.26), not to be confused with the distribution of a discrete random variable, is made up of a limited number of values or alternative outcomes (A, B, C in the figure). Each of these values/alternative outcomes, which need not be sequential, has a probability of occurring, and that probability can vary. The discrete uniform distribution is a special case of the discrete and is the discrete equivalent of the continuous uniform distribution. All integer values in the discrete

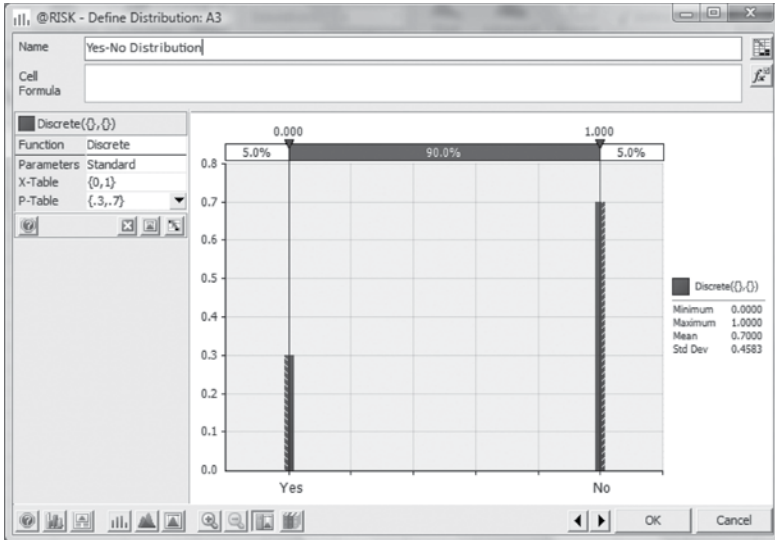


FIGURE 13.25 Bernoulli distribution.

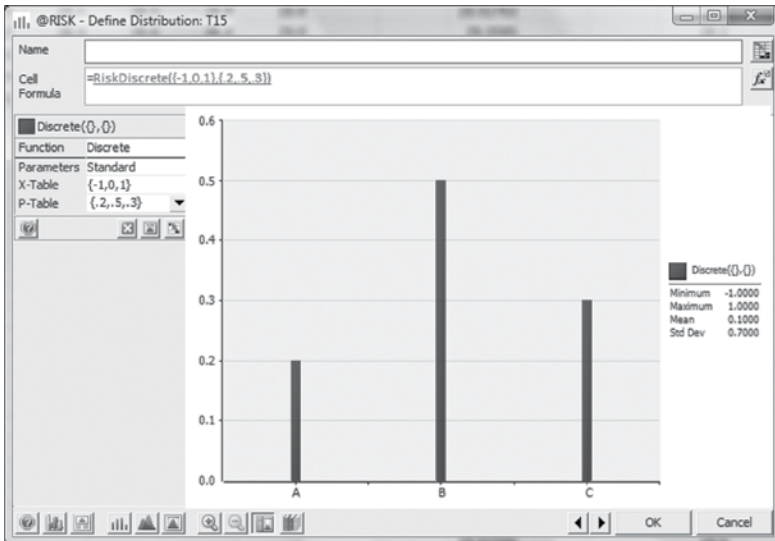


FIGURE 13.26 Discrete distribution.

uniform distribution are equally likely to occur. Its parameters include a number of x-values and the probability of each x-value.

The binomial distribution (Figure 13.27) describes the number of times a particular event with a fixed probability occurs in a fixed number of trials. Examples include the number of defective items in a shipment of 50 items for a given defect rate, the number

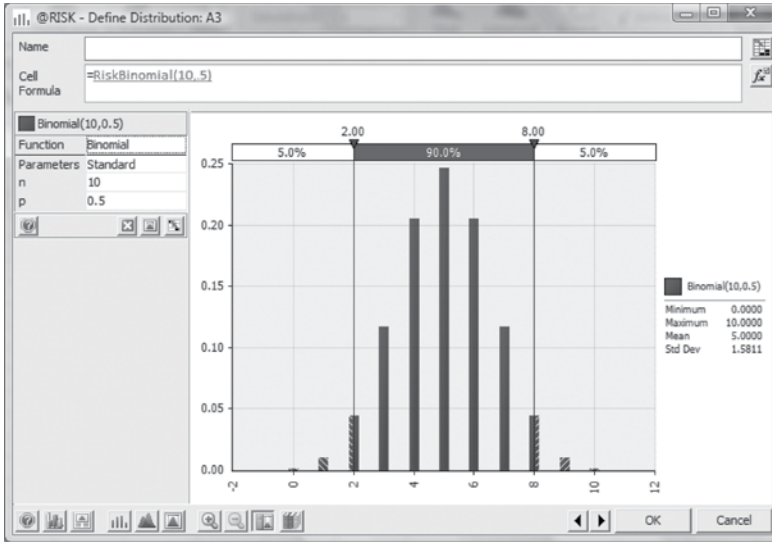


FIGURE 13.27 Binomial distribution.

of contaminated eggs in a gross for a given prevalence, the number of floods with an exceedance frequency of 0.02 or smaller in a 100-year period, and so on. The binomial is one of the most important distributions for risk assessors to learn. Its parameters include a sample size, n , and a probability of occurrence for the event of interest, p .

The Poisson (Figure 13.28) is useful for describing a number of events per unit of measure, that is, a given interval of time or space. Specific examples include such

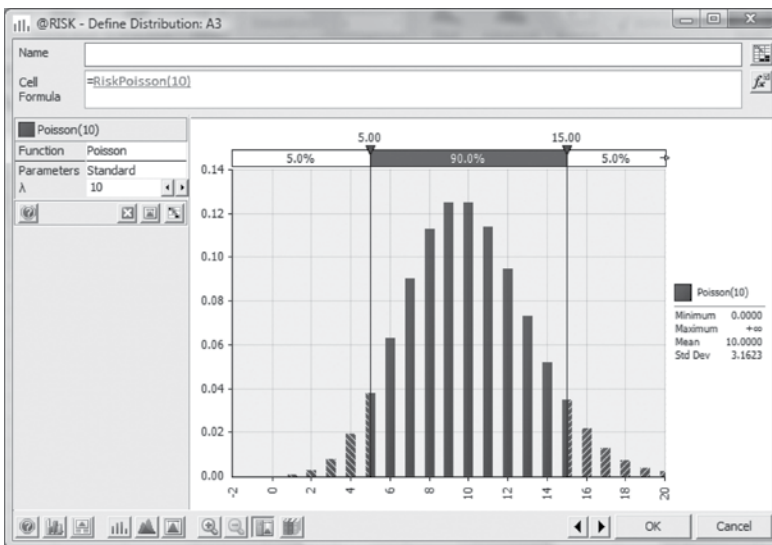


FIGURE 13.28 Poisson distribution.

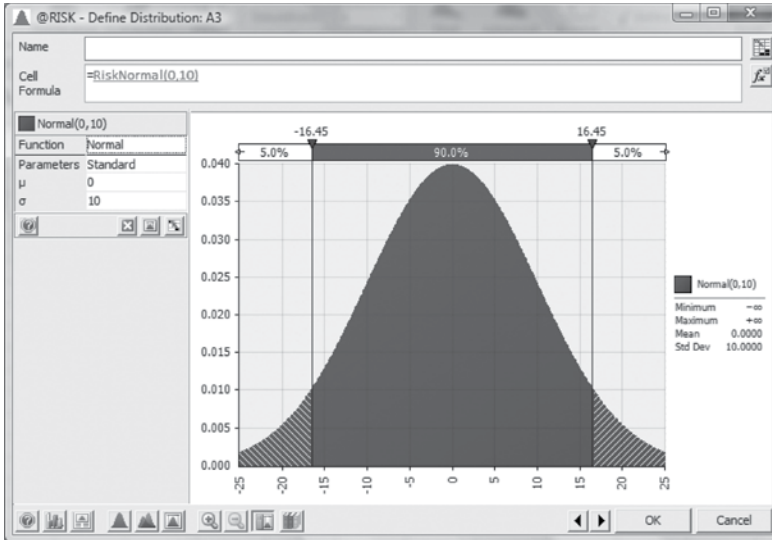


FIGURE 13.29 Normal distribution.

things as vessels or cars per day, houses per hectare, annual shipments, outbreaks per month, flaws per square meter, errors per page, spores per 50-g sample, and so on. The mean (λ) is the only parameter for this distribution.

13.6.3 FOUR USEFUL CONTINUOUS DISTRIBUTIONS

The normal distribution (Figure 13.29) may be both the most important and the most commonly used distribution. It is important because it describes many natural phenomena, especially biological variables such as population heights, weights, IQs, brain size, and the like. It is also useful for pure random processes, and it often describes errors of various types quite well. Quantities that are the sum of a large number of other quantities are also normally distributed by virtue of the central limit theorem. Its parameters are the population mean and standard deviation.

The lognormal distribution (Figure 13.30) describes values that are positively skewed and nonnegative. Charitable giving may be well described by a lognormal distribution. There are relatively few very small contributions which rise to a large number of moderate contributions and then fall off to a declining number of larger contributions. The lognormal also describes many natural physical quantities like particle sizes and chemical concentrations, as well as financial quantities. Quantities that are the product of a large number of other quantities are lognormally distributed by virtue of the central limit theorem. Its parameters are also the mean and standard deviation of the population.

The exponential distribution (Figure 13.31) describes events that occur at random points in time or space. The exponential measures the duration of time (or space)

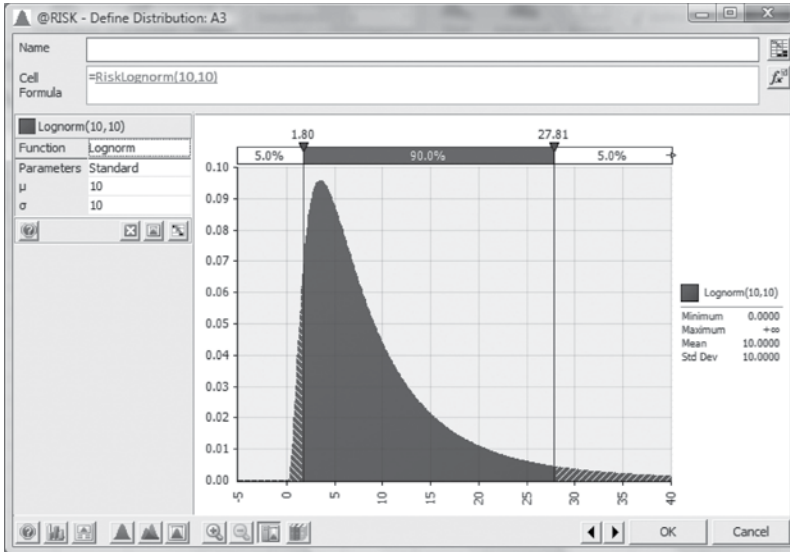


FIGURE 13.30 Lognormal distribution.

between an initial point and the occurrence of some event of interest. For example, time between failures of a piece of equipment, time between arrivals of vessels or people, time between disease outbreaks, the duration of a phone call or other event, and so on are all well represented by an exponential distribution. The mean is the only parameter of this distribution.

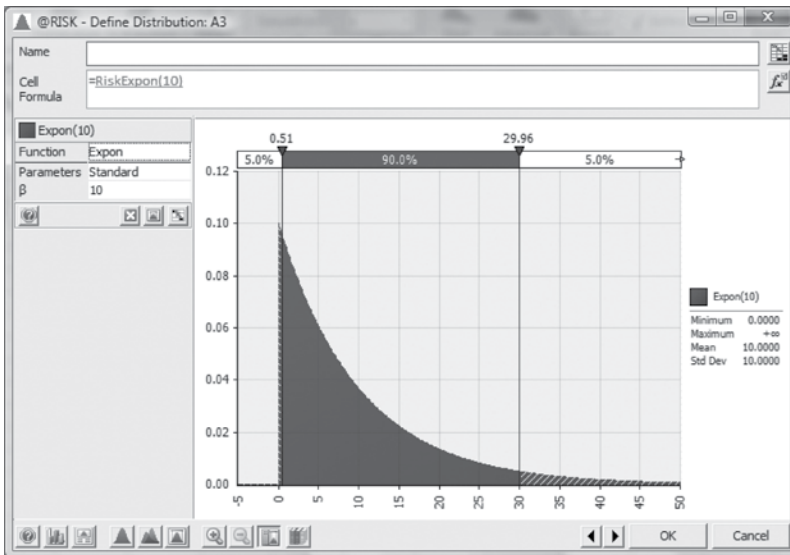


FIGURE 13.31 Exponential distribution.

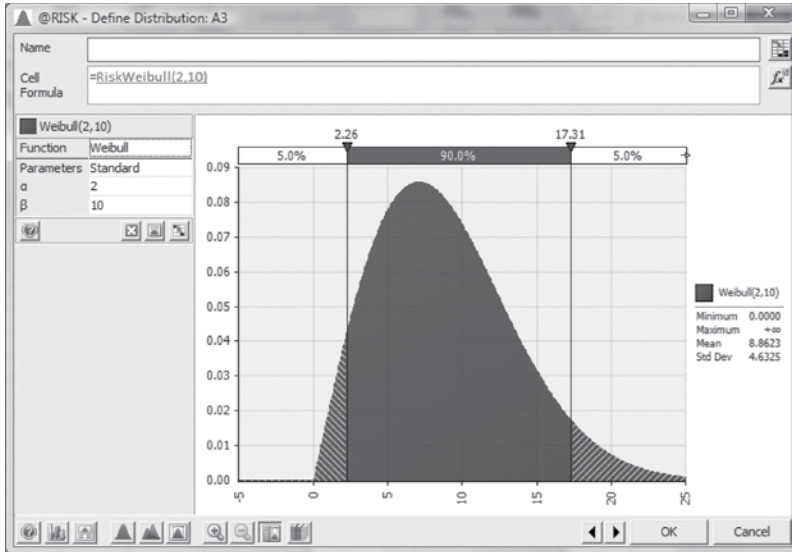


FIGURE 13.32 Weibull distribution.

Weibull distributions (Figure 13.32) are a family of distributions used to describe nonnegative quantities that are not well served by other distributions. It is often used for length of life and endurance data. It is commonly used to describe failure time in reliability studies as well as the breaking strengths of materials in reliability and quality control tests. Weibull distributions are also used to represent various physical quantities, such as wind speed. It has two nonintuitive parameters, α and β .

13.7 SUMMARY AND LOOK FORWARD

If you have good data, consider using an empirical distribution in your probabilistic risk assessment models. If your data are not extensive enough to do that, then devise and follow a careful process for choosing the probability distribution to represent the natural variability and knowledge uncertainty in your instrumentally uncertain model inputs. A nine-step process presented in this chapter is offered for anyone without a better process. Most risk assessors can usually get by on a small handful of distributions. Four sparse data distributions are suggested here for use along with four each of discrete and continuous distributions.

The process described in the chapter works best when risk assessors have some information. Voids and gaps in data are all too common in risk assessment, and we need methods for characterizing our uncertainty in these situations as well. The next chapter describes the use of expert elicitation to tease information out of an expert that is useful for characterizing uncertainty. This is a rapidly growing and frequently abused practice in risk assessment. It is important for risk assessors to understand the heuristics we rely on when forced to consider things we are uncertain about so that their effects can be countered and accounted for when we elicit information from experts. You will learn how to do that in the next chapter.

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14 Characterizing Uncertainty through Expert Elicitation

14.1 INTRODUCTION

How does a risk assessor address the consequence and probability of a risk when the desired knowledge and data are nonexistent or unavailable? The elicitation of scientific and technical judgments from experts, in the form of subjective probability distributions, can be a valuable addition to the evidence base used to support public policy decision making (Morgan 2014). The process of eliciting information from experts, especially in subjective probability distributions, is the subject of this chapter.

Risk analysis is evidence-based decision making that is intentional in its handling of the instrumental uncertainties that could affect decision making. Uncertainty is inevitable. Holes in our data and gaps in our understanding are among the most common causes of a lack of knowledge about a system of interest. Expert elicitation can be a useful way to characterize the uncertainty that results from a lack of knowledge or data.

Expert judgment is not data. Expert elicitation creates neither knowledge nor data. Expert elicitation does not remove uncertainty, it quantifies and characterizes it. Expert elicitation does not fill holes in our knowledge base, it, figuratively, characterizes the uncertainty about the size, shape, and depth of that hole. In so doing, it enables us to be intentional in the ways that we handle instrumental uncertainties in our risk assessments and our decision making. Expert elicitation combines subjective judgment with available knowledge and evidence to produce a type of information that focuses on the likelihood of the nature of an unknown quantity, event, or relationship. When this uncertainty is expressed as a subjective probability distribution it can be especially useful.

Risk managers frequently must ask questions which science alone is incapable of answering. For example, what will happen to accident rates when autonomous vehicles comprise a significant part of the traffic? How will sea level change affect the fortunes of a particular East coast port in this century? A subjective or degree-of-belief approach to probability is useful for many of these situations. We all have gotten quite used to making informal probabilistic judgments about the uncertainty in our own lives with this degree-of-belief approach and we do this with surprising ease and regularity. You don't take an umbrella if you believe it will not rain hard enough to need one. You cross the street if you believe you will not get hit. When you handicap your favorite team's chances to win their next game or the incumbent party's likelihood to retain the White House, you are addressing uncertainty through the subjective assessment of probability. Over time you learn where and when your instincts are more or less good, and you make decisions accordingly.

INFORMAL ELICITATIONS

Expert elicitation can be divided into informal and formal elicitations. Informal elicitations, which are not the focus of this chapter, include self assessment (you decide the values), brainstorming, causal elicitation without structured efforts to control biases, and discussion among peers and colleagues (EPA 1997). These informal techniques are, perhaps, the most common means of filling gaps in our knowledge for routine decision making. These techniques would be best suited for noninstrumental relevant quantities. The formal elicitations of this chapter are generally reserved for the most critical variables in high visibility and controversial analyses, that is, instrumental quantities that can affect decision making.

It is an altogether different situation, however, when the uncertainty we are assessing can have significant implications for others. It is one thing to say I do not think I need an umbrella and another to say we do not think sea level change will affect the fortunes of a specific port this century. In some of these situations, it is important to be more systematic and more careful about how we estimate or characterize uncertain quantities.

This chapter starts by distinguishing personal and professional opinions from expert judgment before considering the circumstances under which one might undertake an expert elicitation. Several types of quantitative descriptions of different uncertain values are presented before subjective probability distributions are discussed. Some distinct challenges presented by subjective probability distributions are considered before we address the elicitation protocol. This is followed by examples of elicitations of subjective probability distributions.

Subjective probability formation, as well as many other forms of decision making, are subject to reliance on a number of heuristics and biases. The more common of these are presented in a discussion of making judgments under uncertainty. The matter of calibrating experts is considered just before the chapter concludes by discussing some issues related to how to handle multiple experts in an expert elicitation.

14.2 PERSONAL OPINION, PROFESSIONAL OPINION, AND EXPERT JUDGMENT

Let us begin with some language. An opinion is a view or judgment formed about something, not necessarily based on fact or knowledge. “Personal” is of or concerning one’s private life, relationships, and emotions rather than matters connected with one’s public or professional career. Therefore, a personal opinion is a view or judgment formed about something based on one’s private experiences. A professional is a person engaged or qualified in a profession. Therefore, a professional opinion is a view or judgment formed about something by a person engaged in a profession that is not necessarily based on fact or knowledge. Ideally, we would hope that professional opinions are based on facts and knowledge. An

expert is a person who has a comprehensive and authoritative knowledge of or skill in a particular area. Judgment is the ability to make considered decisions or come to sensible conclusions. Therefore, an expert judgment is a considered decision or sensible conclusion reached by a person with comprehensive and authoritative knowledge in a particular area. Expert judgment shall be considered preferable to professional opinion which is preferable to personal opinion, while recognizing that all three can be valuable and any of them can be flawed. Relevant uncertainties can be instrumental or noninstrumental, and they can be quantified for risk assessments in any of these three ways.

Now let us make the distinctions concrete. If I estimate the price of a cubic yard of concrete to be a uniform distribution between \$75 and \$200, I am offering a personal opinion. I am not qualified as an estimator. If a cost engineer estimates the price to be normally distributed with a mean of \$108 and a standard deviation of \$11, that is a professional opinion. If the producer of the concrete says it will cost \$117, that is an expert judgment.

In a risk assessment filled with relevant uncertainties there may be room for all three methods for characterizing uncertainty. Relevant but noninstrumental uncertainties may be estimated by personal opinion in some cases without doing any harm to decision making. Instrumental uncertainties should be characterized by professional opinion at a minimum. Expert judgment will be preferred if the decision or its outcomes are significant.

The vast majority of non-instrumental uncertainties can probably be adequately addressed by thoughtful and self-expressed personal and professional opinions supplemented by expert judgment. In a normal risk assessment, many uncertain values will be described by probability distributions for which the assessors estimate the defining parameters. Such uncertainties occur routinely, and they are treated routinely. The methods of the previous chapter represent a “high end” example of self-expressed opinions and judgments.

As part of the evaluation of an ecosystem restoration project downstream of Tenkiller Dam in Oklahoma, our team developed habitat evaluation procedure (HEP) models (U.S. Fish and Wildlife Service 1980) for catfish, bass, and trout. The models consisted of hundreds of variables about which there was uncertainty, either natural variability, knowledge uncertainty, or both. The model outputs, habitat units, were only one of the decision criteria for this project. Most variables in the HEP models were described by minimum, most likely, and maximum value estimates provided by two local resource agency employees. There was no formal elicitation process, professional judgment was sufficient. They were more than competent to answer questions like, “What is the minimum water temperature in this stretch of the river during the summer months?” In addition, the HEP models were not terribly sensitive to minor changes in the input variables. From a practical standpoint there were no real options for more sophisticated analyses as the budget for the work was quite small.

You do not need to complete a formal elicitation process for every uncertain variable in your risk assessment for which you lack sufficient data to choose a distribution in the manner described in the previous chapter. There will be times, however, when experts will be needed to characterize instrumental uncertainties in high profile or controversial risk assessments. In these situations, expert judgment

will be needed and a formal process for harvesting that expert judgment will be warranted. That is when an expert elicitation may be called for.

So, when do you need to do an elicitation? The more the following list tends to describe your decision problem, the better served you will be by a formal elicitation process.

- You lack data and knowledge about instrumental quantities, that is, those that could affect the decision made or the outcomes of a decision.
- Your problem is complex and highly visible.
- Trust in your analytical work is an issue.
- Your risk assessment will provide the basis for public decision making.
- Your risk assessment will provide the basis for a formal rule or regulation affecting industry, nongovernmental organizations (NGOs), or others.
- Your organization has stewardship responsibility for some public value, for example, public health, public safety, water resources, homeland security, and the like.
- There are values in conflict for your issue.
- Your issue is a controversial one.
- There are many stakeholders with diverse views.
- Your issue is subject to intense media or other scrutiny.
- One or more stakeholders are likely to challenge your decision in a court or administrative setting.
- Human life, health, or safety may be affected by your decision.
- There is a clearly critical uncertain variable or two in your risk assessment model.

The ecosystem restoration project mentioned previously met none of these criteria and could be handled through the available sparse data and the professional opinions of those responsible for the analysis. As the importance of the decision grows, as indicated by the preceding list, so does the need for a more formal and credible process for estimating uncertain values in our models.

14.3 WHAT KINDS OF UNCERTAIN VALUES?

Scenarios, models, and quantities can be uncertain. The process is easier to understand if we focus on quantities and, so, we will. Expert elicitation is to be used when there is substantial uncertainty regarding the true values of a quantity. Risk managers often need to make decisions that address complex problems for which there is a lack of direct empirical evidence. Expert elicitation is a means of obtaining and synthesizing expert opinion when data are unavailable or not easily obtainable.

Expert knowledge, experience, and insight are especially useful when the quantities of interest are poorly understood because they are new, rare, or complex; when “hard” data are limited or unavailable, data collection is expensive, or formal modeling is infeasible (Ayyub 2001a,b; Meyer and Booker 2001). Morgan (2014) asserts that the elicitation of scientific and technical judgments from experts, in the form of subjective probability distributions, can be a valuable addition to other

forms of evidence in support of public policy decision making, especially when our decision problems require judgments that go beyond well-established knowledge. Expert elicitation can make a valuable contribution to informed decision making. It can provide insights into the nature of instrumental uncertainty that are not available from any other source.

The U.S. Army Corps of Engineers is relying on novel technologies to reduce the probability that Asian carp would reach Lake Michigan if a project is built at Brandon Road Lock and Dam. Little data exist on the performance of these technologies and the resulting uncertainty could affect the decision that is made or the outcome of a decision once made. This is an ideal situation for an expert elicitation.

Quantitative descriptions include: point estimates, paired comparisons, single-event probabilities, distributions of continuous uncertain quantities, conditionalization and dependence (Cooke and Goossens 1999), and parameters of distributions. Each is considered in turn below.

Assessments that result in point estimates are of limited, if not questionable, value because they give no indication of uncertainty, which, of course, is the entire point of characterizing uncertainty. Expert elicitations that produce point estimates can have the illusion of knowledge or fact, especially to decision makers and others outside the process. It is essential to have some characterization of the uncertainty in such instances.

Paired comparisons have been used when experts are asked to arrange a set of items in ordinal sequence according to some criterion like hazard potential, effectiveness, likelihood, and the like. The work can be tedious, comparing 20 items requires a total of 190 pairwise comparisons. These comparisons fail to produce a characterization of uncertainty, although methods for evaluating the degree of expert agreement and consistency are available (Cooke and Goossens 1999).

Single-event or discrete event probabilities are used to assess the probability that an uncertain event occurs or does not occur. The quantitative estimate takes the form of a point estimate, an interval, or a continuous distribution in the $[0,1]$ interval. Estimating a probability using a probability distribution can be challenging. Examples include the probability a stock price rises today, a specific person contracts cancer, an earthquake occurs this year, it rains tomorrow, an aquatic nuisance species becomes established in a new watershed, and the like.

Distributions of uncertain quantities are used in problems concerned with the value that will be realized by an uncertain quantity that varies across a continuous range. This uncertainty is described by subjective probability distributions. Imagine that an expert is asked to characterize the uncertainty about the amount of oil that could be released in an oil spill, call this quantity X . The expert offers his subjective distribution over the possible values of X . The elicitation may take a number of forms; the expert may specify his cumulative distribution function (CDF), his probability density function (PDF), or he may estimate selected parameters of a distribution like the mean and standard deviation of a normal distribution, or selected quantiles of his distribution like the 5%, 50%, and 95% quantiles.

One must make known the background information upon which the uncertainty descriptions are to be based. Every distribution is conditional on some set of assumptions and some body of evidence. Different experts may offer distributions based on different sets of assumed conditions that may render the various estimates too disparate to be compared. Establishing this background information is an important function of the elicitation protocol. If a distribution's values are dependent on other variables whose values are not preidentified and specified, the subjectively identified distributions will be of limited value.

There may be times when there is general agreement on the shape of the probability distribution to be used and the primary task is to simply estimate the parameters of the distribution. These parameters can be estimated as points, intervals, or distributions. The latter two options lead to second degree distributions, with uncertain parameters. First order distributions are well-served by point estimates of the parameters. For a normal distribution the task is to estimate the mean and standard deviation. It is also common practice to estimate quantile parameters for a distribution, for example by estimating the 5%, 50%, and 95% cumulative probabilities for the chosen distribution. The distributions yielded by these methods are subjective probability distributions, the subject of the next section.

14.4 SUBJECTIVE PROBABILITY DISTRIBUTIONS

The point of expert elicitation is to capture an expert's characterization of the uncertainty about some event or quantity. That quantity may be a probability of a single event or the frequency of an event in a population, or it may be any nonprobability value. A probability distribution can be constructed from p-x pairs, where p is a cumulative probability and x is a realized value of a random variable X. When X is, itself, a probability the process can be challenging.

In an expert elicitation, probability is viewed as a statement of an individual's belief, informed by all the formal and informal evidence that they have available (Morgan 2014). Probability, the p in the p-x pairs, is always interpreted as personal or subjective probability in expert elicitation, that is, it is a measure of a person's degree of belief in something. For example, if an expert says there is a probability of 0.3 that if an oil spill occurs at a specific location it will be less than 10,000 gallons, this expresses the expert's personal degree of belief that a spill in that range will occur. Subjective probabilities differ from one expert to the next because experts all have different extents of factual knowledge and generic experience in their domains of expertise.

These subjective probabilities are not preformed numbers lying hidden in our brain cells waiting to be revealed to the world. They are values that must be carefully constructed when needed. According to the subjectivist view, the probability of an event, such as $P(X) > x$, is a measure of a person's degree of belief that it will occur. Thus, probability is not a property of the event but a property of the expert's judgment (Morgan and Henrion 1990). Because experts may vary in their judgments, my subjective probability of an event may be different from your subjective probability of the same event. Thus, there are no "correct" subjective probabilities, even for experts. Subjective probabilities may be self-expressed or elicited.

Subjective probabilities are often used in risk assessments. They cannot be arbitrary. To be useful they must be coherent, that is, they must obey the laws and theories of probability such as those laid out in [Chapter 12](#). Lindley et al. (1979) posited that the individual expert has a set of coherent probabilities that can be distorted by the elicitation process, so that process must be carefully constructed. Savage (1954) and DeGroot (1970) have argued that a person who wants to make rational decisions when faced with knowledge uncertainty must act as if they have a coherent set of probabilities. Some, like Gigerenzer and Todd (1999), are more forgiving about coherence of the individual and are willing to live with reasonable adaptive inferences about our real-world environments.

If subjective probabilities are not based on formal and coherent constructions of the theory and may in fact be noncoherent, then what status do these probabilities have? Winkler (1967) said there is no built-in prior distribution there for the taking, and different elicitation techniques may produce different distributions. He goes on to suggest that these different distributions are equally valid, even though research has shown that some forms of questioning can lead to invalid responses.

This all means that the elicitation technique matters because experts' statements of probability are likely to be made in response to the question asked rather than based on preanalyzed and preformed coherent beliefs. The purpose of elicitation is to represent the expert's knowledge and beliefs accurately in the form of a good probability distribution (O'Hagan et al. 2006).

14.5 THE ELICITATION PROTOCOL

People do not have well-formed subjective probabilities in their heads. Asking people to make up numbers out of the blue is not a good idea. There is a great deal of literature that says people are not especially good at estimating probabilities, especially small ones. We tend to be amazingly overconfident in our estimates of uncertain things, and we tend to rely on the heuristics discussed later in this chapter. Using elicitation techniques that avoid reliance on heuristics and biases that force people to think about the numbers and calibrate themselves can be useful. If there are systematic ways we tend to err and our goal is to improve the elicitation process and its results, perhaps we can avoid the errors with well-structured formal protocols for assessing uncertainty and eliciting probabilities.

ROLES IN ELICITATIONS

Decision makers will use the results of the elicitation (the client).

Substantive experts have the knowledge about the uncertain quantities.

Normative experts provide probabilistic training, assess the process, validate results, and provide feedback.

Facilitators are experts in the elicitation process and manage the elicitation.

Source: O'Hagan et al. (2006).

There are numerous ways to configure an elicitation. The number of experts, the elicitation method (individual or group), elicitation instrument (interview or questionnaire), and method of aggregation can all be varied. It is useful to have enough experts to get a good characterization of the uncertainty without a great deal of duplication. Six to 12 experts are considered a reasonable number of experts. O'Hagan et al. (2006) opine that group elicitation is best suited to elicitation for tasks with a definitive and demonstrable correct answer. Otherwise individual elicitation may be best. Face-to-face interviews offer obvious advantages for communication, clarification, and completeness, but questionnaires serve a useful purpose when assembling the experts in one place is not an option. Aggregating experts is considered in Section 14.8.

There are any number of elicitation protocols described in the literature. Three are briefly summarized here. The first is a seven-step method proposed by Clemen and Reilly (2001). The steps are:

1. Background identification of variables requiring expert assessment; review of scientific literature
2. Identification and recruitment of experts
3. Motivating experts—establish rapport with experts and generate enthusiasm for the process
4. Structuring and decomposition—explore the experts' understanding of causal and statistical relationships among the relevant variables
5. Probability assessment training—explain the principles of the assessment, the biases and heuristics, and ways to counter them; provide opportunities for experts to practice making probability assessments
6. Probability elicitation and verification—experts make required assessments under the guidance of a facilitator; assessments checked for consistency and coherence
7. Aggregation of experts' probability distributions—if multiple experts were used, it may be necessary to aggregate their assessments.

The second is the Stanford/SRI Assessment Protocol (Morgan and Henrion 1990), which consists of five phases:

1. *Motivating*: Establish rapport with experts, explain need and process, explore motivational bias
2. *Structuring*: Develop unambiguous definition of quantity to be assessed in a form meaningful to experts
3. *Conditioning*: Get experts to think fundamentally about their judgments while avoiding cognitive biases
4. *Encoding*: Elicit and encode the expert's probabilistic judgments
5. *Verifying*: Test judgments to see if they reflect the expert's beliefs

The third is a five-step model for elicitation developed by O'Hagan et al. (2006):

1. *Background and preparation*: The client identifies variables to be assessed

2. *Identify and recruit experts*: The choice may be obvious or it may require some effort; six criteria for experts:
 - a. Tangible evidence of expertise
 - b. Reputation
 - c. Availability and willingness to participate
 - d. Understanding of the general problem area
 - e. Impartiality
 - f. Lack of economic or personal stake in the potential findings
3. *Motivating and training the experts*: Assure the experts that uncertainty is natural; training should have three parts:
 - a. Probability and probability distributions
 - b. Introduction to most common judgment heuristics and biases as well as ways to overcome them
 - c. Practice elicitation with true answers unlikely to be known by the experts
4. *Structuring and decomposition*: Spend time exploring dependencies and functional relationships that meet agreement by experts; precisely define quantities to be elicited
5. *The elicitation*: An iterative process with three parts:
 - a. Elicit specific summaries of expert's distribution
 - b. Fit a probability distribution to those summaries
 - c. Assess adequacy: if adequate, stop; if not, repeat the process with experts making adjustments.

Elicitations are best in a face-to-face setting that allows interactions between the expert and the facilitator. All protocols have several stages, but the elicitation always comes at or near the end of the protocol. Its success depends on preparation and foundations established in the preceding steps. Each of these protocols is described in greater detail in the reference documents.

14.6 ELICITING SUBJECTIVE PROBABILITY DISTRIBUTIONS

The elicitation step is where the information is developed. The expert's statements of probability are judgments made in response to the facilitator's questions. Once again, for emphasis, they are not preanalyzed and preformed beliefs of the expert. Thus, the matter of how one asks the questions is of some importance. The basic choices are to provide an x -value for a variable X and ask for the corresponding cumulative probability, p ; or to provide a p -value and ask for the corresponding x -value.

To better frame the discussion, assume we are interested in estimating the size of a crude oil spill in a waterway that serves several refineries with a subjective probability distribution. A cumulative probability distribution that represents the expert's beliefs about the total number of gallons spilled in an event might look like the hypothetical example in [Figure 14.1](#).

This is a free-form estimate based on an expert's estimation of the quartile values shown in [Table 14.1](#). The curve of [Figure 14.1](#) was constructed by linearly

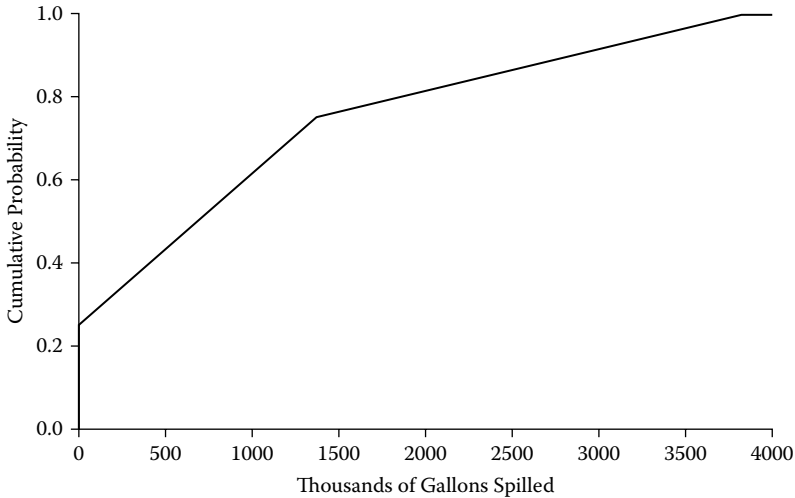


FIGURE 14.1 CDF of the size of an oil spill in the Delaware River.

TABLE 14.1

Oil Spill CDF Elicited from Experts

Cumulative Probability	Thousands of Gallons Spilled
0	0
0.25	5
0.5	668
0.75	1,353
1	3,850

interpolating between the points provided. Note that to define such a distribution, the facilitator can elicit values for x_i , in this case gallons of oil spilled, associated with a given probability (p_i), or the facilitator could provide the x value and ask for associated p values.

An alternative elicitation would be to estimate the uncertain parameters of a specific distribution. This is somewhat similar to the point-estimate elicitation in concept. For this example, imagine it has been determined the size of an oil spill is best represented by an exponential distribution. This assumption imposes a structure on the oil spill problem. The experts are needed to estimate the parameters of the distribution. In this instance, the exponential has only one parameter, the mean. Assuming our experts have estimated this value to be 988,000 gallons, the exponential distribution would be the first-degree distribution shown by the line graph of Figure 14.2. If our experts estimated the mean with a uniform distribution with a minimum of 750,000 gallons and a maximum of 1,500,000 gallons, the second-degree distribution so formed would look like the bar graph of Figure 14.2.

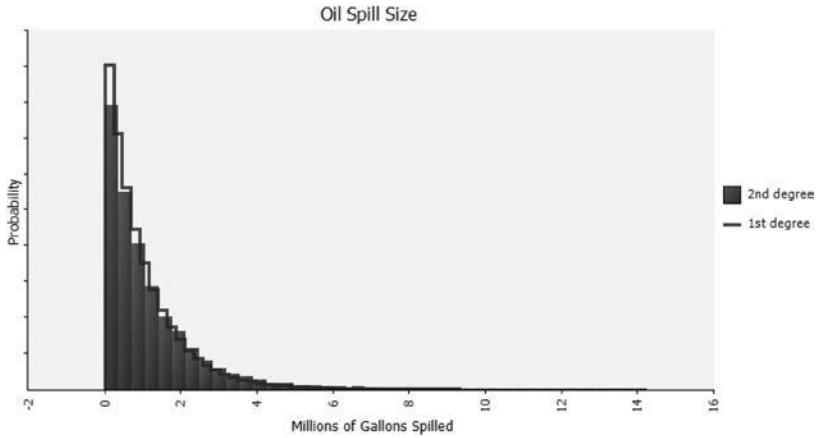


FIGURE 14.2 First and second degree exponential distributions describing the size of an oil spill in the Delaware River.

The p - x pairs of the CDF are a more common way of eliciting information and will be our elicitation focus from now on. That will subsume many of the issues associated with the other elicitations, because it is the more involved process. The size of an oil spill is a continuous random variable. Assuming we are going to elicit the expert’s CDF, there are an infinite number of points that could be elicited. The strategy is to elicit information about a relatively few number of individual (p, x) pairs that enable us to reproduce the expert’s beliefs in the form of a probability distribution.

The information sought is called a summary. The idea is that a few well-chosen summaries will enable us to identify the expert’s beliefs with a high degree of precision. Then, using these summaries, a curve is fitted to them. This can be done by interpolation as shown previously or by fitting a general form function to the points.

The summaries we obtain can, as noted, be based on probabilities or on quantity values. Summaries based on probabilities may be the most common form of elicitation. A basic strategy is to seek specific quantiles that can be used to construct a CDF. For example, one might elicit an x -value for the median value, $p = 0.5$. This divides all possible values in half. The expert may then be asked to find the midpoint of each remaining range, producing the median and then the quartiles. If desired, this process can be extended to the octiles, the 12.5, 37.5, 62.5, and 87.5 percentiles. It is usually difficult for the expert to go beyond these values. Examples of questions that yield the median, first and third quartiles for the oil spill follow:

- Can you determine an oil spill size such that any spill is as likely to be larger than this number as smaller than this number?
- Suppose we have learned the oil spill is smaller than your median. Can you now determine a new oil spill size (lower quartile) such that it is equally likely that this oil spill is larger than or smaller than this value?
- Suppose we have learned the oil spill is larger than your median. Can you now determine a new oil spill size (upper quartile) such that it is equally likely that this oil spill is larger than or smaller than this value?

For contrast, an alternative formulation of the second question might be, “Give an oil spill size such that you think an actual oil spill has a 25% chance of being less than it.” There can be many formulations of your specific questions. As long as the answers yield p-x pairs, a distribution can be elicited. However, there are a great many nuances and lessons learned that are documented in a large and growing literature. The O’Hagan et al. text is essential reading for anyone who intends to work in this area. The Ayyub (2001a,b) text is another essential reference for those interested in more details on the topics introduced in this chapter.

Fixed-value methods work a little differently than the quantile method illustrated above. If we are deriving a CDF we might ask, “What is the probability that an oil spill will be 5,000 gallons or less?” Successively larger or smaller spill sizes probabilities can be sought to flesh out the shape of the CDF. My experience, and that of others, suggests that an expert can fall into a biased rhythm of linear interpolation/extrapolation if the facilitator’s questions have a pattern to them. For example, asking probabilities of oil spills in 5,000-gallon intervals or even in a monotonically increasing (or decreasing) way can lull an expert into an easy pattern of answering that does not require careful thought about the answers. Varying the pattern of your questions can encourage a more analytical response.

For example, one might ask the probability that a spill is 5,000 gallons or less, followed by 150,000 gallons or less, then 70,000 gallons or less, followed by 1,000,000 gallons or less, and so on in an unpredictable way. The idea is to vary the pattern of the questions to avoid simple interpolation or other biased answering schemes and to require more careful thinking about the probabilities. One could vary the question by asking the probability that a spill is 70,000 gallons or more, instead of less. Such questions can help identify problems with coherence in the expert’s assessment of the uncertain quantity. Bounding the CDF, that is, establishing minimum and maximum values when appropriate, is usually going to be a sensitive aspect of the elicitation. Given the anchor-and-adjust heuristic, it is especially important to probe the limits carefully (see box).

BOUNDING A DISTRIBUTION

When eliciting an expert’s distribution, it is often necessary to establish a minimum and maximum value for the quantity of interest. Neither data nor experience are likely to reveal absolute extreme values, when logical limits do not exist (0 is a natural limit for many quantities and the [0,1] interval applies to a number of problems).

When experts must estimate these values, it is important to find nonthreatening ways to challenge their estimates. In the oil spill example, one might ask, “If you were gone for a year and returned to learn there had been a spill of X (some value noticeably larger than the expert’s maximum estimate) gallons, how could you explain that?” If the expert offers a plausible explanation, offer him the opportunity to amend his estimate.

Probe the limits carefully.

It is also possible to ask questions that approximate a PDF for an unknown variable. In this instance we might ask, “What is the probability that if an oil spill occurs it will be between 10 (or whatever the agreed upon minimum size of an oil spill is) and 5,000 gallons? Greater than 5,000 gallons but less than 25,000 gallons?” and so on. The notion for the PDF elicitation is to seek the probability of a quantity being within a fixed interval. The challenge is to assure that all of those fixed interval probability estimates sums to one.

An alternative approach to elicitation is to ask the expert to draw points for the CDF. This is generally not a terribly realistic way to approach the problem, but it has been used in the past.

Estimates of probabilities can sometimes be better analyzed by decomposing the problem. An oil spill problem can be decomposed by focusing on the vessel’s size or the cause of the spill. This can increase the number of elicitation required, or it can entail elicitation of multivariate distributions, which are far more complex. If a problem is to be decomposed, the decomposition can be prescribed by the investigators or by the experts.

To this point, the discussion has emphasized the expert’s unique probability distribution. It is worth emphasizing that the elicitation could elicit p-x pairs, rather than parameters, for well know distributions like the beta or Pert distributions. When this is done, some common values sought are: the 5%, 50%, 95% quantiles; the 1%, 50%, 99% quantiles; or the terciles (33%, 67%). The X variable may or may not be bounded by minimum and maximum values.

Each of the elicitation protocols provides for probability training or conditioning of the experts. This is going to be especially important if some of the uncertain values you seek are probabilities that will be estimated by a subjective probability distribution. Consider the question, “What is the probability that Asian Carp will spread beyond Lake Michigan?” (See box.) Can you determine a probability of spread such that the uncertain probability of spread is as likely to be larger than this number as smaller than this number? If that does not make your head feel like it will explode, little will. Great care must be taken in assuring that your experts are comfortable answering such questions.

EXAMPLE ELICITATION QUESTIONS

When thinking about the number of Asian Carp that could arrive at Brandon Road by the year 2021, please rate the following population sizes by their relative probability of arriving (larger numbers indicate a higher probability):

- Negligible Population _____
- Small Population _____
- Medium Population _____
- Large Population _____
- TOTAL 100 Points

The following questions were answered by having the expert provide minimum, 33rd percentile, 67th percentile and maximum values. Considering the currently existing system that is in place, assume that a large population of Asian Carp have arrived at the Brandon Road Lock and Dam. The number

of fish that will make it all the way from downstream of the lock and dam into Lake Michigan in a year will vary from year-to-year, and that number is uncertain. What do you believe is the number of fish that could pass from below the dam to Lake Michigan in a year?

Assume that Asian Carp have a colony in Lake Michigan. What is the probability that Asian Carp will spread beyond Lake Michigan?

Repeated after each answer was the following question: What were the main considerations in shaping your answer?

Think about whether probability values will be sought as decimals, percentages, or odds. Choose a method that suits the expert assessor's cognitive styles, skills, and preferences (Morgan and Henrion 1990). I have worked with experts who did not finish high school (towboat operators) and Ph.D.'s (epidemiologists and engineers). No one-size probability elicitation fits all needs. It is best to establish the preferred or most promising question style in the foundational work that precedes the elicitation, including the practice elicitations.

14.7 MAKING JUDGMENTS UNDER UNCERTAINTY

To develop useful elicitation procedures and to obtain useful probability estimates, it helps to understand how people form judgments about uncertain values. Research suggests that experts and laypersons alike rely on the use of some common heuristics in forming judgments about uncertain quantities (Tversky and Kahneman 1974). Knowing about these shortcuts and their pitfalls is the first and most important step in avoiding them. Elicitation processes that avoid reversion to these heuristics or at least minimize their impact are better than those that do not.

A heuristic is a mental shortcut we use to solve a particular problem. It is a quick, informal, and intuitive algorithm we use to generate an approximate answer to a reasoning question. Heuristics enable us to quickly make sense of a complex environment, but they sometimes fail to correctly assess the world. When they do, heuristics can lead to a cognitive bias that results in an incorrect conclusion.

Our brains are wired in such a way that it is easier to think dramatically than it is to think quantitatively, and especially probabilistically. Probability is not intuitive, as we have seen. It is not easy to think in probabilistic terms. Instead, we tend to use some rather crude cognitive techniques to help us along. The most common of these heuristics and biases are discussed in the following sections.

14.7.1 OVERCONFIDENCE

Mark Twain once said, "It ain't what you don't know that gets you into trouble. It's what you know for sure that just ain't so." This is the essence of overconfidence; it is the tendency for people to be more confident than the evidence warrants. Overconfidence

is often said to be the most pervasive bias people have. When eliciting subjective probabilities, it can lead to estimates that are closer to zero or to one than they should be and to distributions that are narrower than they should be. There is some evidence to suggest overconfidence increases with expertise and knowledge. Many studies of lawyers, doctors, nurses, managers, entrepreneurs, investment bankers, and others have found that they tend to put great trust in their opinions and overestimate their expertise (Riordan 2013).

Calibration exercises can be effective in making subject matter experts aware of the extent of their overconfidence. Decomposing a problem into several component events may help reduce the effects of overconfidence. It is easier to be overconfident about a general issue than it is to be overconfident about a detailed and specific issue. The strategy for offsetting this bias means conducting more specific elicitations. Alternatively, one might ask an expert what sources of information they rely on for their judgments and whether these are fact-based or simply beliefs and opinions.

14.7.2 AVAILABILITY

Estimates of uncertain quantities are driven by the ease with which previous similar events or instances can be recalled; it can be enhanced by the frequency of events recalled (Hardman 2009). We tend to overestimate the probability of events that come to mind easily and underestimate the probability of events that are not so readily recalled. If a flood just occurred, people tend to overestimate the probability of flooding. If there have been no floods for a few decades, people underestimate the probability of flooding. The more easily examples come to mind, the more probable we think the event is. Similarly, the easier it is to recall instances of a class of events, the larger we estimate that class to be. Most of us use availability instead of the more complex processes we might use to estimate probabilities.

Media coverage affects availability. When low-frequency events receive extensive media coverage—terrorist attacks, levee failure in New Orleans, plane crashes, oil-drilling disasters—it is common to overestimate their probability of occurrence because it is easy to call examples of these things to mind. On the other hand, the probabilities of more common events that do not get the same attention—seasonal flu, automobile accidents, choking on food—are often underestimated.

Members of a team overestimate their own contributions relative to those of others because their own contributions come easily to mind.

Recent events or events that have affected the expert personally may be emotionally paper-clipped memories that are easier to recall. This can cause a temporary increase in the estimates of the likelihood of these events. If a family member is diagnosed with leukemia, it is more likely that a person will overestimate the probability of this disease. The flipside is also true. If there have been no recent occurrences (of home fires or automobile accidents, for example) or it is a problem that has not touched the expert personally (e.g., identity theft or leukemia), probabilities may be underestimated.

Co-occurrences of events can also distort estimates through an availability bias. I grew up at a time when many family members and neighbors associated space launches and extreme weather events. This connection of events was more illusion than cause and effect. After a while, the hurdle for unusual weather was dropped and the window of opportunity for an occurrence was extended, all of which had the effect of a self-fulfilling prophecy. Eventually people saw more co-occurrences than actually happened. A heavy rain, an extreme temperature within weeks of a launch, or a heavy snowfall in the same year could be associated with a space launch. These events are more strongly associated in the mind than in fact. Beliefs about relationships can affect judgments for all kinds of uncertainties. If availability misleads the expert to misinterpret the strength of a relationship, it can affect probability estimates (Gilovich, Griffin, and Kahneman 2002; Sedlmeier and Betsch 2002). Linked events in a scenario, for example, are easier to imagine than the individual events considered in isolation.

The first step in neutralizing the availability bias is to be consciously aware of it. Try not to look at information chronologically. Look at trends from a variety of angles. Continue to question the extent to which you rely on easily recallable events. Consider a longer timeframe. Investigate the history of like events before and after those that come to mind easily. Consult a wider base of evidence. Question commonly accepted views to build a wider perspective of the quantity you are addressing. Expand your focus and include information in addition to the vivid information that captures your imagination. Constructing a comprehensive body of evidence as part of the elicitation read ahead may help offset the availability bias.

14.7.3 REPRESENTATIVENESS

The representativeness heuristic manifests itself in a variety of ways. Tversky and Kahneman (1983) define representativeness as “an assessment of the degree of correspondence between a sample and a population, an instance and a category, an act and an actor, between an outcome and a model.” A person following this heuristic evaluates the probability of an uncertain event by the extent to which it is similar in essential properties to its parent population. Consider an event, A. Instead of calculating $P(A)$, those laboring under the representativeness heuristic will try to fit event A into some more familiar class of events and use that probability instead.

Representativeness bias is especially relevant to the estimation of conditional probabilities. Common representativeness biases are summarized in the following sections. The best way to confront and address the representativeness heuristics that follow begins with awareness of the relevant heuristic and proceeds most logically to doing the math. Not every expert will be adept at the relevant math so it may be helpful to have that expertise available on the elicitation team.

Koehler (1996) found that several of the problems associated with representativeness can be improved by eliciting frequencies instead of single-event probabilities. For example, instead of asking the probability for “Linda is a teller and an activist,” we might ask, “Of 100 individuals like Linda, how many would be bank tellers and how many would be active in the feminist movement and bank tellers?” (Fiedler 1988). Frequency formats help reduce representativeness bias as compared to probability of single-event question formats. Unfortunately, they also increase availability problems.

14.7.3.1 Conjunction Fallacy

Tversky and Kahneman (1983) offered this oft-repeated example of the conjunction fallacy:

Linda is 31 years old, single, outspoken, and very bright. She majored in philosophy.

As a student, she was deeply concerned with issues of discrimination and social justice and also participated in antinuclear demonstrations.

Which is more probable?

Linda is a bank teller.

Linda is a bank teller and is active in the feminist movement.

Most people (usually 80% or more) select the second answer, and this is impossible. How is it possible that Linda is more likely to be a teller (A) and active (B) than that she is just a teller (A). The second answer above is a joint probability, the conjunction of two conditions (A and B). There is no way there can be more people who are tellers and activists than there are people who are just tellers. Surely some tellers are not activists. So, it must be more likely that she is a bank teller.

What is at work here is that the description of Linda is unrepresentative of what most of us think a bank teller would be. This tends to decrease our belief that she is a teller. However, adding the active feminist detail provides a description of Linda that is more representative of an activist. We tend to rely more on the representativeness than we do on the simple facts of probability to gauge the likelihood of the right answer. In other words, we replace a difficult question with an easy question. Instead of calculating a probability we ask does Linda seem like a feminist? One take away from this is do not be misled by highly detailed scenarios. Greater specificity and detail in a scenario lowers its chances of occurring, even if the scenario seems to represent the most probable outcome.

14.7.3.2 Base-Rate Neglect

A base rate is a relative frequency. People will often ignore information about the base rate and estimate probabilities based solely on the information about the event or instance before them. If you have ever been to the doctor and been instructed to have a laboratory test for a rare and serious disease, the chances are good that your emotional response illustrated base-rate neglect.

The simple fact is, absent other specific information, it is highly unlikely you have the rare disease. When the doctor asks you to have the test, you ignore this fact and focus on the fact that they have asked you to get this test. We are likely to overestimate the probability that we have the disease.

Tversky and Kahneman (1982) offered the following example. Suppose the percentage of homosexuals who have a disease is three times higher than the percentage of heterosexuals who have the disease. Pat is diagnosed with the disease. This is all that you know about Pat; you do not even know if Pat is male or female, much less Pat's sexual orientation. What is the probability that Pat is homosexual?

The disease is more representative of homosexuals than heterosexuals, so the representativeness bias would cause most people to overestimate the probability Pat is homosexual. The actual answer depends on the real numbers, so let us use a population of 100%, 10% of whom are homosexual (10). Of them 3 have the disease (30%). There are

90 heterosexuals with a 10% rate of disease (9). Three of 12 people (3 + 9) who have the disease are homosexual, so 25% of all diseased people are homosexual, and the probability that Pat is homosexual is 25%. Base-rate neglect pushes the probability estimate closer to 75% for many people (75% is three times 25%, reflecting the higher prevalence for homosexuals). Whenever possible, pay attention to base rates. They are especially important when an event is very rare or very common.

14.7.3.3 Law of Small Numbers

People fail to understand the nature of randomness. We often expect the properties of a population to be manifest in a small sample. We are inclined to think sample data are representative of the population and do not understand how the variability in a small sample can be very unrepresentative of the population's true parameters. People who have lived a long time on the coast tend to think they have seen just about every kind of storm. So, when they are warned to evacuate, many think they can ride it out like they have the vast array of other storms they have seen in their lifetime. Although 70 years on the coast may be a long time in human terms, it is a trivially small sample in geologic time, and many people have lost their lives to the law of small numbers by overestimating their experience and underestimating the strength of storms.

Take another example exaggerated for effect. The United States is a country of over 300 million people. Imagine we take a random sample of 10 people and use it to profile the age, gender, and race attributes of the United States. If five of our people are, by chance, African-American, two are Asian, and three are white, we would have a very biased view of the population. We would overestimate the probability of some subpopulations and underestimate others like the Hispanic and white populations.

APOPHENIA

You are running late for work, because your alarm did not go off. You step in the dog's vomit in the hall on the way to the kitchen where you learn there is no coffee in the house. The disposal unit mangles a spoon and comes to a whining stop when you hit the switch. You hurry to the car without your keys and have to make a return trip to the house. Any one of these irritants alone would not be too unusual, but together they outline the universe's plot against you. That is apophenia, the perception of connections and meaning among unrelated events.

Our brains are pattern detecting machines. They uncover meaningful relationships among the constant barrage of sensory input we face. The gambler's fallacy is a misperception of probability, where we think a number is due because it has not come up recently. Conspiracy theories, like the belief the twin towers of 9/11 were destroyed by the government are confabulations based on misperceived patterns. Despite a lack of evidence of a causal connection, many parents do not vaccinate their children because they believe they cause autism.

Source: Adapted from Poulsen (2012).

Things that by chance show up in fewer than representative numbers in our small samples get underestimated. Likewise, things that show up more in the sample than the population are overestimated. The tendency to expect samples to be representative of populations can distort our view of reality.

14.7.3.4 Confusion of the Inverse

People tend to confuse conditional probabilities with their inverse. They tend, for example, to think the $P(\text{Test positive}|\text{Disease positive})$ is the same as $P(\text{Disease positive}|\text{Test positive})$. Even doctors have been known to fall prey to this error. A doctor may see a positive test as being representative of having the disease, and they may see having the disease as being representative of a positive test. This could simply be semantic confusion or it could be failure to apply Bayes’ Theorem. In either event it can lead people to misstate probability estimates.

Consider Table 14.2 for an example. The probability that a person is disease-positive is 1%. The test accurately predicts the disease when present (sensitivity) 80% of the time. It correctly predicts the absence of disease 90% of the time. Imagine a patient is given the test for the disease and it comes back positive. What is the probability that the person has the disease? In a study by Plous (1993), doctors said it was about 75%. In fact, the value we seek is $P(D+|T+)$ and that is $800/10700$ or 7.5%! The inverse, $P(T+|D+) = 800/1000 = 80\%$. Clearly, the doctors had inverted the conditional probability, another form of the representativeness bias that can seriously distort probability estimates.

14.7.3.5 Confounding Variables

When trying to predict one value based on other values known to be related, we rarely give sufficient consideration to confounding variables. Most people recognize a relationship between height and weight. There is a tendency to make simple translations from one variable to the next. For example, if a person weighs 10% more than average, there is a tendency to expect them to be 10% taller than average. This translation from weight to height simply does not bear up in reality. There are many other variables that can affect or confound the relationship between height and weight, rendering it far from the representative translation our minds tend to prefer. When we estimate uncertainties based on imperfect relationships, we can over- or underestimate them because we neglect to consider the effect of confounding variables.

TABLE 14.2
Contingency Table for Disease Condition
and Test Result

	Test+	Test–	Total
Disease+	800	200	1,000
Disease–	9,900	89,100	99,000
Total	10,700	89,300	100,000

There are, as you see, several forms of representativeness bias. They can be subtle and often difficult to counteract in a probability elicitation.

14.7.4 ANCHORING-AND-ADJUSTMENT

Many uncertainty judgments require us to produce numerical estimates of things that are not known or that do not have a correct answer. One strategy for doing this is to start with information one knows, an anchor, and then adjust up and down from it until an acceptable value is reached, using what Tversky and Kahneman (1974) called the anchoring-and-adjustment heuristic. The problems begin during decision making, when we humans tend to anchor, or overrely, on specific information or a specific value. When asked to estimate an uncertain quantity, we tend to come up with an initial estimate that is often our estimate of a most likely value like a mean, median, or mode. It comes, often unbidden, from wherever it comes and we do not always or often scrutinize it. Call this value an anchor. We then tend to make adjustments up or down to this value based on new circumstances. Once the anchor is set, there is usually a bias toward that value. We may identify the anchor, or an anchor may be provided for us. The major problem with this bias is that we rarely question the origin of the anchor and we rarely make adjustments to it sufficient to include extreme values.

Sometimes the anchor is provided to us. Imagine arriving at a restaurant where you are told the wait is 15 minutes. At 25 minutes you are feeling very frustrated and ready to leave. Now, imagine you were told the wait was 30 minutes. At 25 minutes your hope is rising. If both parties are seated at 25 minutes one is frustrated to be seated so late and the other is happy to be seated sooner than expected. When we are provided a piece of information we anchor on it and overrely on it.

The adjustment heuristic cuts down on mental processing time. We are better at relative thinking than absolute thinking. It avoids the need to reprocess information and recalculate values. The problem is that adjustments are anchor-centric, and we tend to stay too close to the anchor. A poorly chosen anchor can lead to poor adjustments. The anchors we come up with are often arrived at rather spontaneously, often with little analytical thought. The anchors we are provided are of unknown accuracy. Unless our anchors are challenged, we often do not understand the role they play in subsequent judgments.

Don't use the Internet to answer the following question; use your expertise. What is the driving distance from Sacramento, California, to Little Rock, Arkansas? I do not expect you to be able to guess such a quantity precisely, so give me the minimum mileage it could be and the maximum mileage it could be so that you are 90% sure you have estimated correctly. In other words, estimate a realistic interval for the distance, not one somewhere between zero and a million miles!

If you are like most people, when the original question was asked, a number popped into your mind. You somehow came up with a most likely or best-guess number. That is your anchor. When asked for a minimum and a maximum, most people tend to subtract a number from the anchor and then add roughly the same number to the anchor to get their interval. Did you? Did you make enough of an adjustment to capture the true distance?*

Even experts rarely do so.

* Google Maps reports the distance as 1,960 miles by car.

Assessments of probabilities as well as other quantities are subject to the anchoring-and-adjustment bias. Many elicitation questions come with anchors embedded in them. For example, we may ask the towboat captain the probability it takes more than two hours to get from point A on the waterway to point B. Two hours has now been established as an anchor. Alternatively, the question could be asked as, “State the time at which there is a 60% chance you could travel from point A to point B on the waterway.” The anchor is now 60%. These values could affect the response to all subsequent questions.

The anchoring-and-adjustment heuristic has important implications for the order and nature of questions posed in an elicitation. It can be reduced by avoiding anchors, that is, do not embed them in the questions. You may be able to help prevent experts from anchoring by exploring the upper and lower limits the quantity can take before examining central tendencies. Make sure people have time to think rationally about a quantity; pressure makes people default to anchors. More personally, observe yourself thinking, look for instances where you are adjusting a number instead of thinking critically. Identify the factors that could push you toward a larger value and think of their effects. Then do the same for a smaller value. Strive to replace your relative thinking with absolute thinking.

14.7.5 MOTIVATIONAL BIAS

Bias is hard to avoid because we are often completely oblivious to our own biases. In addition to the cognitive biases identified here, there is the possibility of motivational bias. People may want, consciously or otherwise, to influence a decision; they may perceive that they will be evaluated based on the outcome; they may suppress their uncertainty to appear more knowledgeable; or they may have a strong position on a question (Morgan and Henrion 1990). Some people may just be cockeyed optimists while others are perpetual pessimists. Any of these outlooks can bias an estimate.

People, including experts, sometimes find an incentive to offer information that does not reflect their expert knowledge. People who have figured out what kinds of answers are most likely to secure more desirable outcomes may be motivated to provide those answers regardless of their true beliefs. In some situations, the rewards and punishments associated with over- or underestimating quantities vary significantly. Underestimating a human health risk has a greater risk to the expert than overestimating that risk, for example. Criminal lawyers will rarely tell you things will be fine. They are inclined to emphasize the seriousness of the defendant’s situation. It makes higher fees easier to swallow. Estimates of uncertain quantities may be affected by implicit incentives as well as explicit ones.

Intentional motivational bias may be impossible to prevent. Unintentional motivational biases may be reduced if you can identify some of the biases of the individual or their organization. So, for example, if you have an expert from an environmental group known to oppose the activity that has given rise to your expert elicitation, it might be helpful to ask the expert to explore other perspectives. Supposing the navigation industry is known to support the activity, one might ask what the expert thinks they would say, then ask if there is a rational explanation for the differences. Adopting different perspectives can be an effective strategy for addressing many of these heuristics.

14.7.6 CONFIRMATION BIAS

Confirmation bias is a tendency to search for or interpret information in a way that confirms one's preconceptions. The problem is people, including experts, have been shown to actively seek out and assign more weight to evidence that confirms their hypothesis, and ignore or underweigh evidence that could disconfirm their hypothesis. Confirmation bias not only affects how people gather information, but also how they interpret and recall information. We need look no further than politics for a plethora of examples. If you like the incumbent president of your country, you likely get your news from sources that share your view and you see alternative sources as biased. If you dislike the incumbent you likely do the opposite. Furthermore, every action the incumbent takes is filtered through your like/dislike lens. We tend to seek information that supports our existing beliefs. This type of bias can prevent us from looking at a situation objectively. It can also influence the decisions we make and can lead to poor or faulty choices made when we fail to see the world as it truly is.

Warren Buffett said, "What the human being is best at doing is interpreting all new information so that their prior conclusions remain intact."

To neutralize confirmation bias we must look for ways to challenge what we think we see. It can be difficult to motivate people to do that. Seeking information from a range of sources that provide multiple perspectives is a good place to start. These data sources can be included in an elicitation read ahead or it can be made part of the discussions that precede the elicitation. A free and open discussion with the intention of revealing information that challenges your view on a subject can be helpful. Assigning the role of "devil's advocate" to a person not on the expert panel can be an effective way to introduce evidence that is otherwise overlooked. Tasking experts with examining evidence that conflicts with their beliefs may help.

14.7.7 FRAMING BIAS

One of the critical steps in an elicitation is to frame the questions; this is where things can often go wrong. The way a problem is framed or question is posed can profoundly influence the choices we make and the answers we give. In an elicitation, people tend to accept the frame they are given. It is rare that they would pause to reframe it in their own words.

Framing bias suggests that how something is presented, the "frame," influences the choices people make. This can interfere with the notion that rational choosers should always make the same decision when given the same data. Tversky and Kahneman (1982), in their explorations of framing theory, found otherwise. In their experiment, they gave some students a decision phrased in positive terms as a choice between a sure gain and an uncertain gamble. Most students exhibited risk aversion and chose the sure gain option. Other students were given the same choices phrased in negative

terms as a choice between a sure-loss option and the risky gamble. The majority exhibited risk seeking tendencies and chose the risky gamble. This showed the frame could affect the choice people made.

A “framing effect” occurs when factually equivalent descriptions of a decision scenario lead to systematically different decisions depending on how they are phrased. Advertisers and politicians have mastered the art of framing. Meat is always 80% lean and never 20% fat. Framing effects can also affect our memories and reinforce other heuristics. What politician uses cost, expense, pay, or tax when touting the merits of their latest initiative?

To counteract this bias, try posing problems in a neutral way that combines gains and losses or embraces different reference points. Choose a frame that captures all of what’s important. Encourage experts to make sure they are understanding the real problem. Help them look at the problem from other perspectives. For example, reverse the context. If you are creating the risk, how would you see things if you were bearing the risk? In some instances, it may help to choose a high-level perspective for framing. For example, looking only at project-by-project risk may result in a portfolio of overly conservative projects.

Clemen and Reilly (2001) offer a general suggestion for improving estimates based on knowledge of the many heuristics summarized here. Awareness of the heuristics can help people learn to become better assessors of probabilities. Knowing how not to think does not guarantee one will not think in these ways, but it does give the conscientious assessor a fighting chance. If assessors can recognize the effects as they occur, they may be able to avoid or countervail them.

O’Hagan et al.’s review of the literature finds that many of the biases mentioned here are ephemeral and can be eliminated entirely in some instances. The literature also suggests some people are more prone to these biases than others. More intelligent people are more likely to be able to reason through the biases and avoid them. The bottom line, however, remains the same. A careful elicitation protocol is the best way to address these problems.

14.8 CALIBRATION

Morgan and Henrion (1990) reported, “The most unequivocal results of experimental studies of probability encoding has been that assessors are poorly calibrated.” If we go to all the trouble of a formal subjective probability elicitation, it would be nice if we could have some confidence in its results. The tricky part is if we say there is a 0.9 chance an oil spill will be less than 1 million gallons and a 2-million-gallon spill occurs, does that mean we were wrong? The answer, of course, is no. Only statements of absolute certainty, that is, $p = 0$ or $p = 1$, can be proven right or wrong by subsequent observations.

That means the strength or weakness of our elicitation more or less rises and falls with our process and our experts. Experts who are overconfident overestimate the actual frequency of events in their subjective probabilities. They might estimate a spill size that occurs with a 0.4 probability as having a 0.7 probability. Underconfident experts do the opposite. They might estimate the probability of that spill as 0.3.

Overextremity is another common pattern of estimation by experts. This is neither over- nor underconfident; rather it is a mix of both. These folks tend to overestimate the likelihood of low-probability events and underestimate the likelihood of high-probability events.

If it is important enough, your experts can be calibrated so you and they can learn how well they tend to recognize and evaluate their uncertainty. One common way to calibrate an expert is to ask a series of questions with factual answers that are unlikely to be known by the expert. Ideally, these questions will be from the domain of knowledge most relevant to the elicitation.

There are three general styles of calibration. One relies on asking a large number of a variety of questions as well as the expert's confidence in the correctness of the answers. The questions might include such things as how many gallons in an acre-foot of water, what is the capital of Zambia, and what is the currency used in Thailand? Experts are asked to express the likelihood that their answer is correct. With enough such questions, one would expect a well-calibrated expert to get about 60% of the questions they said they were 60% confident in to be correct, 70% of the questions they are 70% confident about correct, and so on.

Binary calibrations are a second common technique. This consists of a series of true/false questions such as the state of Idaho borders Iowa, the Baltimore Colts won the 1973 Super Bowl, blue light has a shorter wavelength than green light, and so on. The expert answers each question and then identifies the confidence that the answer is correct as 50%, 60%, 70%, 80%, 90%, or 100%. You total all of their percentages and convert it to a decimal to identify the expected number of correct answers. Suppose there are 100 questions and the sum of all confidence ratings is 6240%. As a decimal that is 62.4, so that is the expected number of correct answers. An expert with fewer than 62 correct answers is overconfident. One with more than 62 correct answers is underconfident. The expert with close to 62 correct answers is well calibrated.

A third technique requires experts to estimate quantitative questions with 90% confidence intervals. They might be asked the distance from Kiev to Paris, the height of Mount Denali, the mean weight of an adult male boxer dog, and so on. A well-calibrated expert will get 90% of the answers within their interval estimates. Those with fewer than 90% correct are overconfident, and those with more than 90% are underconfident. Other more sophisticated techniques and scoring rules, like the Brier Score (Brier 1950), have also been used.

The calibration process, prior to an elicitation, is one of the most effective ways to make an expert aware of the overconfidence bias. Once aware, many educated experts are able to neutralize that bias.

14.9 MULTIPLE EXPERTS

Multiple experts will frequently be used when an elicitation is needed. Assuming the task is to elicit a probability distribution, the group can be used to create a single distribution (behavioral aggregation), or each individual expert may provide his or

her own distribution. In this latter case, it may be desirable or necessary to eventually combine them all into a single distribution (mathematical aggregation) sometimes called the composite expert or the synthetic decision maker.

The literature on strategies to combine experts' probabilistic judgments is extensive. Clemen and Winkler (1999, 2007) provide excellent overviews of this literature. Combining the judgments of different experts may be a sensible thing to do at times. However, the purpose of an expert elicitation is to quantitatively describe the uncertainty being characterized. If the experts' judgments about the relevant science are noticeably different, then it may be best not to combine the separate judgments. Instead it may be prudent to run separate analyses using the inputs provided by the individual experts to explore how the different opinions affect the outcomes of interest. It is wise to consider the spread of expert assessments as valuable information that should always be part of the reporting. There is no reason to combine expert assessments if you do not need to (Cooke and Probst 2006).

Faced with uncertainty, decision makers invariably prefer agreement or an unambiguous consensus from experts. It is not reasonable to expect total consensus when dealing with difficult uncertainties. When scientists disagree, any attempt to impose agreement can cause people to confuse consensus with certainty. The goal should be to quantify uncertainty, not to disguise it with consensus (Aspinall 2010). Thus, multiple judgments are to be preferred to a single judgment whenever practicable.

One common model for elicitation is to have individual experts develop their own distributions and then to share these results, anonymously, with the group of experts. In a plenary session, they consider their results in discussion and then allow the experts to modify their elicitations based on what they learn from the discussion that ensues. This method still produces as many distributions as there are experts. Using each of the individual distributions as a sort of sensitivity analysis, to establish whether or not the differences among the experts make much of a difference in model outputs and decisions, is a solid strategy. This method has the advantage of providing what amounts to high and low estimates of the outputs of interest, which may help bound the uncertainty about these values.

There are a number of techniques available for aggregating individual distributions when a single estimate is required or desired. Bayesian methods (Clemen and Winkler 1999), opinion pooling that assigns weights to the distributions, and Cooke's classical method (Cooke 1991) are all in common usage. O'Hagan et al. (2006) suggest that the average of the distributions provides a simple, general, and robust method for aggregating expert knowledge. Averages may be computed across probabilities, that is, averaging all x values for each selected probability, or across x values, that is, averaging all probabilities for a given x value. They report that the former is most common and less preferred by those with an interest in characterizing the uncertainty. Averaging across p values rather than x values has the disadvantage of masking the uncertainty that exists when there is a wide range of opinions.

Structured expert judgment, also known as Cooke's classic method, is a highly regarded method for developing a rational consensus among expert opinions. This process includes a calibration of the expert's proficiency using a set of domain relevant seed questions. The elicitation is then conducted using one of the standard protocols. The expert's performance is, measured based on statistical accuracy and informativeness (the degree to which the expert concentrates his or her probability mass on a small region of the number line). Weights are assigned based on each expert's performance, and a composite is produced.

Source: Cooke and Probst (2006).

Group elicitation seems to offer substantial and relatively untapped potential for modelers.

O'Hagan et al. argue that it offers better synthesis and analysis of knowledge through group interaction. The facilitator's role grows ever more important when group dynamics play such a significant role. The process should encourage sharing knowledge as opposed to opinions. It should also recognize expertise and differences in expertise as well as make effective use of feedback from the group. At the same time, the process must avoid domination by individuals or by shared knowledge. Groups can have an even stronger tendency toward overconfidence, especially if group-think sets in. The challenge of avoiding group reliance on heuristics remains with a group process. Of greatest concern is the tendency for group consensus to mask the true extent of the uncertainty.

14.10 SUMMARY AND LOOK FORWARD

There will be times when you simply do not have all the data you wished you had for your risk assessment. Some of those times you will not have the luxury of being able to commission and wait for research to fill those voids. Subjective probabilities can be useful in filling in data gaps and voids.

Not every subjective probability estimate warrants a formal elicitation. Nonetheless, assessors are well advised to follow good elicitation techniques whenever they estimate subjective probabilities. Spoken language has proven to be notoriously imprecise when trying to express our beliefs about things that are uncertain. Hence, we have come to rely on numerical estimates of probabilistic information and probabilistic estimates of numerical information. The most consistent result in all the related literature is that we are notoriously bad at estimating probabilistic information. There are several well-known heuristics we have come to rely on that short-circuit any analysis of uncertain data. Consequently, it is important to devise and use elicitation techniques that can limit the damage done by these heuristics.

Now that we have a pretty good idea how probability distributions are chosen and elicited, we turn in the next chapter to the Monte Carlo process to see how this technique is used. Probability distributions are used more often in simulations than in analytical

calculations in risk assessment, and the Monte Carlo process is an extremely powerful and useful technique for propagating the uncertainty in our model inputs through a model. [Chapter 15](#) takes a peek behind the curtain of the Monte Carlo process to see how it works so you can better understand how your risk assessment models work.

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15 Monte Carlo Process

15.1 INTRODUCTION

We have considered the art of modeling, a method for choosing a probability distribution, and a method for eliciting subjective probability distributions. What we need now is a way to propagate the information in our input distributions to characterize the range of potential results for our model outputs. Interval methods and fuzzy methods are quantitative techniques that can be used, but they are not probabilistic. Methods that are quantitative and probabilistic can be divided into analytical and numerical methods.

Analytical methods are used when we are solving explicit equations. There are a good number of risk problems that can be solved to yield exact solutions. If the probability of an electrical component failing is 1% and we have 1,000 components, we can calculate the expected value of failed components ($0.01 \times 1,000$). We can also use the binomial distribution to calculate the probability of any number of failures from 0 to 1,000. Unfortunately, few risk problems are simple enough to solve for specific solutions, in part because of the ubiquitous nature of uncertainty. On the other hand, many risk problems are simply too difficult or impossible to solve through analytical methods.

ANALYTICAL METHODS AND NORMAL DISTRIBUTIONS

Normal distributions lend themselves handily to exact analytical solutions. The sum of normal distributions is also a normal distribution. The mean of the sum of normally distributed inputs is the sum of the means of each input distribution. The variance of that sum is the sum of the variance of the inputs. Such simple relationships, unfortunately, do not hold for nonnormal distributions of inputs. This limits our ability to use analytical methods for many risk problems.

Numerical methods provide a versatile alternative solution method with broad applicability and flexibility for characterizing the effects of natural variability and knowledge uncertainty. The Monte Carlo process is the most common numerical method for propagating distributions through a model, and it is the subject of this chapter. It is essentially a sampling process. Random input values are sampled from input distributions and are used in models to calculate output values. A Monte Carlo simulation produces a sampled distribution of output values.

15.2 BACKGROUND

In the last part of the nineteenth century, several people used simulation to approximate the value of pi. This was done by randomly dropping needles on a board

with parallel lines^{*}. In the early twentieth century, British statisticians advanced some unsophisticated Monte Carlo work. W. S. Gosset, a/k/a Student, used experimental sampling for several applications, including his now famous t-distribution (Pillana 2010). The theoretical basis for the Monte Carlo method was understood in the nineteenth century, long before the ability to perform the numerical calculations was practical. Modern Monte Carlo methods can be traced to work on the atomic bomb during World War II. Kochanski (2005) describes Manhattan Project scientists trying to calculate the probability that a neutron from one splitting uranium atom would cause another atom to split. The equations had to mirror the complicated geometry of the actual bomb, and the answer had to be right. If the first test failed, it would take months to acquire enough uranium for another attempt.

The scientists solved the problem starting in about 1944 by using many mechanical calculators and the Monte Carlo process to follow the trajectories of individual neutrons. At each step, they calculated the probabilities that a neutron either was absorbed, escaped from the bomb, or started another fission reaction. Using random numbers and appropriate probabilities, they observed simulated neutrons stopping their fission reactions or starting new fission chains. The great insight here was that simulated trajectories would have identical statistical properties to the real neutron trajectories, and reliable answers could be had for important questions about the bomb. The code name for the method, Monte Carlo, was taken from the city in Monaco, where roulette wheels routinely generate random numbers.

15.3 A TWO-STEP PROCESS

The Monte Carlo process begins by replacing parameters in a model with distributions that represent natural variability or knowledge uncertainty in the model inputs. The Monte Carlo process is, in essence, a sampling method. Given a probability distribution, the Monte Carlo process randomly selects a value from that distribution. In a model with many probability distributions, a random value is selected from each distribution in the model. The programmed calculations are then executed using the sampled values, and outputs are generated. These outputs can be saved.

SOME TERMINOLOGY

Iteration: One recalculation of the model during a simulation. Uncertain variables are sampled once during each iteration according to their probability distributions. The sampled values are used to complete the model's calculations.

Simulation: A collection of iterations, that is, a technique for calculating a model output value many times with different input values. The purpose of a simulation is to get a complete range of all possible scenarios and their resulting outputs.

^{*} Pi is estimated by dividing $(2 \times \text{needle length} \times \# \text{ needles tossed})$ by $(\text{the distance between lines} \times \# \text{ needles that cross a line})$.

For the next iteration of the model, a new set of random values is selected from the input distributions, and the model's calculations are executed again until a sufficient number of output values have been obtained.

The Monte Carlo process, itself, consists of two steps. The first step is to generate a simple random number. The second step is to transform it into a useful value using a specific probability distribution.

15.3.1 RANDOM NUMBER GENERATION

To generate a random value from a probability distribution, the Monte Carlo process begins with a simple random number between 0 and 1. Imagine a complex spreadsheet model with hundreds of probability distribution inputs in it. Now imagine that we might want to run 10^5 or more iterations of the model. Each input for each iteration requires its own unique simple random number. The Monte Carlo process begins with a method to generate this very long list of random numbers. A 100,000-iteration simulation with 200 probability distributions in its inputs would need 20 million random numbers, for example.

There has been much discussion about the ability of various methods to generate such a set of truly random numbers. What is needed is a series of random numbers that are statistically independent, that are not autocorrelated, and that show no cycles or periodicity in the numbers generated. The numbers so generated are often called pseudo-random numbers because the same sequence of numbers can be replicated by using the same seed and the same calculation method. A good pseudo-random number generator should be able to produce many millions or billions of numbers. We will simply call these values random numbers.

There are many algorithms available for generating simple random numbers. The mid-square method, attributed to John von Neumann, who worked on the Manhattan Project, is one of the first methods used. It is no longer in use because of problems that will soon become obvious. Nonetheless, it is handy to use for an example because it is easy to follow. Just understand that much more sophisticated and efficient algorithms are used now.

Let us suppose we have a risk assessment model and one of the inputs is a random number uniformly distributed between the values 10 and 50. We want to see how the Monte Carlo process generates a number in this range.

The mid-square method needs a seed value to begin to generate the sequence of random numbers. This seed can be any number at all. Let us use a seed = 2,123. The method proceeds simply by squaring this seed:

$$2,123^2 = 4,507,129$$

Because we started with a four-digit number, we take the middle four digits of this value. If there is an uneven number of digits, we simply need to decide beforehand how to identify the middle four digits. In this instance, if an odd number of digits occurs we will have one more digit in front than behind our number. Accordingly, we obtain 0712 as the middle of the square. Because we began with four digits, we divide this number by 10^4 and obtain a random number between 0 and 1, namely, 0.0712.

Of course, this value does not meet the needs of our input distribution, so we will examine how this value is transformed into a value that is useful to us in the next section. What we need now is our next random number. The mid-square value becomes the seed for the subsequent value.

$$712^2 = 506,944; r_2 = 0.0694$$
$$694^2 = 481,636; r_3 = 0.8163$$

And so, on it goes.

The problem with this technique is that some seeds generate very short sequences of numbers before the pattern repeats itself. Other sequences end abruptly. Imagine we chose a seed of 1,000. Follow the steps above and see how many random numbers it generates. This is one reason that this method is no longer used.

Now that we have a sequence of numbers 0.0712, 0.0694, 0.8163, and so on, we need a method to transform them into numbers we can use in our model.

The details of the random number generator are usually handled by the software you use. Palisade’s @RISK software offers a number of random number generators, as seen in Figure 15.1, but few users of the software will have any reason to use any but the default Mersenne Twister. This generator was developed in 1997 to correct flaws found in older algorithms. It provides fast generation of very high-quality pseudo-random numbers.

Random number generators require a seed to initiate them. This seed is often chosen at random from the computer’s internal clock. However, it is sometimes useful to be able to duplicate the sequence of random numbers so that the same values are generated for model inputs in subsequent model runs. For example, it is common practice to run the same model several times to investigate the efficacy of different risk management options. When this is done, we’d like to ensure that the

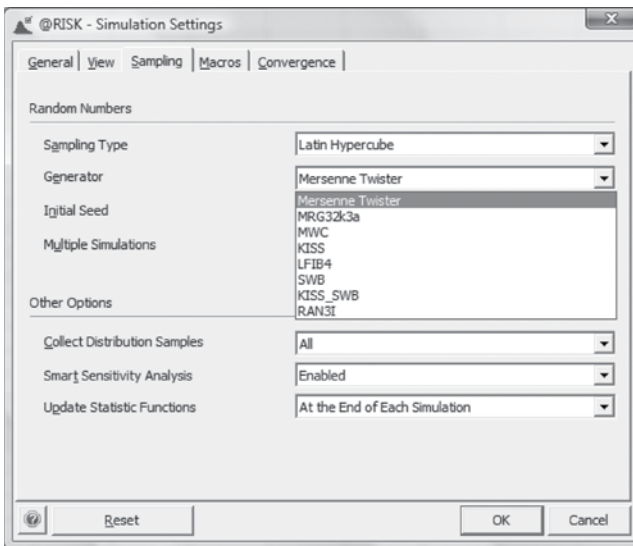


FIGURE 15.1 Random number generators available with Palisade’s @RISK software.

only differences in the model runs are those that can be attributed directly to the risk management option. When this is desired, a fixed seed should be used. The @RISK software described in Appendix A, provides this option.

15.3.2 TRANSFORMATION

Imagine that spreadsheet model with hundreds of inputs once more. Once a random number generator has produced a sequence of numbers long enough to meet the needs of the simulation, a different random number from that list of random numbers is assigned to each cell for each iteration. A random sample of one value is generated from each input distribution based on the simple random number assigned to the cell for that iteration and the mathematics of the distribution chosen. That sampled value is entered into the risk assessment model to calculate one estimate of the model output(s). In most cases the simple random number, like the value 0.0712 previously mentioned, will need to be transformed to create a number that is actually useful to the assessment model. In this case we want a number uniformly distributed between 10 and 50, and 0.0712 does not meet this criterion.

The Monte Carlo process can use several methods for transforming a simple random number to a random value from the probability distribution of each model input. The easiest method is to use the cumulative distribution function (CDF) method. The random number 0.0712 is the 7.12 percentile of the uniform distribution, so we only need to calculate the 7.12 percentile for the input distribution and use it.

The function of random variables method is another way to generate a random value. Assume a uniform distribution, $U(a,b)$, where the minimum $a = 10$ and the maximum $b = 50$. To obtain a value, x , from this distribution we use the function:

$$x_i = a + (b - a)r_i$$

where r_i is a simple random number. In this case, the equation becomes $x = 10 + 40r_i$.

Substituting the r_i assigned to that particular cell, we would see the following values sampled from $U(10,50)$.

$$\begin{aligned} x &= 10 + (50 - 10).0712 = 12.9 \\ x &= 10 + (50 - 10).0694 = 12.8 \\ x &= 10 + (50 - 10).8163 = 42.7, \text{ etc.} \end{aligned}$$

Similar functional transformations are done for other distributions. The math simply gets more difficult for more complex distributions.

If you are working with a spreadsheet risk assessment model with several probability distribution inputs and hit the recalculate key, you will see the numerical values in these input cells changing. This two-step process is being executed for each cell with a distribution in it. Each time you recalculate the values, a new and unique simple random number is assigned to each cell and then transformed into a value that is consistent with the probability distribution in that cell. Each random number is used in only one transformation in one cell. This is why you need a good random number generator. Fortunately, the commercially available Monte Carlo process software takes care of these steps.

15.4 HOW MANY ITERATIONS?

How many times do you have to run your model? How many iterations do you need? You have two options for running a simulation. You can predetermine the number of iterations you want, or you can predetermine a level of precision for selected outputs, like the mean or standard deviation of the distribution for an output. Iterations continue until the simulation results achieve convergence with the desired precision.

Most new users of the Monte Carlo process are likely to use a predetermined sample size, that is, a number of iterations. But how large should the sample size be? The answer depends on the nature of the desired output information and the desired numerical precision for the model output.

As a rule of thumb, based on experience and absent more rigorous proof, I have used the following order-of-magnitude guidelines.

- 10^2 iterations are sufficient for means to stabilize
- 10^3 iterations enable you to estimate outcome probabilities
- 10^4 iterations are enough to define the tails of your output distribution
- 10^5 iterations or more if extreme events are important

If you are only interested in expected values in a relatively simple linear model, these often converge quickly with only a few hundred iterations. If you want to be able to have a reasonably good definition of the CDF for the output, so that you can estimate a range of outcome probabilities, you need several thousand iterations. When the shape and thickness of the tails of your distribution are important, that is, when you care about the less frequent events, you may need tens of thousands of iterations. If extreme events are your primary interest, it could take in excess of 100,000 iterations.

Given the power and speed of computers and the available software, it is no longer unusual to run large simulations. However, some models are large and complex, and it may not be possible to run a large number of iterations. In these latter cases, it may be more desirable to establish a desired level of precision in your outputs.

During the first several iterations, output statistics, like the mean or standard deviation, can jump about and change dramatically. As the number of iterations increases, these values tend to stabilize. After a while, an unusually high or low value has a diminishing impact on the sample statistics. Once these statistics have stabilized, the time spent running additional iterations may yield little information of added value, especially when you are most interested in those very statistics.

To use the convergence option with @RISK you can set the convergence tolerance. This allows you to specify how close you want to come to the distribution's true parameter value. [Figure 15.2](#) shows a 3% convergence tolerance for the mean and standard deviation. This means that once the output distribution yields means and standard deviations within 3% of their true value, it can stop. If you are more interested in tail values, you would choose a percentile value in those tails as the statistic to monitor. The confidence level specifies that you want your estimate of the mean of each output simulated within the 3% tolerance to be accurate 95% of the time. As the figure shows, you can monitor all outputs or you can choose to designate specific ones.

There is an important caveat to consider. It may not make sense to run a large number of iterations to obtain a highly precise numerical estimate of a model output

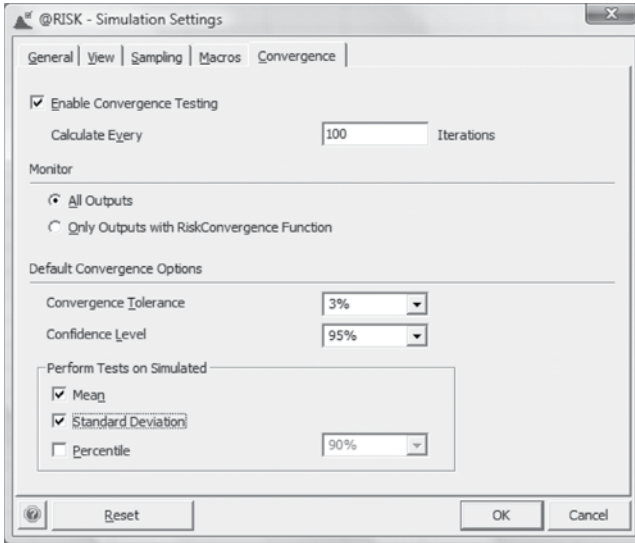


FIGURE 15.2 Using convergence tolerance to control the number of iterations.

if your assessment is based on sparse data. If you have data quality limitations for critical model inputs or if your model depends on a large number of assumptions, you should not spend too much time and effort trying to achieve a high degree of precision for the 99.99 percentile of a model output, for example. If your model input distributions are highly uncertain, more iterations are not going to improve the precision of your output estimates.

15.5 SAMPLING METHOD

Most Monte Carlo software chooses your number of iterations in one of two ways: Monte Carlo sampling or Latin hypercube sampling. Latin hypercube sampling (LHS) uses stratified sampling without replacement (Iman et al. 1980). To see how it works, suppose we want to sample five values from a normal distribution with a mean of 100 and a standard deviation of 10. With LHS, the probability distribution is split into n intervals of equal probability, where n is the number of desired samples. In this example, the CDF is split into five equiprobable intervals, as shown on the vertical axis of Figure 15.3. The projection of these intervals on the horizontal axis will vary in size as shown.

During the simulation, each of the n intervals is sampled once. Within each equal probability interval, the value chosen can be based on the median value (median Latin hypercube sampling) or it can be chosen at random (Latin hypercube sampling). LHS has the advantage of generating a sample that more precisely reflects the shape of a sampled distribution than simple random (Monte Carlo) sampling does. The advantage of LHS is that the mean of a set of simulation results approaches the “true” value more quickly.

Monte Carlo sampling does not stratify the distribution into n intervals of equal probability. Figure 15.4 shows a hypothetical result that by chance samples all five points between the values 85 and 100. When n is large there is no practical difference between

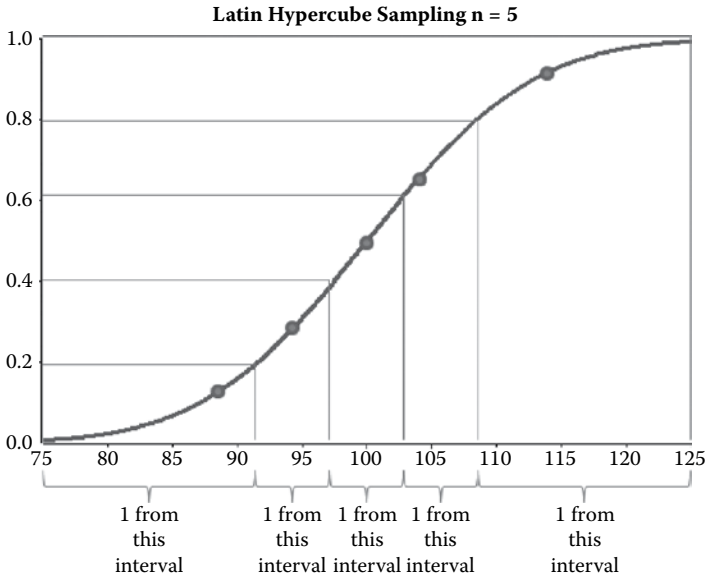


FIGURE 15.3 Latin hypercube sampling for N = 5.

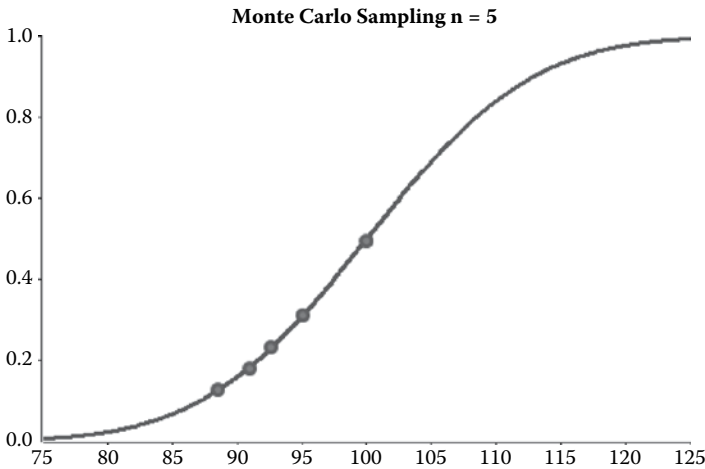


FIGURE 15.4 Monte Carlo sampling for N = 5.

the two sampling methods. In general, LHS is considered more efficient in the sense that it can reveal more information about the distribution it samples from for most sample sizes.

15.6 AN ILLUSTRATION

Figure 15.5 presents a simple picture of a Monte Carlo simulation model. It shows two random variables being multiplied together. One is the number of coffee drinkers

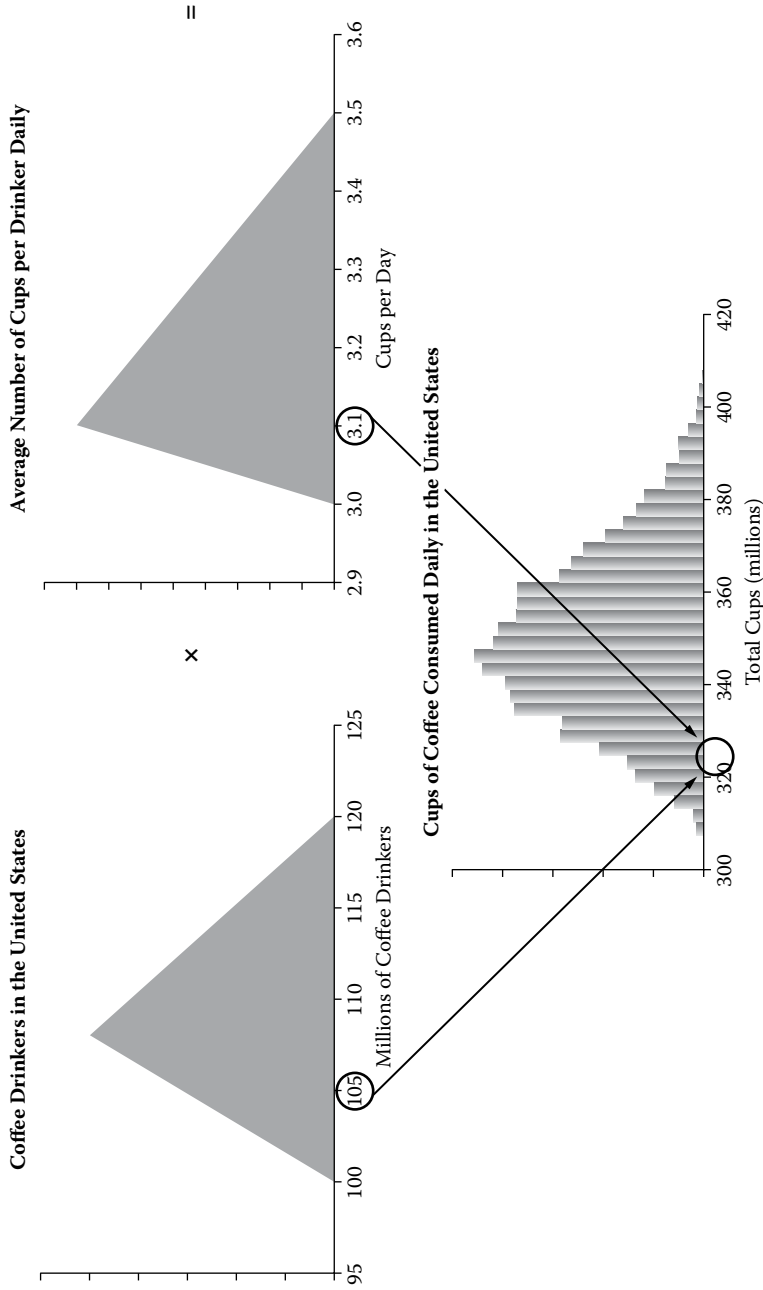


FIGURE 15.5 A simple illustration of the Monte Carlo process is a two-variable model.

in the United States. The other is the average number of cups consumed by coffee drinkers on a daily basis. Both numbers are uncertain and are represented by triangular distributions. The data used are hypothetical.

It is not always necessary to specify a distribution for all or most variables in a risk assessment model. Doing so may be useful for exploring the full range of natural variability and knowledge uncertainty, but it is not always cost-effective or necessary to do so. It is often advisable to restrict the use of probability distributions to significant variables and parameters (EPA 1997).

A value from each distribution is randomly chosen via the two-step process described previously and then the model's calculations are executed. In the example, the number of drinkers (Triangle(100,108,120)) sampled is 105 million and the average number of cups of coffee (Triangle(3, 3.1, 3.5)) is 3.1 cups per day. The two values are multiplied together to yield 325.5 million total cups per day. This is a single estimate of the output value and it constitutes one iteration. This process was repeated 5,000 times and the results are shown in the output distribution. Monte Carlo simulations are a preferred method for probabilistic risk assessment.

15.7 SUMMARY AND LOOK FORWARD

The Monte Carlo process samples individual values from a probability distribution so that they can be used to characterize the range of potential outputs in uncertain situations. It is a two-step process that requires the generation of a simple random number and a means to convert that number to a useful value from the chosen distribution. It is a calculation-intensive numerical process that has become immensely popular and easy to use with advances in personal computers and spreadsheet software.

The Monte Carlo process can be added to a wide variety of model structures. When probabilistic methods like that are added to scenario-structuring tools, like event trees, for instance, they create a powerful bundle of tools called probabilistic scenario analysis (PSA). PSAs are the subject of the next chapter. It begins by considering several different kinds of scenarios and different ways of analyzing and comparing them. It then presents an introduction to tree models and presents an example of a PSA using an event-tree structure.

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16 Probabilistic Scenario Analysis

16.1 INTRODUCTION

Probabilistic scenario analysis (PSA) refers to a bundle of tools and techniques that make use of scenarios, probabilities, and probabilistic analysis. Most quantitative risk assessments are likely to be some form of probabilistic scenario analysis. Deterministic quantitative risk assessments would be the exception.

Many decisions are hard because they are complex. They involve inherent uncertainty and have conflicting objectives. The various stakeholders with an interest in the decision are likely to hold many different perspectives. Scenarios can address these aspects of a decision problem.

A scenario is literally an outline or synopsis of a play. Scenarios can be used to describe the present or the past. They are most often used to describe possible futures.

Risk scenarios are readily used to provide the answers to our four informal risk assessment questions:

1. What can go wrong?
2. How can it happen?
3. What are the consequences?
4. How likely is it?

Think of scenarios as the stories we tell about risks. They are a series of events that could happen. In risk assessment, a scenario is defined by a set of assumptions about model input values and how those variables are related to one another. Thus, scenarios could be different model formulations that tell substantially different stories. Or they could simply involve different values for uncertain inputs that lead to different outcomes in a model with an unvarying structure.

We begin the chapter by considering different types of scenarios and proceed to considering three types of scenario analysis: monolithic, deterministic, and probabilistic. Scenarios are often developed so that they can be compared to help risk managers choose the most desired future. Three common methods of comparing scenarios are reviewed: before and after, without and with, and gap analysis.

Tree models are one of the easier and more useful techniques for constructing orderly scenarios. This chapter focuses on event trees as one of the most useful and accessible tools for structuring risk scenarios. Once the basics of event trees are presented, the probabilistic methods of preceding chapters are added to them in an example that demonstrates a very powerful and useful set of risk assessment tools.

16.2 COMMON SCENARIOS

If a scenario is an outline for a play, it is convenient, then, to think in terms of well-established plot lines to begin to consider the different types of scenarios that are used most commonly. Three types of scenarios come up over and over again in risk assessment. They are as-planned, failure, and improvement scenarios.

The first story we might want to tell about our system is the one where everything works exactly as planned. This “as-planned scenario” describes the system in which we are interested operating free of any failures. It is a surprise-free scenario. In the example of an engineering system, all the loads on the structure are as anticipated, and every feature functions as it was designed to function. In a food safety system, every feature of the system functions as planned and consumers experience no exposure to a hazard.

An as-planned scenario is not necessarily a risk-free scenario, as many systems are designed with some degree of risk built into them. Airplane design trades off wing strength and body weight, for example. Levees are designed to be overtopped in a specific location. The principle characteristic of an as-planned scenario is to show every risk management feature of the system functioning just as it was designed to do.

To illustrate the idea, let us introduce the example we will use later in the chapter. The system shown in Figure 16.1 is designed to prevent imported contaminated carcasses from entering the food supply. It begins with the unknown condition of the carcass’s contamination. All the as-planned outcomes are shown in the figure.

The second plotline for a class of scenarios is the failure scenario. The model in Figure 16.1 shows one failure scenario. Failure scenarios tell the story of how various elements of the system might interact under certain conditions that result in undesirable outcomes. Thus, failure scenarios intentionally challenge the notion that a system will function as planned. Any aspect of an as-planned scenario may be challenged. Failure scenarios may illustrate one or multiple modes of system failure. These failures are usually sources of risk.

The best-known failure scenario may be the worst-case scenario. The worst-case scenario is usually constructed using the analyst’s judgment to choose that set of circumstances or, once the model is specified, the set of input values that will yield the worst possible outcome from a model. For a building design, this could be the highest possible loads during a category 5 hurricane that coincides with a magnitude

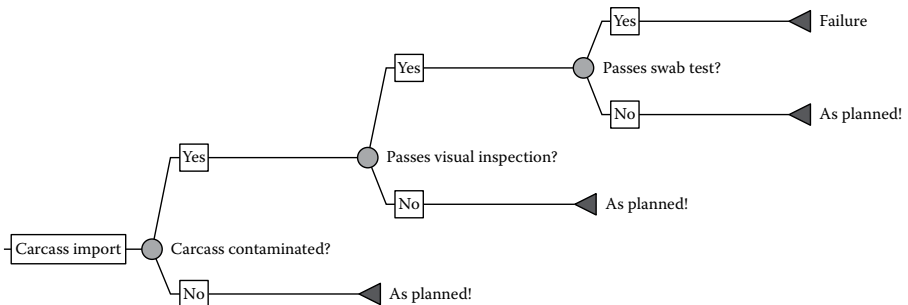


FIGURE 16.1 As-planned scenarios for carcass import model.

8 earthquake. The basic appeal of the worst-case scenario is that if it occurs and the outcomes are still acceptable, then we think we have little to worry about. The worst-case scenario is a deliberate exaggeration of the risk in a given situation. If the system continues to function at an acceptable level during the worst-case scenario, decision makers have often assumed that there is no need to further assess the risk. This is often flawed thinking, because failure in less than the worst-case scenario is possible, so we will return to the worst-case scenario again in the next chapter.

The third type of scenario plotline is the improvement scenario. Risk analysis often results in new risk management options (RMOs) that have a direct effect on risks. Improvement scenarios often describe how the RMOs affect the failure scenario. They are used to evaluate risk management options. The “best” improvement scenario often points to the RMO that will be implemented. Let us reconsider our simple model with some improvement scenarios as seen in Figure 16.2.

Kill steps have been added to the process in the form of steam pasteurization and irradiation. Considering each kill step separately would give rise to two more improvement scenarios. In some improvement scenarios, the structure of the scenarios will change; in other cases only the input values will differ. For example, the original model of Figure 16.1 could be used to represent an improved scenario if live animals were vaccinated, thereby reducing the number of contaminated carcasses, or if a better visual inspection method or swab test was introduced. In any of these cases the structure of the model would remain as shown in the figure. The input values (not shown in the figure) along the branches would change to reflect the improvements.

In addition to the broad categories of scenario plotlines, there are some other commonly used scenarios. The best known of these is the existing condition. Others include the worst case, best case, most likely, do nothing, future without additional risk management, locally preferred, industry-preferred scenarios, and so on. These scenarios are often deterministic rather than probabilistic, which brings us to our next topic.

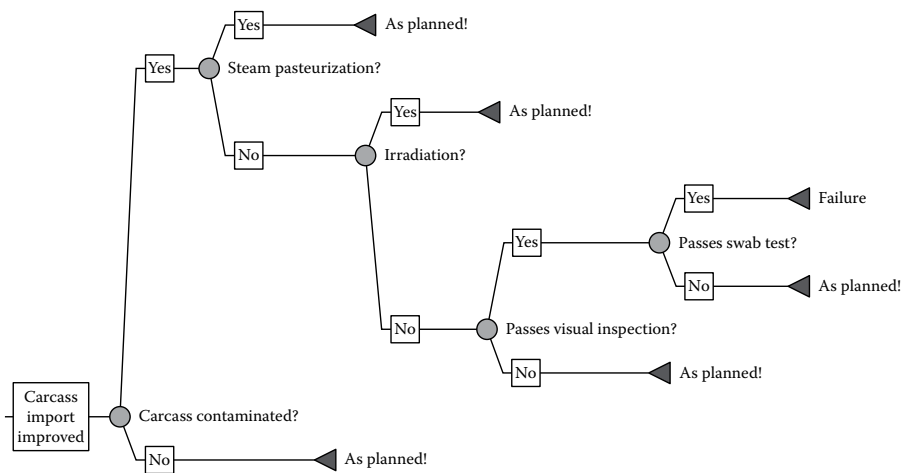


FIGURE 16.2 Improvement scenarios in carcass import model.

16.3 TYPES OF SCENARIO ANALYSIS

There are three kinds of scenario analysis: monolithic, deterministic, and probabilistic. The first requires the invention of language. I doubt you will find monolithic scenario analysis anywhere in the literature. People have long used scenarios for decision making. Before the rise of risk analysis, it was common practice to develop and present a scenario as if it were a *fait accompli*, when in fact it was simply one of many possible story lines about a problem or opportunity. So, I will use the notion of a single unchallenged scenario, or a monolithic scenario, to represent decision making where uncertainty is not explicitly recognized. Monolithic scenarios are often used by the political system to describe the results of a proposed program or change. If elected I will do the following ... this tax reform will ... this new legislation will ... and there follows a monolithic scenario that carefully ignores the uncertainty inherent in the proposed changes. Monolithic scenario analysis (MSA) uses only one scenario for decision making.

When we move from a single scenario to a few selected scenarios we are engaging in deterministic scenario analysis (DSA). DSA defines and examines a limited number of specific scenarios. This can be a useful way to organize and simplify an avalanche of data into a small number of possible future states of the system being modeled. The scenarios so identified are usually chosen for specific reasons. They may be exploratory, such as with the worst-case, most likely, and best-case scenarios; or they could be chosen for strategic or tactical reasons. For example, we might look at the effects of three different flu vaccines on morbidity rates.

There are some serious limitations to deterministic scenario analysis. First, only a limited number of scenarios can be considered. Second, the likelihoods of these scenarios often cannot be estimated with much confidence. Third, this approach is inadequate for describing the full range of potential outcomes.

Probabilistic scenario analysis, on the other hand, overcomes these limitations by combining probabilistic methods, for example the Monte Carlo process, with a scenario generation method like event tree models to produce a PSA. A PSA may produce measures of probability, measures of consequence, or measures of risk, which combine the probability and consequence measures into a single value. Whatever its outputs, it is distinguished by its ability to produce a wide array of potential outputs.

16.4 SCENARIO COMPARISONS

The effectiveness of an RMO is often judged on the basis of changes in decision criteria observed through scenario comparisons. Take the example in [Table 16.1](#). If no additional risk management is undertaken (most likely future), there will be 5,000 illnesses but there will be no costs associated with reducing them, as no effort will be made to do so.

If risk management option A is implemented, illnesses will be reduced to 2,500 at a cost of \$1 million. If we compare these two scenarios we get the changes noted in the table. Illnesses are cut in half at an additional cost of \$1 million. Option B eliminates all the illnesses but at a much greater cost. Risk managers would be expected to choose the best option based on performance differences revealed by scenario comparisons.

TABLE 16.1
Simple Scenario Comparisons

	Illnesses	Cost
Most likely future	5,000	\$0
Future under RMO A	2,500	\$1,000,000
Change due to RMO A	-2,500	-\$1,000,000
Future under RMO B	0	\$1,000,000,000
Change due to RMO B	-5,000	-\$1,000,000,000

If scenario comparisons are to be useful for decision makers, they must identify features in scenarios that make a difference, that is, show things that are important and that matter to decision makers. That means that risk assessors, with input and feedback from risk managers, need to carefully identify decision criteria and include them in their scenario analyses. These are the measurable criteria upon which decisions will be based. In best practice, these metrics will reflect some or all of the risk management objectives. Recall that when these objectives are met, problems are solved and opportunities are realized. Scenario comparisons must begin by comparing things that matter, and that will usually include some comparison of risk estimates.

The complexity of some problems combined with lack of data and other uncertainties make risk assessment a rigorous and often difficult undertaking in many situations. Assessors may be happy if they can provide an estimate of the existing risk. Projecting risks over time is not yet common practice in many communities of practice. Nonetheless, the best comparisons of scenarios would consider whether a risk was static, growing worse, or self-attenuating over time.

There are three basic comparison methods, first introduced in [Chapter 3](#). We will revisit them here in a bit more detail. For simplicity, the discussion will focus on a single decision metric. In actual practice, a scenario comparison would likely involve multiple decision criteria, each of which would be compared.

Current practice often relies on a static estimate of the existing risk. This estimate often becomes the baseline scenario against which all comparisons are made. The most common scenario comparison is a before-and-after comparison, as illustrated in [Figure 16.3](#). This takes an estimate of the risk before any additional risk management measures are implemented (the baseline scenario) and compares it to the risk estimate that would occur under the improved conditions with the risk management option in place and functioning (the improvement scenario). The difference between these two risk estimates is calculated in a before-and-after comparison. That value is most often a static estimate of the difference in the risk. It usually ignores any trends in the risk itself as well as any phase-in of the risk management option’s effectiveness over time.

The use of this comparison method is widespread. Its greatest weakness is that it does not take into account changes in the risk over time. In dynamic systems, risks may increase or decrease with environmental or other factors. RMO effectiveness may also vary depending on the phase-in period for the RMO and associated compliance rates. In the case of mechanical or other physical risk management measures, their effectiveness may change over time with wear and tear.

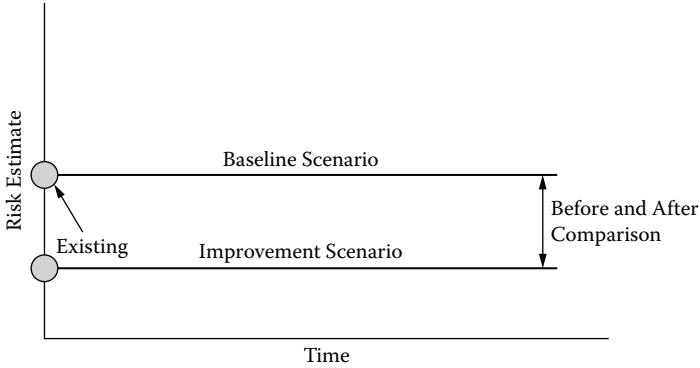


FIGURE 16.3 Conceptual before-and-after scenarios comparison.

To account for these kinds of changes, a without-and-with comparison is preferred (Figure 16.4). This example shows that if no additional action is taken to manage the risk, the risk estimate increases steadily over time. This is called the “without condition” and it represents the most likely future condition without any additional risk management options implemented. For the convenience of understanding the without-and-with comparison, let us assume that this future can be represented by a single path. The concepts also hold true for uncertain futures, but the explanation just grows more complex without adding much understanding; so, let us just follow one path.

Figure 16.4 shows a risk that is growing worse, although some risks may actually be self-attenuating and could have a negative slope into the future. Likewise, the path of the risk estimate with RMO A in place, the “with condition,” is stylistic as well. It shows a future in which it takes some time to realize maximum risk reductions. This could be because measures that comprise the RMO are phased in over time, or it could reflect the fact that those required to implement the RMO comply at different rates.

Under the without-and-with condition scenarios comparison, a proper analysis would have to estimate the changes in risk (and any other dynamic decision criteria) over time.

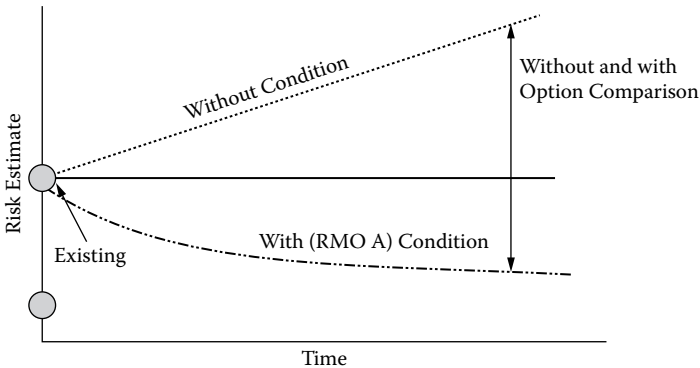


FIGURE 16.4 Conceptual without-and-with condition scenarios comparison.

The original baseline estimate is still shown (the unlabeled line) to provide a reference point. If, for the convenience of this argument, we consider the baseline as the before condition and the lowest position of the with condition as the after condition, it is easy to see that the previously presented static view of the RMO’s performance provides a dramatically different picture than the without-and-with condition comparison.

In general, the without-and-with condition comparison is more accurate and preferred. In practice it is often too difficult to do well, and a before-and-after estimate is used in its place. However, it is important to note that some risks, by their nature, are relatively static. For example, many public health issues affect a relatively fixed percentage of the population, so these risks will only change as the population changes. Most food safety risk assessments use a before-and-after comparison. If population growth is low, then treating these problems as static problems does no great disservice in trade for the computational simplicity of assuming a static problem. These are assumptions that should be made explicitly clear and documented in any risk assessment.

A third kind of comparison is predicated on some higher authority establishing a tolerable level of risk or a risk reduction target. As seen in [Figure 16.5](#), once a target is established, risk managers try to hit the target. When the target is ambitious, some RMOs may fall short of the target, establishing a gap between the desired level of performance of the RMO and its actual performance. In other instances, the target may be exceeded. Gap analysis is a comparison technique that focuses on the distance between the desired target and the actual performance. Frequently, when an option falls short of the target, additional measures will be considered to mitigate this shortfall. Water quality targets are often set administratively or by legislation. Targets are not uncommon for environmental issues, international standards provide a set of targets, and targets are also common organizational performance measures. Gap analysis is frequently used in conjunction with mitigation banking for environmental issues.

Risk managers would presumably adopt one of these comparison methods for a given risk management activity and apply it across all the risk management options it is considering. [Table 16.2](#) is replicated from [Chapter 3](#). It shows the effects associated with three different RMOs using a without-and-with condition scenario comparison. Each column was prepared using the same without condition. It is the with condition

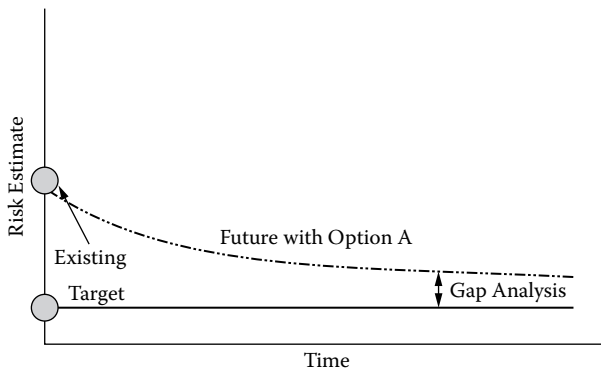


FIGURE 16.5 Conceptual gap-analysis scenarios comparison.

TABLE 16.2
Without-and-With Condition Scenario Analysis for
Alternative Risk Management Options

	RMO 1	RMO 2	RMO 3
Illnesses reduced	-30,000	-40,000	-10,000
Illnesses remaining	20,000	10,000	40,000
Costs	+\$150 million	+\$500 million	+\$100 million
Benefits	Decrease	Decrease	No change
Jobs	-2,000	0	-500

(or the after condition or the gap in the other comparison methods) that varies for each and every RMO.

There are five decision criteria in the table. This means that a without-and-with analysis was done for each of them. For any one column, there is one improvement scenario, and decision makers can focus on the differences among the decision metrics to see how they would most likely be affected under each scenario. When the scenario comparisons are based on a probabilistic scenario analysis, the individual numbers in the example would be replaced by distributions.

The FDA’s risk assessment of *Vibrio* in oysters summarizes a number of scenario comparisons.

Table 16.3, taken from that risk assessment, provides a good example of a scenario comparison. The columns show risk management scenarios. They include a without

TABLE 16.3
Actual Scenario Comparisons Taken from FDA’s Risk Assessment of *Vibrio* in Oysters

Region	Predicted Mean Number of Annual Illnesses			
	Baseline	Immediate Refrigeration	(2-log Reduction) Freezing	(4.5-log Reduction) Heat Treatment
Gulf Coast (Louisiana)	2,050	202	22	<1
Gulf Coast (non-Louisiana)	546	80	6	<1
Mid-Atlantic	15	2	<1	<1
Northeast Atlantic	19	3	<1	<1
Pacific Northwest (dredged)	4	<1	<1	<1
Pacific Northwest (intertidal)	192	106	2	<1
Total	2,826	391	30	<1

Source: Food and Drug Administration. 2005. Center for Food Safety and Applied Nutrition. *Quantitative Risk Assessment on the Public Health Impact of Pathogenic Vibrio parahaemolyticus in raw oysters*, chap. 5. <http://www.fda.gov/Food/ScienceResearch/ResearchAreas/RiskAssessmentSafetyAssessment/ucm185190.htm>.

condition (the baseline) risk estimate with three risk management options: immediate refrigeration, freezing, and heat treatment. These comprise the with conditions. The rows show the results from geographic scenarios. The reader is left to calculate the impacts of the various scenarios by comparing the improvement scenarios to the existing scenario.

16.5 TOOLS FOR CONSTRUCTING SCENARIOS

Scenarios can be activity-driven, process-driven, or event-driven. These sorts of models are often built in spreadsheets or more sophisticated programming environments. Working with spreadsheet models is discussed in [Chapter 11](#). Two useful models amenable to the spreadsheet environment are influence diagrams and tree models. Each is described in the following sections. Trees are especially useful for visually splitting and separating the uncertainty in a problem into enough levels for intuition to function most effectively.

16.5.1 INFLUENCE DIAGRAMS

An influence diagram provides a simple visual representation of a decision problem and its uncertainty. Influence diagrams are a simple tool for identifying and displaying the essential elements of a decision problem, that is, the decisions to be made, the payoffs to be realized, and the uncertainties that influence these elements and the relationships among them. As a tool, influence diagrams help the assessor find the structure of problems and identify subsequent analytical tasks, including data collection. They are often useful for conceptualizing the problem before modeling its details. As a decision aid, they pose concise problem statements.

GUIDELINES FOR DESIGNING INFLUENCE DIAGRAMS

1. It should have only one payoff node.
2. It should not contain any cycles. A cycle is a “loop” of arcs in which there is no clear endpoint. To recognize a cycle, trace back from the payoff node. If you come across the same node more than once in the same path, your diagram contains a cycle.
3. It should avoid barren nodes. Barren nodes are chance or decision nodes that do not have successors, and thus do not influence the outcome of the model.

Source: PrecisionTree User’s Guide.

Influence diagrams consist of nodes and arcs that connect the nodes. Nodes typically include decisions drawn as squares, uncertainty or chance shown as circles, and payoff nodes as diamonds. The relationships among the different nodes are shown by arcs between nodes. An arc points from a predecessor node to a successor node. Unlike a flow chart, however, influence diagrams are not necessarily sequential.

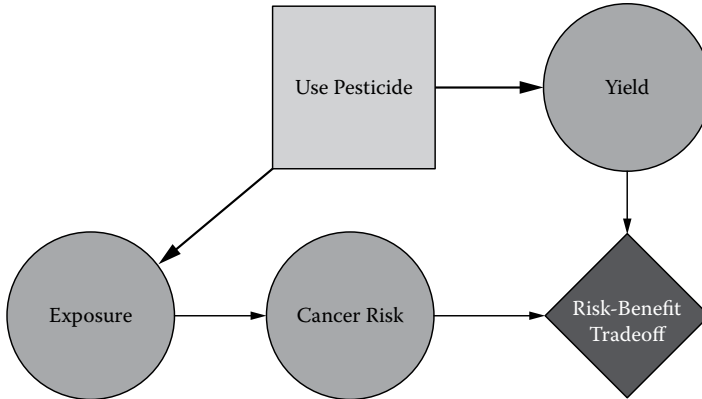


FIGURE 16.6 Influence diagram for a pesticide risk.

Palisade PrecisionTree uses arcs to identify three different kinds of influence between two nodes. When the value of one node is influenced by a predecessor node, there is a value influence. When one node must occur before (or after) another, there is a timing influence. When the structure of an outcome is affected by the outcome of a predecessor node, there is a structure influence. The direction of an arc is important.

A simple influence diagram is shown in [Figure 16.6](#). It represents the problem of estimating the net value to society of using a pesticide on agricultural products. The basic decision is whether to use a pesticide or not. If it is used, yields may increase but so could exposure to the carcinogenic pesticide. If the decision is not to use the pesticide, exposure is decreased but yield might be also.

The diagram is compact, and it efficiently portrays major elements of the decision problem. It is also easy to understand and therefore is accessible to nonexperts. This makes problems easier to explain to others. Although, in fairness, more complex influence diagrams can be somewhat bewildering to those unfamiliar with the tool.

The diagrams are also useful for explaining what influences what. Pesticide use, for example, does not directly affect the cancer risk unless there is exposure to the pesticide. Thicker arcs indicate a structural influence; the thinner ones show a value influence. A drawback to influence diagrams is that while they are excellent for showing the structure of a problem, they fail to reveal many details that are sometimes quite important. For example, we do not know the nature of the dose-response relationship from this diagram. An influence diagram is often an excellent tool for beginning to structure a decision problem. They are especially useful when constructing the conceptual model for a risk assessment. A detailed example of an influence diagram is provided in [Chapter 19](#).

16.5.2 TREE MODELS

Tree models are used to explore how systems respond to challenges. They are handy ways to catalogue as-planned, failure, and improvement scenarios. Tree models comprise a series of nodes, branches, and endpoints used to map a scenario or an

issue to aid our understanding and solution of a problem. There are four relatively common kinds of tree models:

1. Event trees
2. Probability trees
3. Fault trees
4. Decision trees

Event trees use forward logic. There is a single initiating event (a flood occurs or a load is exceeded, and so on) that can lead to many possible outcomes (endpoints). The nodes in an event tree are all uncertain or chance events; there are no decisions to be made. There are no events that are controlled by the decision makers. The model shows the sequence of chance events that can lead to desirable or undesirable outcomes. The outputs of an event tree can include the probabilities of arriving at the various endpoints as well as consequences and other impacts of interest. These may include things like profits or dollar damages, numbers of deaths, miles driven, or any other metric germane to the decision problem.

Probability trees are a specific kind of event tree. The only outcome of a probability tree is the estimated probability of arriving at an endpoint. No other impacts are quantified.

Fault trees differ from the others in that they use backward logic, as shown in Figure 16.7. This figure shows the different pathways by which a hamburger could

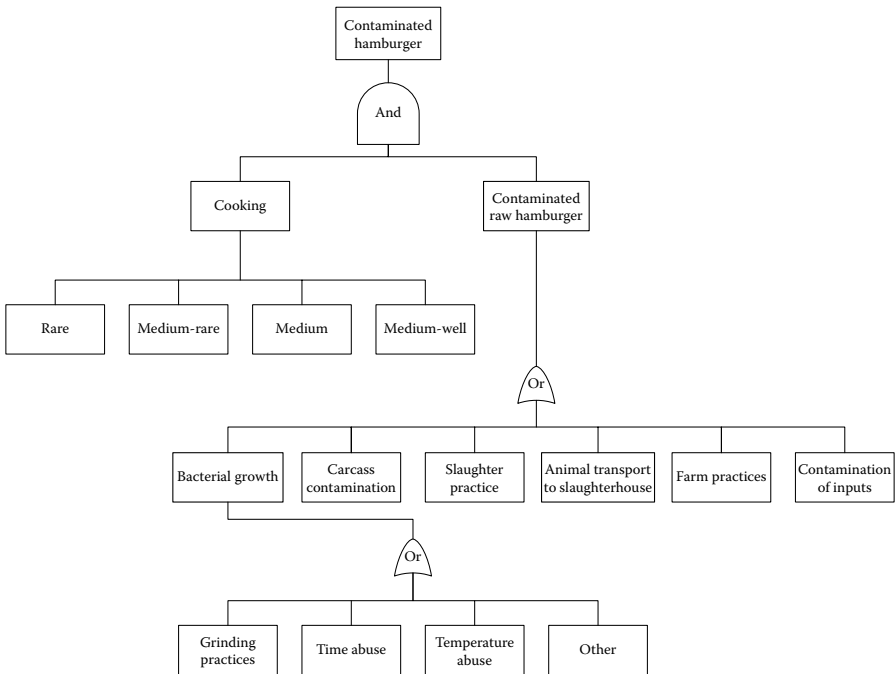


FIGURE 16.7 Fault tree analysis for contaminated hamburger.

have become contaminated with a pathogen like *E. coli* O157:H7. Fault trees begin with an endpoint, outcome, or result and work backwards to find the most likely cause of the fault. Murder investigations, structure failures, airplane crashes, food-borne illness outbreaks, and the like are examples of outcomes that set off investigations back toward the cause. Any of these might be modeled by a fault tree. As with event trees, all nodes are uncertain or chance events. Although different impacts can be tracked in a fault tree, they commonly focus on identifying the most likely path from an endpoint back to its originating event; thus, probabilities are usually the only metrics in a fault tree. For more on fault trees see the U.S. Nuclear Regulatory Commission's *Fault Tree Handbook* (1981).

In a single-stage decision tree, all decisions (there can be more than one) are made at the beginning of the model. Then all uncertainties are resolved in the remainder of the model. Examples can include making insurance purchase decisions or operating a water control structure to regulate water levels. Multistage decision trees are characterized by opportunities to make decisions as uncertainties are resolved. Their logical structure follows some sort of decision, chance, decision, chance pattern. Managing a response to an evolving natural disaster like a flood, drought, wildfire, or earthquake would involve numerous decision opportunities, as would managing a stock portfolio. Decision trees differ from the others in that there are nodes that can be controlled by the decision maker, so there are decision nodes and chance nodes. Decision trees use forward logic. They usually include impacts in addition to probability measures.

While fault trees have their own symbol sets, event trees are composed of nodes and branches. Typically, the nodes are:

- Circles to represent uncertain, chance, or probability events
- Squares to represent decision opportunities
- Triangles to represent endpoints

Nodes also represent points in logical time, which may differ from chronological time. Nodes that appear before (i.e., to the left of) other nodes are predecessor (or parent) nodes. Those that appear after a node are successor (or children) nodes. Choose any node in a model, and every predecessor to that node is assumed to have already occurred. Decisions that precede it have been made, and the chance or uncertain events before it have been resolved. For nodes to be considered predecessors or successors, they must be directly connected by one or more branches.

“Tree time” is a logical time and may not be a chronological time. For example, if we wanted to develop a model that shows how construction material and neighborhood quality affect the likelihood that a home will be broken into and entered (B&E), which of these attributes should come first in the model: construction material or neighborhood quality?

Figure 16.8 shows the model with construction material first. There is no reason other than the modeler's choice for putting that before the neighborhood quality. Thus, not all tree models need to have a literal chronological sequence. However, once a model is built, the sequence of elements imposes a logical time on the model's structure. Consequently, branches leading into a node have already occurred and

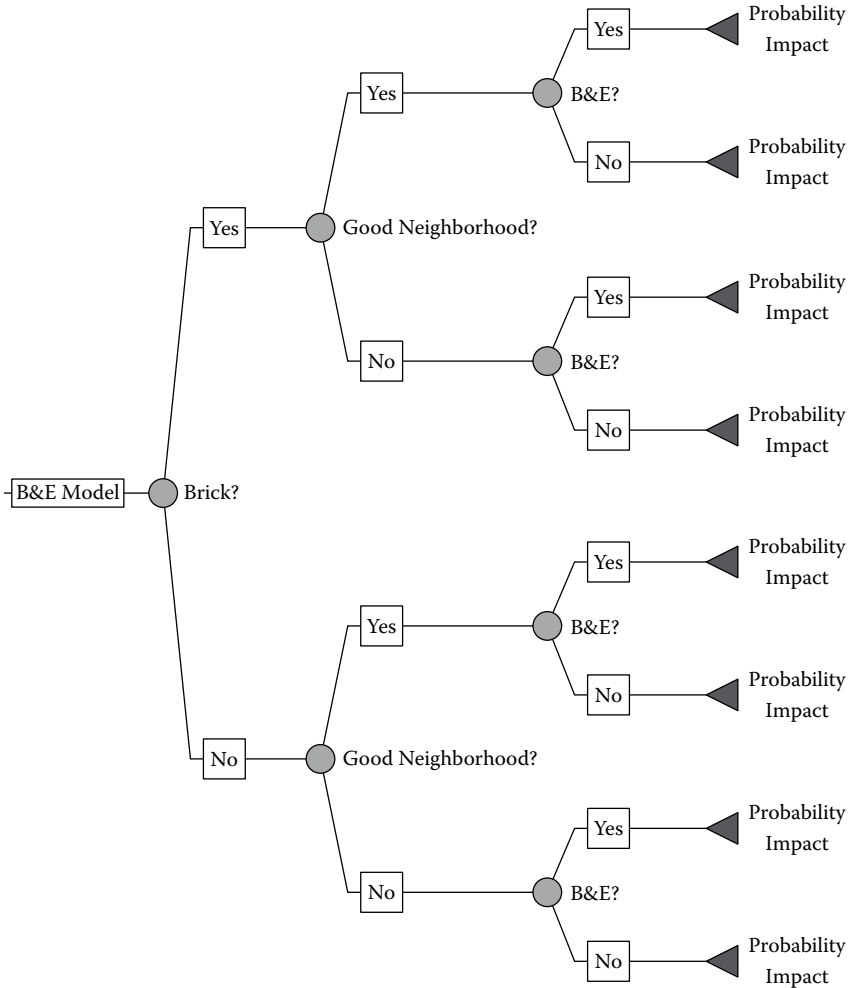


FIGURE 16.8 An example of logical time in an event tree model.

represent knowledge that the analyst now has. Branches leading out of or following a node have not occurred yet. In this example, that means construction material is resolved and has become known before the quality of the neighborhood is resolved.

The location of the node represents a point in the logical sequence and in the logical time of the model. A decision node represents the point in time (or in the model) when the decision maker makes a decision. A chance node shows the point in time (or in the model) when the result of an uncertain event becomes known. An endpoint marks that point in time (or in the model) when the process has ended, the problem is resolved, or the eventual fate beyond this point is no longer of concern to decision makers.

Branches from a chance node show the possible outcomes of uncertain events. You have no control over these. Branches from decision nodes are the possible decisions that can be made, and you can control these. Branches have values associated with

them. Probabilities are listed on top of the branch. They must obey all the laws of probability theory. Quantitative estimates of other impacts are listed on the bottom of the branch. Use Bernoulli pairs for branches when possible, for example, branches labeled yes/no, failure/success, and so on. They make your model more transparent to others. This suggested style, however, is not always possible or desirable.

Nodes, branches, and endpoints must be mutually exclusive and collectively exhaustive. Pay particular attention to endpoints. They define your sample space; make sure they identify and include all possible outcomes of interest to your decision problem.

As noted previously, probability values must obey the laws of probability. Other quantitative impacts must obey the laws of logic. Pay attention to the units of measurement you will use. It is easy for novice model builders to lose the continuity of units in a model. One may begin a model using bushels of oysters as an impact metric, while the endpoints are expected to be the number of people who get sick. Oysters cannot suddenly change into people in a tree model. Be consistent in your units throughout the model. Multiple impacts, like bushels of oysters and the number of eaters, can be tracked through the model. A tree model may constitute the entire risk assessment model or it may be but one module in a larger model.

Models end when you have answered the risk manager's questions or you no longer care what happens next. A tree model need not trace the entire history of every object or entity that enters the model. For example, suppose we are interested in estimating the number of vessels that run aground in a channel because their draft exceeds the channel's controlling depth. This tree may begin by asking if the vessel depth exceeds the controlling depth. If a vessel does not, you may not be interested in what happens to it even though some of those vessels may run aground for other reasons. The relevant point for the model may be that our risk management option, deepening the channel, may have no effect on groundings that are due to operator error, mechanical failure, bad weather, and causes other than channel depth.

16.6 ADDING PROBABILITY TO THE SCENARIOS

Up until now we have emphasized scenarios and tools for their construction. It is time to consider why and how probability enters the picture. The simple answer is that we use probabilities because there is natural variability in natural and anthropogenic systems, and there is knowledge uncertainty virtually everywhere we turn. Uncertainty gives birth to many possible scenarios. We cannot describe them all in a DSA, and some of them may be important to the decision process.

Probability is the language of natural variability and knowledge uncertainty. If we want our scenario models to deal effectively with these two phenomena they must be probabilistic.

Probability can be added to a scenario model in a variety of ways; one of those we have examined is the Monte Carlo process. Once a scenario structure has been built, we can readily replace point estimates with probability distributions that represent the natural variability and knowledge uncertainty inherent in these values. Different scenarios yield different outcomes. The probabilities of particular outcomes or values greater or less than specific outcomes may be important. The example of the next section will demonstrate how this all comes together.

16.7 AN EXAMPLE

Consider a hypothetical example familiar from earlier in the chapter. Suppose you import carcasses of meat for human consumption from another nation. Those carcasses may or may not be contaminated by a particular pathogen that is a public health concern in your country. The herds from which the carcasses come may or may not be vaccinated against the pathogen. The carcasses themselves may or may not be pathogen-free. When the carcasses arrive in your country they are first subjected to organoleptic testing (look, smell, feel) for pathogen presence. Carcasses that pass that test are next subjected to a swab test that is considered more sensitive.

The fate of carcasses that are not contaminated are of no concern to us. Even if we incorrectly think it is contaminated, we do not care, it will be removed from the food supply in an abundance of caution. A carcass that fails the first test is removed from the human food supply chain. Likewise, a carcass that fails the swab test is removed. We have been asked to answer the following questions:

- What is the probability that an imported carcass contaminated with the pathogen will enter our food supply?
- How many infected carcasses could enter the food supply annually?

Our task is to design a model that enables us to answer these questions.

There are some data available to us. Over the last 10 years we have imported an average of 2,000 carcasses with a standard deviation of 200 annually. The prevalence of the pathogen in the herds from which our carcasses are culled is no less than 0.01 and no more than 0.03. Most of the studies show it has been about 0.016. Our inspection service claims that it is somewhere between 80% and 87% effective in detecting this pathogen through visual inspection. The literature suggests the swab test is somewhere between 93% and 98% effective when properly administered.

We saw the basic model, reproduced in [Figure 16.9](#), earlier in the chapter. This describes and structures a specific scenario. The first node asks if the carcass is contaminated or not. This is an example of logical time that often confuses new modelers. Bear in mind that a model is an abstraction from reality. This model simply shows that some carcasses are contaminated when they enter the country. We do not know how many or which ones they are, but that does not prevent us from thinking about the problem in this way.

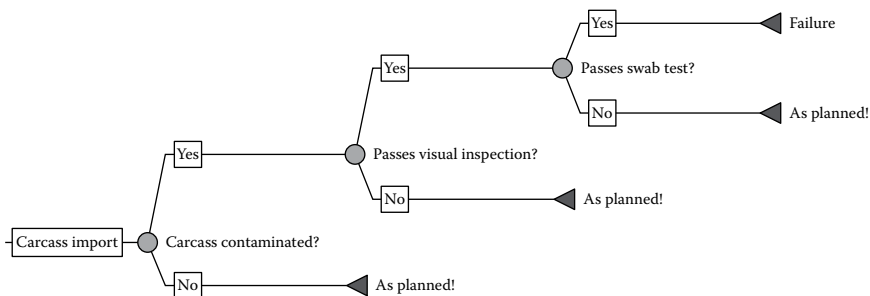


FIGURE 16.9 Carcass import event tree model.

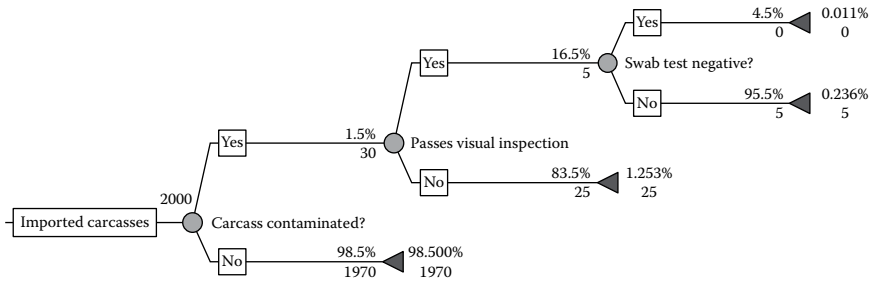


FIGURE 16.10 Prototype model without natural variability and knowledge uncertainty.

Structuring the model in this way enables us to track the contaminated carcasses in the model. An alternative formulation of the model could have begun with the visual inspection and then the swab test, waiting to reveal the state of the carcass after all the examinations had been done. This would have revealed false positive results for the inspection and the swab test. Had that been part of the decision problem, that is, one of the questions we were trying to answer, it would have been the preferred formulation.

Let us begin by using a single best estimate for each value, as shown in Figure 16.10, and ignore natural variability and knowledge uncertainty in this first formulation of the model. In other words, let us build our prototype model. The values entered are the expected values calculated from the data listed previously. The number of contaminated carcasses in this model (30) is the product of the prevalence (1.5%*) and the number of imports (2,000). Of these, 16.5% (5) pass the visual inspection. Continuing with a model free of natural variability, 4.5% of these 5 are rounded to zero, and no contaminated carcasses enter the food supply. As this deterministic model is structured here, there will never be a contaminated carcass entering the food supply. The probability of a contaminated carcass entering the food supply is low, 0.011%, and 0.011% of 2,000 is zero.

The deterministic model is not realistic because it does not address the natural variability in the world. Even with a given prevalence of the pathogen and a fixed number of carcasses, we would not always expect exactly 30 contaminated carcasses. If you observed 31 or 29 contaminated carcasses, would you be surprised? I would suspect not, as it is but a chance occurrence. Introducing variability enables us to better model the possible outcomes.

Using the simple binomial distribution in Figure 16.11 to model the variability with $n = 2,000$ and $p = 0.015$, we can see the range of possible results and their likelihoods. For 90% of the time we'd expect to see between 21 and 39 contaminated carcasses in a year. With incredibly good luck we might observe fewer than 10, and with incredibly bad luck we might have more than 50.

Likewise, there is variability in the number of contaminated carcasses that are not detected during inspection or by the swab test, so we replace the products in the prototype model with binomial distributions for these activities as well. Figure 16.12

* The expected value differs from the assumed mode of 1.7%.

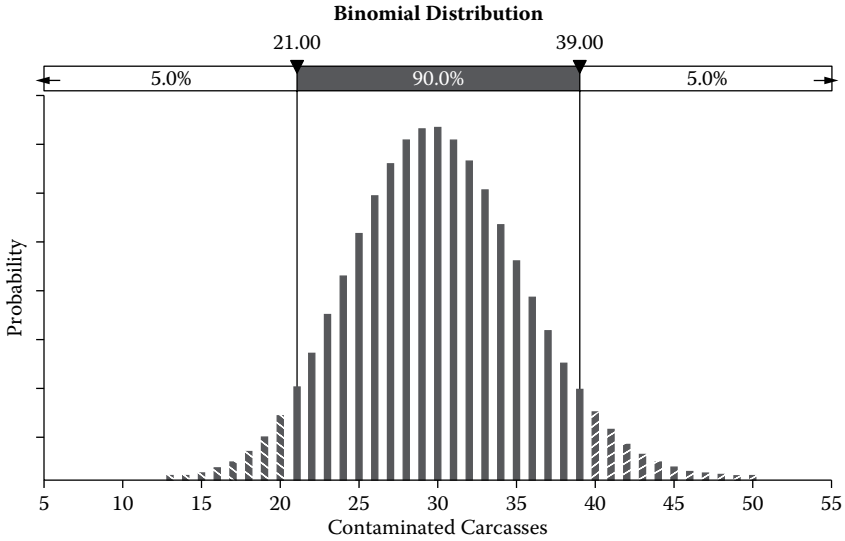


FIGURE 16.11 Binomial distribution with $n = 2,000$ and $p = 0.016$.

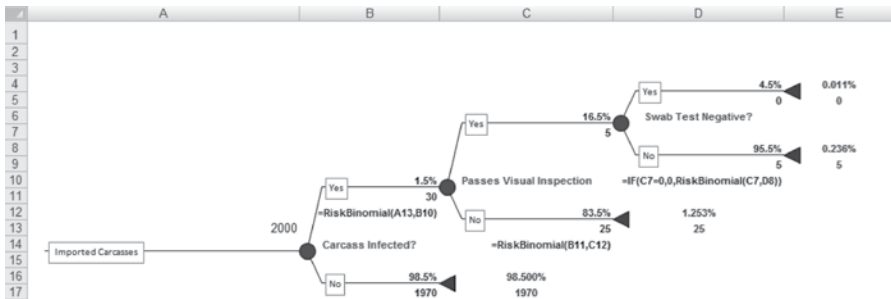


FIGURE 16.12 Carcass import model specified with some natural variability in it.

shows the model with natural variability incorporated. The syntax* for the binomial distributions is shown beneath the cell where the binomial distribution appears. This is one example of how probability is added to a scenario tool to account for some of the natural variability in the world.

Using the same expected values and allowing for natural variability, the model result changes from the constant zero seen in [Figure 16.10](#) to the 5,000-iteration simulation result shown in [Figure 16.13](#). The most common result is far and away no carcasses entering the food supply. The maximum number of carcasses observed in 5,000 iterations was three carcasses. Once we account for natural variability in the world, the expected value rises from zero to 0.22 carcasses annually.

The rightmost binomial distribution of [Figure 16.12](#) is preceded by a logical IF statement. It effectively says that if there are no carcasses that passed the visual

* The syntax used in the figures is that of Palisade Corporation's @RISK software.

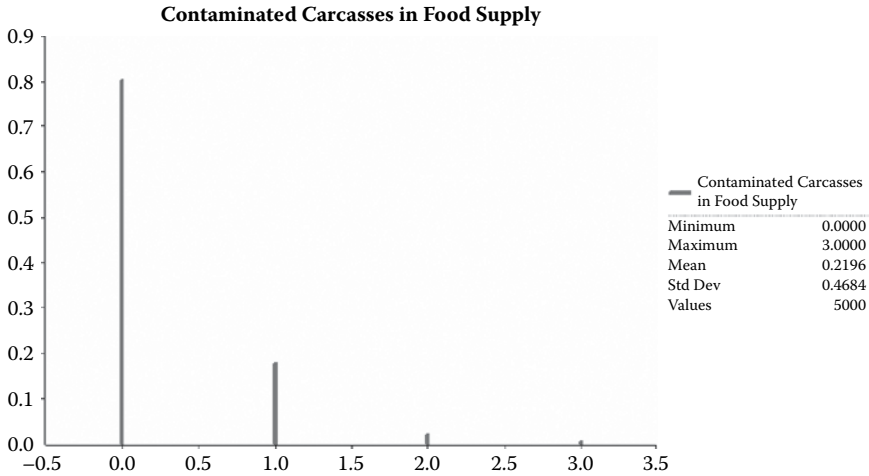


FIGURE 16.13 Output of import model specified with partial variability.

inspection, then just put a zero here as well; do not use the binomial distribution. If a zero is entered for the sample size, n , in the binomial, you will receive an error message. The IF statement prevents this error.

These results were obtained accounting only for natural variability in the model. We have not yet let the number of carcasses imported vary nor have we addressed the uncertainty in the other values. The next step is to incorporate all variability and to honestly portray our knowledge uncertainty about the model inputs using probability distributions.

Figure 16.14 shows the syntax that describes the distributions (in the adjacent cell) used to represent the natural variability and knowledge uncertainty in this model. This is how probability is layered over a scenario model to produce a probabilistic scenario analysis.

The newly introduced distributions, seen in Figure 16.15, show the variability in the number of animals imported (Normal(2,000, 20)). Note that the normal distribution is

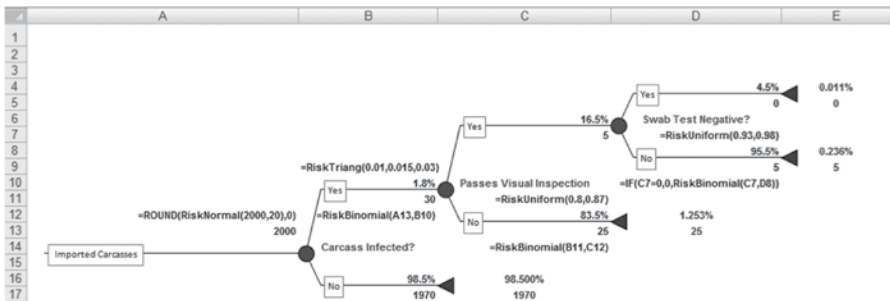


FIGURE 16.14 Final carcass import model accounting for natural variability and knowledge uncertainty.

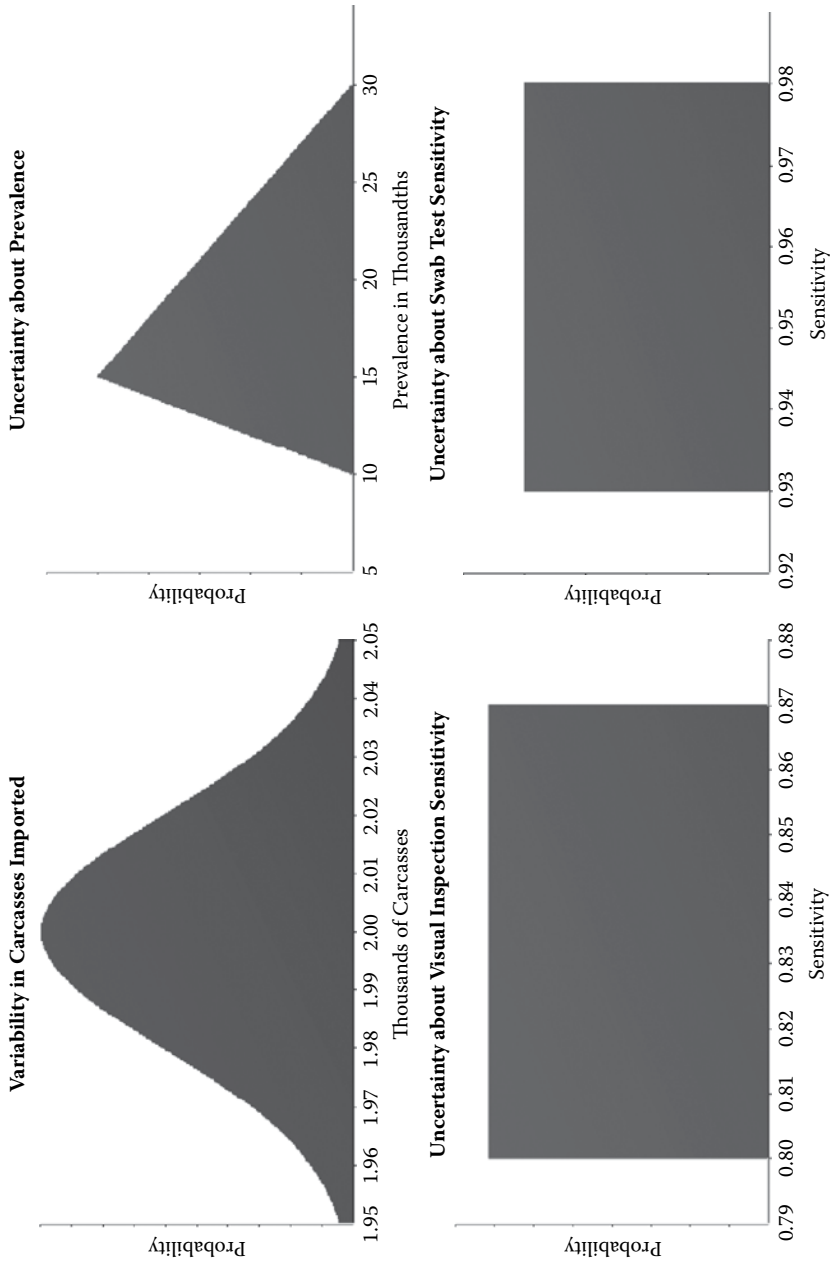


FIGURE 16.15 Probability models for one naturally variable and three knowledge uncertainty model inputs.

a continuous variable while carcasses are discrete. The value sampled from the normal distribution is converted to a discrete value using the = ROUND function of Excel. The other three newly added distributions reflect the available data and the relatively broad range of uncertainty we have about these three continuous values in the model.

All that remains at this point is to run the model and answer the questions posed at the start of this section, which began with: What is the probability an imported carcass contaminated with the pathogen will enter our food supply?

The probability that a contaminated carcass will enter the food supply is not the same as the frequency with which that will happen, because there is variability in the world. This value is found just to the right and above the topmost endpoint of the model (cell E4) seen in Figure 16.14. (Rounding prevents you from precisely reproducing the values shown in the figure.) Each iteration of the model produces a new estimate for this output. The results of the simulation are shown in Figure 16.16. The minimum observed value was 0.00003, and the maximum was about 0.0004. The expected value is 0.0001, essentially unchanged from the first crude formulation of the model, shown in Figure 16.10. This makes sense, however, because we used expected values in the prototype. In the long run, about one in 10,000 carcasses will be contaminated and will slip into the food supply. What that might look like in actual fact is addressed in the next question and answer.

How many infected carcasses could enter the food supply annually? The minimum number of contaminated carcasses to enter the food supply is, as previously noted, zero, which happened 76.5% of the time. The maximum number to enter the food supply in this simulation was four. The expected value is 0.27 carcasses per year. This figure differs from the previous results of a maximum of three and an expected value or 0.22 from the model that incorporated only part of the natural variability. When we finally expressed our total uncertainty, the likelihood of one or more contaminated carcasses entering the food supply was greater. The model output value for the second question is presented in Figure 16.17.

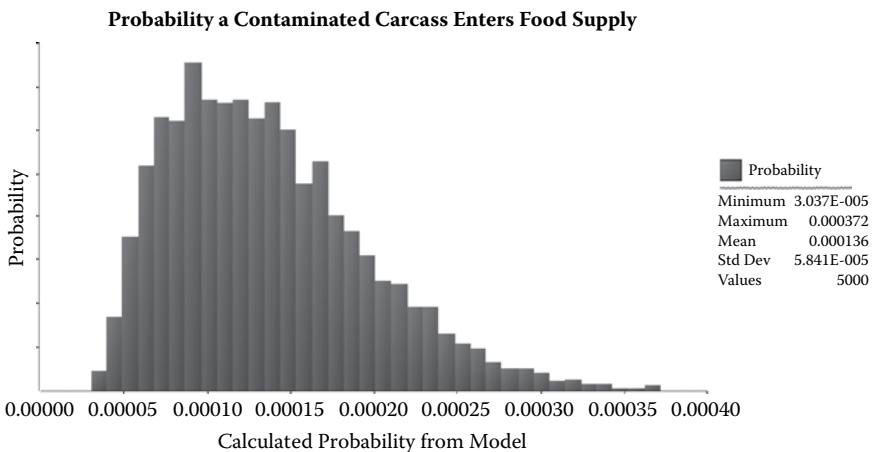


FIGURE 16.16 Estimate of the probability that a contaminated carcass enters the food supply.

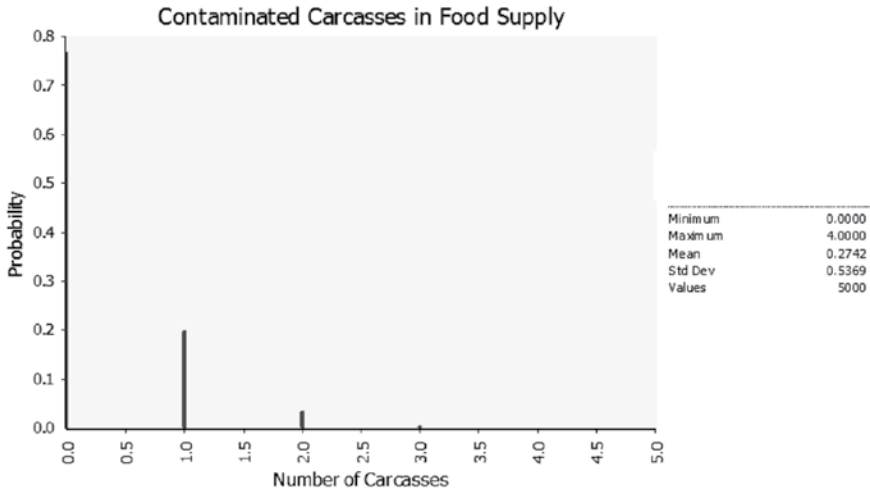


FIGURE 16.17 Estimate of the annual number of contaminated carcasses entering the food supply.

Event trees are visually instructive and easy to work with for a wide variety of risk issues. Carefully layering probability onto the event tree models may sometimes require the analyst to modify the software’s built-in function and capability. Examples of that were seen in this simple model, where rounding functions and a logic statement were used. As a bundle of tools and techniques, probabilistic scenario analysis currently remains the methodology of choice for most probabilistic risk assessment.

16.8 SUMMARY AND LOOK FORWARD

Scenario analysis is an essential risk assessment tool. Constructing as-planned, failure, and improvement scenarios is an essential part of both qualitative and quantitative risk assessment. Risk assessors make extensive use of deterministic and probabilistic scenario analysis. Once in a while a monolithic scenario is used for decision making, but hopefully not in risk analysis. DSA and PSA rely on scenario comparisons to place risks in a useful context for decision makers. Without-and-with condition comparisons are preferred for exploring the efficacy of risk management measures. When probabilistic methods are added to the available suite of scenario structuring tools and techniques, this produces a very powerful suite of tools called probabilistic scenario analysis. Most probabilistic risk assessments are some form of a PSA.

Chapter 17 covers sensitivity analysis. Sensitivity analysis is the study of how the variation in a risk assessment output can be apportioned to different sources of variation. Sensitivity analysis is the bare minimum expectation for addressing uncertainty in an explicit fashion in any kind of risk assessment, qualitative or quantitative. Numerous techniques are presented for both qualitative and quantitative sensitivity analysis.

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17 Sensitivity Analysis

17.1 INTRODUCTION

Expect that knowledge uncertainty will never be reduced to zero. Know that natural variability will never disappear. These two simple facts mean that the risk characterization from your risk assessment is, at best, an informed estimate. At worst, it may be well-intentioned speculation. What assessors and managers both need to know is that the outputs of a risk assessment are conditional answers based on the data and data gaps, on the assumptions and estimation tools, and on the techniques and methodologies used to arrive at the answers. They also need some idea of where the assessment answers lie on the continuum between the best estimate and well-intentioned speculation.

A simplistic schematic of a decision situation is shown in [Figure 17.1](#). A risk assessment has several inputs that include knowledge, data, policy, and information in many forms. Data gaps and other forms of uncertainty are ubiquitous characteristics of these inputs.

Assumptions made to help address uncertain inputs find their way into the model and affect model outputs, e.g., risk characterizations and the like, which, in turn, influence the risk management decision. Any methodologies used to address the knowledge uncertainty and natural variability in inputs will result in a similar chain of events. Likewise, assumptions made about the model's structure will influence outputs and decisions.

Sensitivity analysis is the study of how the variation* in a risk assessment output can be apportioned, qualitatively or quantitatively, to different sources. Complex risk assessments may have dozens of input and output variables that are linked by a system of equations and calculations. Risk assessors need to consider how sensitive a model's output, a risk characterization, or other important assessment outputs are to changes or estimation errors that might occur in model inputs, model parameters, assumptions, scenarios, and the functional forms of models. This information must then be effectively conveyed to risk managers so they can explicitly consider its significance for their decision making.

Some risk assessment outputs and the decisions that rely on them may be sensitive to changes in assumptions and input values. However, it is not always immediately obvious which assumptions and uncertainties most affect outputs, conclusions, and decisions. The purpose of sensitivity analysis is to systematically find this out.

A good sensitivity analysis increases the assessor's and manager's confidence in the risk assessment model and its predictions. It provides a better understanding of how model outputs respond to changes in the inputs. Because risk assessments

* Variation includes the effects of natural variability and knowledge uncertainty.

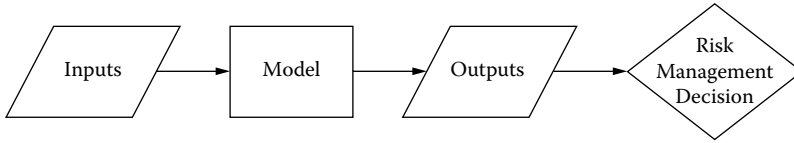


FIGURE 17.1 Decision model schematic.

can be qualitative or quantitative, sensitivity analysis can likewise be qualitative or quantitative. In a qualitative sensitivity analysis, the assessor identifies the uncertainties affecting the assessment and forms a judgment of their relative importance. A quantitative sensitivity analysis quantifies the variation in model outputs that is caused by specific model inputs and the model structure.

Some sensitivity analysis should be an integral component of every risk assessment. This is the point in a risk management activity when the risk analysis team focuses intentionally on better understanding the things we do not know and their importance for decision making. The results of the sensitivity analysis will provide insight into the importance of different sources of uncertainty.

Sensitivity analysis has at times been called what-if analysis. It can be used to answer questions like those below, which build on questions first provided by Mokhtari and Frey (2005).

- How might the decision be changed by increases or decreases in selected input values?
- What is the range of values a parameter can assume in a function without changing the decision?
- By how much must a value change to lead to an alternative best decision?
- How sensitive is our output to forecast error or other changes in inputs?
- Which inputs contribute most to the variation in the output?
- Which inputs are most responsible for the best (or worst) outcomes of the output?
- What is the rank order of importance among the model inputs?
- Are there two or more inputs to which the output has similar sensitivity, or is it possible to clearly distinguish and discriminate among the inputs with respect to their importance?
- Might changes in our decisions/actions improve our outputs?
- Does the model respond appropriately to changes in assumptions and inputs?

This chapter is divided into sections that address qualitative and quantitative approaches to sensitivity analysis. Material that could have been included in both of the sections will be addressed in the quantitative sensitivity analysis discussion. The most common sensitivity analysis methods are relatively simple techniques. There are others that are quite complex. The quantitative sensitivity analysis discussion summarizes methods from across this continuum. Examples are provided for the simpler methods; references are provided for the more complex ones.

17.2 QUALITATIVE SENSITIVITY ANALYSIS

Risk analysis is a framework for making decisions under uncertainty. Because your uncertainty cannot be eliminated, it is critically important to explore the importance of the uncertainty that remains prior to making a decision. A qualitative sensitivity analysis characterizes the uncertainty and its potential significance to decision making in nonnumerical ways. This is done to aid risk managers who need to make decisions in the face of this uncertainty. Quantitative sensitivity analysis is almost always preferred when it is feasible. Qualitative sensitivity analysis, being more subjective, is generally less reliable. At a minimum, qualitative sensitivity analysis provides a greater degree of confidence in assessment outputs and management decisions based on them for having identified and considered critical data gaps and other sources of uncertainty.

Qualitative sensitivity analysis has been defined quite differently in some of the literature. Pianosi et al. (2016) say that in qualitative sensitivity analysis, sensitivity is assessed qualitatively by visual inspection of model predictions or by specific visualization tools like, for instance, tornado plots, scatter (or dotted) plots or representations of the posterior distributions of the input factors. In the view adopted in this text, this would more appropriately describe a form of exploratory quantitative analysis. The language is messy.

A basic methodology for qualitative sensitivity analysis includes:

- Identifying specific sources of uncertainty
- Ascertaining the sources of instrumental uncertainty
- Qualitatively characterizing the instrumental uncertainty

A reasonable objective for qualitative sensitivity analysis is to identify the sources of uncertainty that exert the most influence on the risk assessment outputs.

17.2.1 IDENTIFYING SPECIFIC SOURCES OF UNCERTAINTY

Identifying specific sources of uncertainty often begins with an acknowledgment that uncertainty exists. This is not always as easy as it seems it should be (see sidebar). A significant number of organizations still want to know “the number,” and there is no incentive for acknowledging uncertainty in such a culture.

Once we are ready to acknowledge that uncertainty exists, we must recognize it when it is present. Knowledge is a relative commodity, and when we are used to working with relatively little data, for example, a lot of data can sometimes mask the uncertainty that remains. The assessor must be able to separate what is known from what is unknown in a decision problem.

We need to be able to identify and point to an input, assumption, scenario, or model and say this is uncertain. When we have done that, it is helpful to say why it is uncertain, i.e., identify what the cause of the uncertainty is. Next, it is useful to say

how uncertain the cause of the uncertainty is and why the uncertainty is important. The initial goal is to honestly identify the things we do not know. A useful output from this step is a list of inputs recognized as uncertain, by type of input. The next step is to figure out which of them matter most.

THE CHANNEL BOTTOM

In an early proof of concept risk assessment for the U.S. Army Corps of Engineers an experienced engineer was questioned about a point estimate of the percentage of rock in a channel bottom. This is an important determinant of the cost of channel deepening. Offered the opportunity to bound this estimate he refused, insisting that he had better information from sample borings and more data than he had ever had in a long and successful career. He insisted there was no uncertainty about this value and was offended that we might think otherwise. His estimate turned out to be almost less than half of the actual rock content. Costs quickly doubled and he is now a proponent of risk assessment.

17.2.2 ASCERTAINING THE SOURCES OF INSTRUMENTAL UNCERTAINTY

An instrumental uncertainty is one that could affect the decision that is made or that could affect the outcome of a decision. Candidate instrumental uncertainties include those things that can affect model outputs, risk characterizations, conclusions, answers to the risk manager's questions, or other important decision criteria.

The best place to begin to identify the most important sources of uncertainty may be by considering what people say is important. Use the relevant theory, read the professional literature, talk to an expert, reason it through for yourself, and listen to what people are saying. Respect the wisdom of crowds and experts!

You need not be concerned about every uncertainty in your risk assessment. Using the extent of uncertainty may be a poor gauge of the importance of an uncertainty. Focus first on identifying relevant uncertainties and then on identifying relevant and instrumental uncertainties. See [Chapter 2](#) to review those concepts.

If you have used a mental or other model, look at the structure of the model. It reflects the extent to which a physical system or phenomenon is understood. Is there any aspect or element of the model that has more influence on its outputs than any other? It is almost invariably the case that some model elements have a disproportionate influence on model outputs. If so, these elements may be potential sources of instrumental uncertainties.

Which inputs can you control or affect? It is generally wise to pay extra attention to those things you can control, or at least affect. Inputs that people say are important, that are influential in your model, and that you can affect may well be relevant uncertainties. Take that list of uncertain inputs you prepared and put an asterisk next to each one that

you suspect may be instrumental. Now it is time to characterize that uncertainty in ways that risk managers can understand and consider in decision making.

17.2.3 QUALITATIVELY CHARACTERIZING THE UNCERTAINTY

The World Health Organization (2008) offers a useful scheme for qualitatively characterizing the uncertainty in your assessment, assuming that you know which outputs are instrumental to decision making. Although developed for use with chemical exposure assessments, it has general applicability. To qualitatively identify the most critical uncertainty, think of the process as locating each relevant uncertain item in the three-dimensional space shown in [Figure 17.2](#). Values near the origin are the least uncertain. A low, medium, or high score is determined by the assessor for each of the axes. The most significant uncertainties are those with the highest scores for all three dimensions. The axes may be differentially weighted or not. Following the WHO process, level of uncertainty is more important than appraisal of the knowledge base, which is more important than subjectivity of choices. Explicit weights need not be assigned because the characterization is a sequential one, as seen in the hypothetical example in [Table 17.1](#).

The level of uncertainty dimension expresses the degree of severity of the uncertainty, from the assessor's perspective. A scale ranging from low to high has been suggested, as shown in [Figure 17.3](#) (WHO 2008).

A low score means that a large change in the source of uncertainty would have a small effect on the results. Inputs scored as medium would have proportional effects on outputs. A high score implies that a small change in the source of the uncertainty would have a large effect on the results. As qualitative inputs are scored in this dimension, it is helpful to indicate whether the uncertainty is reducible or irreducible (see [Table 17.1](#)) so that risk managers better understand their options for addressing the level of uncertainty.

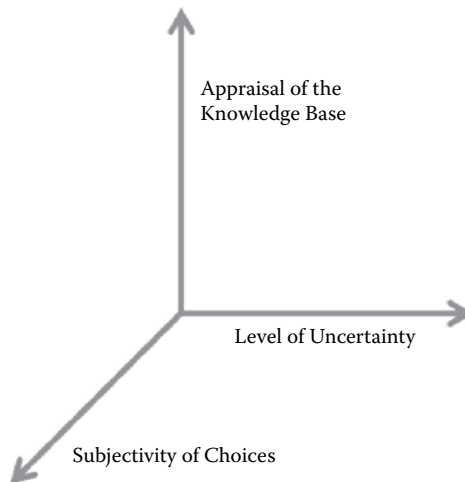


FIGURE 17.2 Three-dimensional space of qualitative risk assessment. (World Health Organization 2008.)

TABLE 17.1
Sample Summary of the Evaluation of Uncertainty in a Qualitative Risk Assessment

Sources of Uncertainty	Characteristics of Uncertainty		
	Level of Uncertainty	Appraisal of Knowledge Base	Subjectivity of Choices
Scenario	Medium	Low	Medium
Model	Conceptual	High	Medium
	Mathematical	NA	NA
Inputs			
Input 1 (irreducible)	Low	Low	Low
Input 2 (reducible)	High	Medium	Low
Input 3 (reducible)	Medium	Medium	High

The appraisal of the knowledge base is based on accuracy, reliability, plausibility, scientific backing, and robustness, all seen on the vertical dimension axis of [Figure 17.4](#) (WHO 2008). It is intended to rate the adequacy of the state of knowledge about the input. A low uncertainty in the knowledge-base rating suggests the qualities listed in the first column. The other columns illustrate the two other possible ratings of medium and large.

The final dimension along which to rate an uncertain input is the subjectivity of the choice the assessor had in making an assumption about this input. The aspects of the choice include the choice space, intersubjectivity among peers and among stakeholders, influence of situational limitations (e.g., money, tools, and time) on choices, sensitivity of choices to the analysts’ interests, and the influence of choices on results. Descriptions for each aspect can be read across the vertically arranged rows in [Figure 17.5](#) (WHO 2006).

The WHO method proceeds to rank sources of uncertainty by aspects; first, ranking sources of uncertainty by level of uncertainty, then appraisal of the knowledge base, and finally by subjectivity of choices. A hypothetical qualitative summary evaluation of the uncertainty in an assessment is shown in [Table 17.1](#). Imagine that

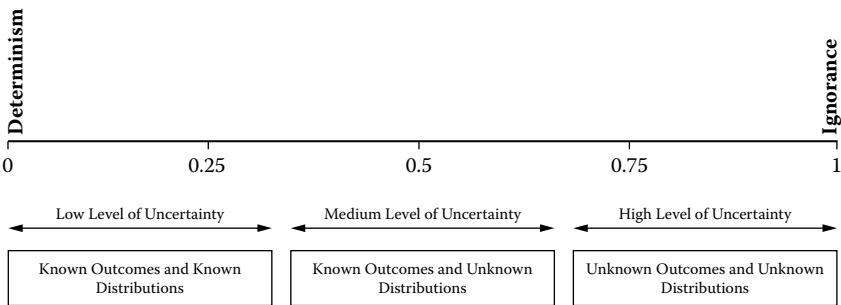


FIGURE 17.3 Rating the level of uncertainty. (World Health Organization 2008.)

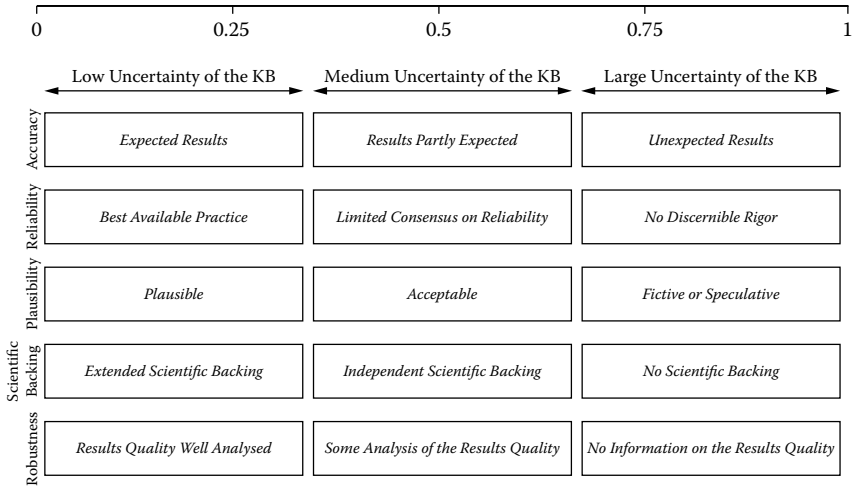


FIGURE 17.4 Rating the appraisal of the knowledge base. (World Health Organization 2006.)

the preceding qualitative sensitivity analysis steps have identified the base scenario, the conceptual models, and three of its inputs as potential sources of instrumental uncertainty. If we follow the WHO rationale and consider the three dimensions of uncertainty as sequential screening tools, we would find the model and input 2 of most interest because each scored high on the first screening criterion. Subsequent screening criteria are used to refine the sorting process. Both the model and input 2 are rated medium on the knowledge-base criterion. Moving to the subjectivity-of-choices criterion identifies the conceptual model as the more significant uncertainty

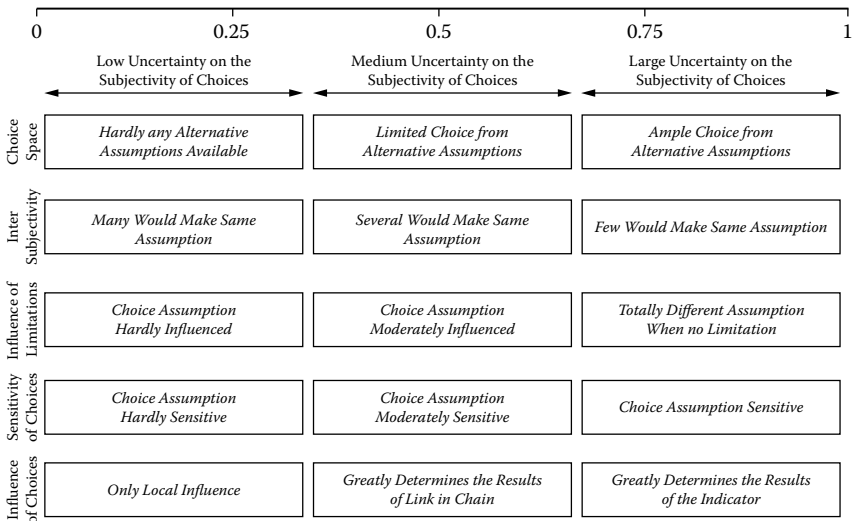


FIGURE 17.5 Rating the subjectivity of choice. (World Health Organization 2006.)

in this case. Between the two medium levels of uncertainty for the scenario and input 3, input 3 is rated as more significant based on an appraisal of the knowledge base.

Once the uncertainties have been identified in this or another manner, it remains for the assessor and the manager working together to subjectively evaluate the significance of these findings for the purposes of risk management. The risk manager should explicitly consider the results of such a sensitivity analysis and how changes in input 2 or the model might affect the decision or its outcome. His decision could include additional research to minimize the reducible uncertainty. Progressing to a quantitative risk assessment may be an option for some situations. Systematically exploring the impact of alternative assumptions or ranges of values on the decision to be made is, hopefully, an obvious response to uncertainty in a qualitative assessment.

17.2.4 VARY THE KEY ASSUMPTIONS

A sensitivity analysis structured as described in the previous section is not going to be done for every qualitative assessment. However, doing no sensitivity analysis is unacceptable. The absolute, bare minimum sensitivity analysis is to carefully and systematically explore and vary the assumptions that underlie the assessment's instrumental uncertainty. When we separate what we know from what we do not know during a risk assessment, it is necessary to find effective means for dealing with that which we do not know. Making assumptions about uncertain values is one of the most common and expedient ways of addressing uncertainty.

We make two basic kinds of assumptions. Those we know we are making, i.e., explicit assumptions, and those we do not know we are making, i.e., implicit assumptions. Explicit assumptions should be documented, written down, and preserved for the attention of assessors and managers and other interested parties. Implicit assumptions are often not recognized by the assessors or managers. Peer review by multidisciplinary reviewers can be an effective technique for detecting implicit assumptions. It often takes someone outside one's own discipline, specialty, or organization to recognize the assumptions we make as the common practice of our fields and organizations.

To the extent that we use assumptions to address uncertainty and to enable ourselves to move forward with our assessments, we should routinely test the sensitivity of our assessment outputs to those assumptions. The simplest way to do this is to first make a list of the key assumptions used in a risk assessment. Next, explore what happens as you drop or challenge each assumption individually and replace it with alternative assumptions. Do your outputs change? Do the answers to the risk manager's questions change? Might any of these changes affect the risk management decision? If so, that information needs to be conveyed to the risk managers. For example, imagine an assessment of the risks of a nuclear power plant site. Suppose we have assumed sea level rise of one foot or less in the next 100 years. If it is more than that, this site will be surrounded by water year-round. This is information that needs to be carefully communicated to risk managers. We have assumed sea level rise will pose no hazard, but that is a remaining uncertainty.

It can sometimes be instructive to explore what happens as you drop/change your assumptions in combinations. Assumption dropping is a very effective kind of

qualitative sensitivity analysis that can also be useful in quantitative assessments. When the assumptions do make a difference to your assessment outputs and answers that could affect decision making, you have identified an instrumental uncertainty. Risk managers should respond accordingly either by reducing the uncertainty through additional data collection or research or by having the risk assessors address the assumptions more thoroughly in their assessment, perhaps with probabilistic risk assessment methods. The final obvious alternative for risk managers is to take the knowledge of that sensitivity into account when making a decision.

17.3 QUANTITATIVE SENSITIVITY ANALYSIS

There are four classes of quantitative sensitivity analysis tools. These are scenario, mathematical, statistical, and graphical analysis. In the discussion that follows, example methods from each class are described. The more popular methods are illustrated by reference to a simple cost estimating example.* Two of these methods will rely on different examples that are better suited to the methods demonstrated.

17.3.1 SCENARIO ANALYSIS

Analyzing the sensitivity of assessment results to the scenarios we use is called scenario analysis. The base-case scenario for most risk assessments is either an existing condition or the “without” additional risk management options (RMOs) condition. In the simplest scenarios, model inputs are entered as point estimates that represent the “best guess” as to the true but unknown value of each input. Rather than to alter these inputs one or two at a time, scenario analysis alters the entire scenario. If we think of scenarios as the stories we tell about risks, these alternative scenarios include different plot lines such as best case, worst case, common practice, the most likely case, a locally focused scenario, a new policy scenario, and so on.

The alternative scenarios can vary markedly in their structure and details. When a new scenario is considered as a starting point for the assessment it can sometimes lead to a markedly different characterization of the risk. Existing, as-planned, failure and improvement scenarios are all subject to scenario sensitivity analysis. It is worth noting that scenario analysis does not require the construction of structurally different scenarios. The alternative scenarios may simply comprise alternative sets of input values within an unchanging scenario structure. The goal is to focus on the structural elements or inputs of a scenario that give rise to instrumental uncertainty and to vary them to explore the sensitivity of risk characterizations and answers to the risk manager’s questions to these plausible different scenarios. If they could alter the decision or the outcome of a decision, risk managers must carefully consider this information.

One of the most commonly used alternative scenarios is the worst-case scenario. If we can identify and live with the worst-case scenario, a common and sometimes

* Cost-estimating examples are used in this chapter and the next one. Although they may not spring first to mind when thinking about risks, they have the advantage of being easily understood and accessible to readers from every discipline. The risk of a cost overrun or under-estimating the cost of an action can be significant. As such they provide a friendly context for learning the concepts.

wrong presumption is that we can live with lesser scenarios as well. Consequently, assessors will sometimes try to envision the most extreme negative set of input values possible.

Engineers and public health officials, to name just two professions, are biased toward designing systems conservatively to try to minimize or eliminate the chance of adverse outcomes. The engineering profession in particular has regarded conservatism in design as the accumulated wisdom of centuries of experience that has taught that the conditions of the real world are not always predictable and it makes good sense to provide some margin of error for unforeseen events. This drive toward conservatism has led to the widespread propagation and use of worst-case scenarios.

There is no real formal definition of a worst-case scenario. It is simply that future in which everything that can reasonably go wrong does go wrong. If the worst-case scenario yields an acceptable result, decision makers in the past have often assumed there is no need to manage a risk. On the other hand, worst-case scenarios that result in unacceptable consequences often have lead decision makers to take precautions to preclude the worst-case scenario from occurring.

Despite its widespread usage, the worst-case scenario is not without its problems. First among these is that introducing this conservatism into an analysis focuses policy and possibly resources on what is often a deliberately unrealistic scenario. This is precisely what risk assessment is designed to prevent. Second, given any worst-case scenario, an even worse case can, paradoxically, still be defined. Third, the likelihood of a worst-case scenario may be so small as to lead to the waste of efforts, materials, and other resources in attempts to reduce it. Fourth, there is an almost hypnotic appeal to think that if we have covered the worst-case, we have covered everything. Failure in the better-than-worst-case world is still possible and is often overlooked with a worst-case orientation to risk management. Nonetheless, worst-case scenarios are likely to remain useful and popular failure scenarios to investigate. In general, though, it is not wise to make policy based on worst-case scenario analysis.

Other scenarios can be evaluated for the benefit of risk assessors and managers alike. An optimistic or best case (if everything that can break our way does) scenario may be of interest to risk-taking risk managers, for example. Different stakeholders may proffer alternative views of the future that should be explicitly considered in scenario analysis. The risk assessors may develop a range of scenarios to reflect their concerns about the key uncertainties in a risk assessment. What the team assumes about climate change, sea level rise, geopolitical events, natural disasters, technological advancements and the like could have important ramifications for decision making. The most likely scenario is often uncertain and any number of scenarios can be developed. Deterministic scenario analysis is not an uncommon sensitivity analysis approach.

When assessors use scenario analysis, the idea is to compare the different situations to identify differences in important model outputs. Differences that make a difference for decision making are important, and assessors and risk managers must become aware of them in a sensitivity analysis. Risk managers then must decide how much to weigh the range of potential outcomes that could result from the residual uncertainty in the decision-making process.

17.3.2 MATHEMATICAL METHODS FOR SENSITIVITY ANALYSIS

Mathematical methods rely on calculating outputs for a range of input values or for different combinations of input values. These methods differ from statistical methods, which rely on simulations in which inputs are represented by probability distributions. Although mathematical methods do not describe variance in outputs due to variance in inputs as statistical methods do, they are still useful in estimating the impact of a range of input values on model outputs. In addition, mathematical methods can help identify the most important inputs, and they are useful for verifying models. Sensitivity of model outputs to individual inputs or groups of inputs can be explored by various means (Frey and Patil 2002).

Several sensitivity analysis methods presented in the pages that follow use the cost estimate example seen in Table 17.2. These are the costs of dredging a navigation channel and using the material to create wetlands by placing it behind geotube barriers

TABLE 17.2
Cost Estimate for Channel Dredging

A Description	B Quantity	C Unit	D Price	E Amount
Lands and damages	0	LS	\$...	\$...
Relocations				
Lower 20 pipeline, 653+00	425	LF	\$730.00	\$310,250
Remove 8" pipeline, 678+00	1,000	LF	\$50.00	\$50,000
<i>Total—Relocations</i>				<i>\$360,250</i>
Fish and Wildlife Facilities (Mitigation)				
Oyster reef creation	0	ACR	\$...	\$...
<i>Total—Fish and Wildlife Facilities</i> (Mitigation)				<i>\$...</i>
Navigation, Ports and Harbors				
Mobe and demobe	1	LS	\$500,000.00	\$500,000
Pipeline dredging, Reach 1	576,107.00	CY	\$2.78	\$1,601,577
Pipeline dredging, Reach 2	1,022,769.00	CY	\$2.60	\$2,659,199
Pipeline dredging, Reach 3A	1,182,813.00	CY	\$3.16	\$3,737,689
Pipeline dredging, Reach 3B	736,713.00	CY	\$2.76	\$2,033,328
Scour pad, Reach 1	17,550	SY	25.69	\$450,860
Geotubes, 30', Reach 1	1,400	LF	\$188.52	\$263,928
Geotubes, 45', Reach 1	4,912	LF	\$222.18	\$1,091,348
Scour pad, Reach 3	38,750	SY	\$25.69	\$995,488
Geotubes, 45', Reach 3	13,940	LF	\$222.18	\$3,097,189
<i>Total—Navigation, Ports and Harbors</i>				<i>\$16,430,606</i>
<i>Subtotal</i>				<i>\$16,790,856</i>
Engineering and Design	8%			\$1,343,268
Construction Management	6%			\$1,007,451
<i>Total project cost</i>				<i>\$19,141,576</i>

Abbreviations: LF = linear feet; LS = lump sum; CY = cubic yards; SY = square yards; ACR = acres.

adjacent to the shoreline. Note that row and column locations are provided. This may be helpful for interpreting some of the tables and figures that follow. The first column (A) describes the basic work item, column (B) provides the quantity in the units of column (C). The price (D) is per unit. The amount (E) is the product of the quantity and unit price. The subtotal sums the total amounts that precede it in the table. Of this total, 8% and 6% are calculated to cover, respectively, advanced engineering and design (AED) as well as construction management (CM). They are added to the subtotal to obtain the total project cost, \$19.1 million, the only output of interest for this example.

The numerical values shown in the table are the best point estimates of the cost estimators. For the mathematical methods, the model is treated as a deterministic one. Once we progress to the use of statistical sensitivity measures, these point estimates are replaced by probability distributions and a Monte Carlo process is then used to simulate results. Assume that there is knowledge uncertainty and natural variability “sprinkled” among the various inputs required to estimate the total project cost.

17.3.2.1 Nominal Range Sensitivity

Nominal range sensitivity is a mathematical method used for deterministic, rather than probabilistic, models. It is usually used to identify the most important input(s) (Cullen and Frey 1999), and this can be useful for setting research and data collection priorities.

Nominal range sensitivity analysis is also known as one-at-a-time analysis (OAATA). It works by evaluating the effect of changes in an individual input on an output variable. This local sensitivity is conceptually equivalent to a partial derivative. Although simple, this technique has at least two key shortcomings: (1) it does not account for simultaneous variation of multiple model inputs; and (2) it does not account for any nonlinearities in the model that create interactions among the inputs. Nonetheless, for simple linear models, OAATA can be instructive.

The selected input may be changed incrementally or allowed to vary across its entire range of plausible values while holding all other input values constant, usually at their nominal, mean, representative, or base-case values. This is sometimes done to identify threshold values that result in significant changes in model outputs. It can also be used to identify which uncertain variables may have the greatest impact on outputs of interest in the risk assessment. Alternatively, a plausible range of variation, say $\pm 20\%$, may be applied to one or more inputs. Morgan and Henrion (1990) call the change in the model output due to a unit change in the input the sensitivity or swing weight of the model for the chosen input variable. This sensitivity analysis can be repeated for as many input variables as desired.

LIMITATIONS OF ONE-AT-A-TIME ANALYSIS

Do not automatically equate the magnitude of an uncertain variable with its influence. Consider two random variables expressed by the following uniform distributions: $A = U(10^7, 10^8)$, $B = U(2, 6)$. Some might be tempted to assume A is more influential because of its sheer magnitude.

It is essential to know the structure of your model and nonlinearities can change everything you think you know about sensitive variables. For example, consider a new variable, C , that is a function of A and B . If $C = A + B$; A dominates. If $C = A^B$; B dominates.

Dependence and branching in a model can also create flaws with the logic of OAATA. Consider this example:

```
If X<50 then
Y = Z + 1
Else
Y = Z100
```

What value will you set X equal to when you investigate the sensitivity of Y and Z ?

Bearing in mind that the sensitivity can be described in terms of a change in output for a unit or any given percentage change in the input variable value, the direction or sign of the change is especially useful to note. Nominal range sensitivity analysis works best with linear models where rank orders can be easily established based on this measure of sensitivity. In nonlinear models, output sensitivities may depend on interactions with other inputs that may not always be obvious and therefore cannot be placed in a rank order.

This method is easy to use. It is most reliable: when assessors have a good idea of the plausible range of input values; in linear models when the effect of a one-unit change in an input does not depend on the starting value of the input; and when there is no significant interaction of the chosen input with other input variables. When interactions are possible among variables, this method is likely to produce an inadequate description of the range of possible input values and, therefore, output responses.

To illustrate this technique, consider the quantity of pipeline dredge material in reach 1 from the cost estimation case study in (cell B20) [Table 17.2](#). What happens to total costs if that quantity increases 20%? [Table 17.3](#) shows the effect of a 20% increase in the reach 1 dredging quantity on total project costs. Only the reach 1 dredging cost line is shown as it is the only change in the model inputs.

A 20% increase in this one input causes total project cost to rise by \$365,000, a 1.9% increase in total project cost. Note that the simple nature of this example renders the one-unit change in the input (from 576,107 to 576,108 CY) a trivial exercise. Every cubic yard costs the same \$2.78 in the model. The \$320,000 change increases to \$365,000 to reflect allowances for AED and CM.

The input changes investigated may be percentages of a value, like the 20% increase used here, or specific values of interest can be chosen. For example, we might ask what happens to total project costs if the dredging quantity in reach 1 rises to 750,000 CY. This process can be repeated for as many individual inputs as desired.

TABLE 17.3
One-At-A-Time Analysis Example for Dredging Cost Estimate

Description	Quantity	Unit	Unit Price	Amount	Change
Original Estimate					
Pipeline Dredging, Reach 1	576,107	CY	\$2.78	\$1,601,577	NA
Total Project Cost				\$19,141,576	NA
20% Increase in Reach 1 Quantity					
Pipeline Dredging, Reach 1	691,328	CY	\$2.78	\$1,921,893	\$320,316
Total Project Cost				\$19,506,736	\$365,160

It is easy to see that two or more inputs could be varied simultaneously in a similar fashion. This is a simple method, but it is tedious.

Palisade Corporation's TopRank 7.5 (see Appendix A for details on the use of this software) can be used to conduct both a one-way what-if analysis and a multiway what-if analysis. This is done by allowing the assessor to vary a fixed-point estimate of an input by some plus or minus percentage. To demonstrate this technique, vary every variable input in the model (excluding the percentages for engineering design and construction management and the number of mobilization and demobilizations of equipment, cell B19) by $\pm 20\%$.

Allowing each input to change one at a time, first by its minimum and then by its maximum value, we see which inputs have the greatest potential impact on total project cost in [Table 17.4](#). Only the top ten inputs are shown. The table identifies the input by name and location in the model. This name is chosen automatically by the software. The first input is the quantity of pipeline dredging material in reach 3a. It is found in cell B22 of the model. When it assumes its minimum value of 946,250 CY, total project cost is \$18,289,383, a decrease of 4.45%. When the maximum of 1,419,375 CY is substituted into the model, costs rise to \$19,993,769, an increase of 4.45%. The table shows the top ten most influential inputs. The software output evaluates every input one-at-a-time, so that if you are interested in the effect of a specific input you can find it readily. A graphic display of this result is shown under the discussion of graphic sensitivity techniques.

It is often common practice to build models initially using plausible values or point estimates of expected values. In a complex model there could be dozens or even hundreds of inputs. Many models lack the transparent simplicity of our example. When that is the case, the risk assessor may not want to go to the time and trouble to bound each input or to specify a probability distribution to use for each model input if it has little or no effect on the model output(s) of interest. A one-way what-if analysis (equivalent to OAATA) will quickly identify those inputs that the assessor ought to focus attention on when considering the effects of uncertainty.

Presuming no more data than the values shown in [Table 17.2](#), the OAATA summarized in [Table 17.4](#) provides the assessor with a clear identification of the inputs with the most significant impact on total cost. [Table 17.5](#) goes one step further

TABLE 17.4
Top Ten Inputs from a One-Way What-If Analysis for the Total Project Cost Output

Rank	Input Name	Cell	Minimum			Maximum		
			Output		Input Value	Output		Input Value
			Value (\$)	Change (%)		Value (\$)	Change (%)	
1	Pipeline Dredging, Reach 3A/ Quantity (B22)	B22	18,289,383	-4.45	946250.4	19,993,769	4.45	1419375.6
2	CY/Price (D22)	D22	18,289,383	-4.45	2.528	19,993,769	4.45	3.792
3	Geotubes, 45', Reach 3/Quantity (B28)	B28	18,435,417	-3.69	11152	19,847,735	3.69	16728
4	LF/Price (D28)	D28	18,435,417	-3.69	177.744	19,847,735	3.69	266.616
5	Pipeline Dredging, Reach 2/Quantity (B21)	B21	18,535,279	-3.17	818215.2	19,747,874	3.17	1227322.8
6	CY/Price (D21)	D21	18,535,279	-3.17	2.08	19,747,874	3.17	3.12
7	Pipeline Dredging, Reach 3B/ Quantity (B23)	B23	18,677,977	-2.42	589370.4	19,605,175	2.42	884055.6
8	CY/Price (D23)	D23	18,677,977	-2.42	2.208	19,605,175	2.42	3.312
9	Pipeline Dredging, Reach 1/Quantity (B20)	B20	18,776,416	-1.91	460885.6	19,506,736	1.91	691328.4
10	CY/Price (D20)	D20	18,776,416	-1.91	2.224	19,506,736	1.91	3.336

Note: Top ten inputs ranked by percent change.

by showing additional percentage changes in the model inputs. The ranking of inputs is identical to that seen in [Table 17.4](#). Here you see that the software enables you to examine a change of $\pm 20\%$ and $\pm 10\%$ in the same analysis. These expanded results support spider plots, which are discussed in section 17.3.4.3.

Analyses like those seen in the tables can be prepared for a variety of ranges of change in the input values. They need not be $\pm 20\%$ and the number of increments can vary from the five used for this example. In a linear model this produces a reliable indication of those inputs to which the model output will be most sensitive. If your assessment model has multiple outputs, a separate OAATA must be performed for each output. These results are a valuable guide for handling uncertainty in subsequent iterations of the model. This kind of analysis helps the risk assessor understand which uncertainties have the greatest influence on output quantities of interest. With this information the assessor can prioritize data gaps and future research needs.

TABLE 17.5
An Expanded One-Way What-If Analysis for the Total Project Cost Output

Input Name	Cell	Step	Input Variation			Output Variation		
			Value	Change	Change (%)	Value (\$)	Change (\$)	Change (%)
Pipeline Dredging, Reach 3A/ Quantity (B22)	B22	1	946250.4	-236562.6	-20.00	18,289,383	(852,193)	-4.45
		2	1064531.7	-118281.3	-10.00	18,715,479	(426,097)	-2.23
		3	1182813	0	0.00	19,141,576	(0)	0.00
		4	1301094.3	118281.3	10.00	19,567,673	426,097	2.23
		5	1419375.6	236562.6	20.00	19,993,769	852,193	4.45
CY/Price (D22)	D22	1	2.528	-0.632	-20.00	18,289,383	(852,193)	-4.45
		2	2.844	-0.316	-10.00	18,715,479	(426,097)	-2.23
		3	3.16	0	0.00	19,141,576	(0)	0.00
		4	3.476	0.316	10.00	19,567,673	426,097	2.23
		5	3.792	0.632	20.00	19,993,769	852,193	4.45
Geotubes, 45; Reach 3/Quantity (B28)	B28	1	11152	-2788	-20.00	18,435,417	(706,159)	-3.69
		2	12546	-1394	-10.00	18,788,496	(353,080)	-1.84
		3	13940	0	0.00	19,141,576	(0)	0.00
		4	15334	1394	10.00	19,494,646	353,080	1.84
		5	16728	2788	20.00	19,847,735	706,159	3.69
LF/Price (D28)	D28	1	177.744	-44.436	-20.00	18,435,417	(706,159)	-3.69
		2	199.962	-22.218	-10.00	18,788,496	(353,080)	-1.84
		3	222.18	0	0.00	19,141,576	(0)	0.00
		4	244.398	22.218	10.00	19,494,646	353,080	1.84
		5	266.616	44.436	20.00	19,847,735	706,159	3.69
Pipeline Dredging, Reach 2/Quantity (B21)	B21	1	818215.2	-204553.8	-20.00	18,535,279	(606,297)	-3.17
		2	920492.1	-102276.9	-10.00	18,838,427	(303,149)	-1.58
		3	1022769	0	0.00	19,141,576	(0)	0.00
		4	1125045.9	102276.9	10.00	19,444,725	303,149	1.58
		5	1227322.8	204553.8	20.00	19,747,874	606,297	3.17
CY/Price (D21)	D21	1	2.08	-0.52	-20.00	18,535,279	(606,297)	-3.17
		2	2.34	-0.26	-10.00	18,838,427	(303,149)	-1.58
		3	2.6	0	0.00	19,141,576	(0)	0.00
		4	2.86	0.26	10.00	19,444,725	303,149	1.58
		5	3.12	0.52	20.00	19,747,874	606,927	3.17
Pipeline Dredging, Reach 3B/ Quantity (B23)	B23	1	589370.4	-147342.6	-20.00	18,677,977	(463,599)	-2.42
		2	663041.7	-73671.3	-10.00	18,909,777	(231,799)	-1.21
		3	736713	0	0.00	19,141,576	(0)	0.00
		4	810384.3	73671.3	10.00	19,373,375	231,799	1.21
		5	884055.6	147342.6	20.00	19,605,175	463,599	2.42

(Continued)

TABLE 17.5 Continued
An Expanded One-Way What-If Analysis for the Total Project Cost Output

Input Name	Cell	Step	Input Variation			Output Variation		
			Value	Change	Change (%)	Value (\$)	Change (\$)	Change (%)
CY/Price (D23)	D23	1	2.208	-0.552	-20.00	18,677,977	(463,599)	-2.42
		2	2.484	-0.276	-10.00	18,909,777	(231,799)	-1.21
		3	2.76	0	0.00	19,141,576	(0)	0.00
		4	3.036	0.276	10.00	19,373,375	231,799	1.21
		5	3.312	0.552	20.00	19,605,175	463,599	2.42
Pipeline Dredging, Reach 1/Quantity (B20)	B20	1	460885.6	-115221.4	-20.00	18,776,416	(365,160)	-1.91
		2	518496.3	-57610.7	-10.00	18,958,996	(182,580)	-0.95
		3	576107	0	0.00	19,141,576	(0)	0.00
		4	633717.7	57610.7	10.00	19,324,156	182,580	0.95
		5	691328.4	115221.4	20.00	19,506,736	365,160	1.91
CY/Price (D20)	D20	1	2.224	-0.556	-20.00	18,776,416	(365,160)	-1.91
		2	2.502	-0.278	-10.00	18,958,996	(182,580)	-0.95
		3	2.78	0	0.00	19,141,576	(0)	0.00
		4	3.058	0.278	10.00	19,324,156	182,580	0.95
		5	3.336	0.556	20.00	19,506,736	365,160	1.91

As we have cautioned, there may be times when it does not make sense to vary one input at a time. The desired changes in a model can always be made manually, but this is very limiting, especially when the assessor would like to explore the sensitivity of model outputs to the many different inputs. TopRank offers the capability to conduct multi-way what-if analysis. As with the one-way analysis, the assessor can choose a percentage by which to vary the inputs, identify which variables to consider in a multiway analysis, and how many to consider at a time. An examination of all possible combinations of two-at-a-time variable inputs is summarized for the cost estimate in [Table 17.6](#). This shows the top five input combinations from the model.

The report shown provides the results of an analysis of the extremes, i.e., when both inputs assume their minimum values and when both inputs assume their maximum values. It should come as no surprise that the ranking of paired variables mirrors the results of the OAATA. Detailed outputs are provided by TopRank for the multi-way what-if analysis, so that additional pairs of inputs and additional combinations of values (%) can be explored.

17.3.2.2 Difference in Log-Odds Ratio (Δ LOR)

A specific application of the nominal range sensitivity methodology is the log-odds ratio method. This mathematical methodology can be used when the output of interest is a probability. That means our cost example does not lend itself to this method, so we will briefly switch to a different example. First, we need to understand the method.

TABLE 17.6
Top Five Inputs from a Two-at-a-Time Multiway What-If Analysis for Total Project Cost

Rank	Multi-Way Name	Output Variation			
		Minimum		Maximum	
		Value (\$)	Change (%)	Value (\$)	Change (%)
1	Pipeline Dredging, Reach 3A/ Quantity [B22] CY/Price [D22]	\$17,607,628	-9.79%	\$21,016,401	9.79%
2	Pipeline Dredging, Reach 3A/ Quantity [B22] Geotubes, 45', Reach 3/Quantity [B28]	\$17,583,224	-8.14%	\$20,699,928	8.14%
3	Pipeline Dredging, Reach 3A/ Quantity [B22] LF/Price [D28]	\$17,583,224	-8.14%	\$20,699,928	8.14%
4	CY/Price [D22] Geotubes, 45', Reach 3/Quantity [B28]	\$17,583,224	-8.14%	\$20,699,928	8.14%
5	CY/Price [D22] LF/Price [D28]	\$17,583,224	-8.14%	\$20,699,928	8.14%

Note: Top five inputs ranked by percent change.

The odds ratio or odds of an event is simply $\frac{P(A)}{1 - P(A)}$ or, in words, it is the ratio of the probability that the event occurs to the probability that the event does not occur (Gordis 1996). The log of the odds ratio or logit simply takes the log of the odds ratio, i.e., $\text{logit} = \log \frac{P(A)}{1 - P(A)}$.

With this definition ΔLOR can be defined as follows:

$$\Delta\text{LOR} = \log \left(\frac{\frac{P(A)}{1 - P(A)}}{\frac{P(B)}{1 - P(B)}} \right) \tag{17.1}$$

Which simplifies to:

$$\Delta\text{LOR} = \log \left(\frac{P(A)}{1 - P(A)} \right) - \log \left(\frac{P(B)}{1 - P(B)} \right) \tag{17.2}$$

Or

$$\Delta\text{LOR} = \text{logit } P(A) - \text{logit } P(B) \tag{17.3}$$

If we now define event B to be the original probability estimate and event A is the probability recalculated with changes in the sensitive input, then a positive ΔLOR means that a change in the selected input increases the probability of the event. A negative ΔLOR means that a change in the input decreases the probability of the event. The larger the ΔLOR value, the greater is the sensitivity of the probability output to changes in that input. ΔLOR is subject to many of the same limitations as the nominal range sensitivity when it comes to nonlinear models.

An example for a single variable is presented in the two event-tree models shown in Figure 17.6. This model represents a small boat harbor where shoaling has decreased the depth of the navigation channel. Vessels come into the harbor with oil and other commodities. Some vessels have drafts that exceed the controlling depth of the channel. This affects the probability of a marine casualty occurring. Casualties include groundings, allisions, and collisions.

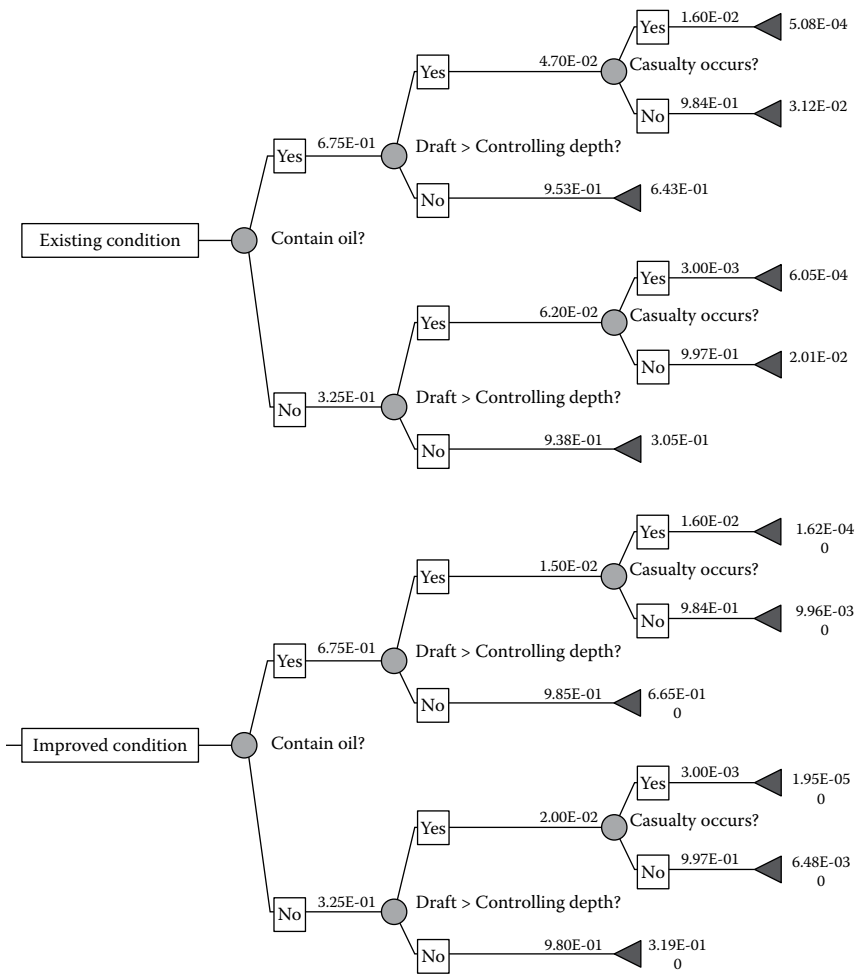


FIGURE 17.6 Example of event-tree models for the difference in log-odds ratio.

TABLE 17.7
Difference in Log-Odds Ratio Calculation

Condition	Probability		Ratio	Logit
	Casualty	No Casualty		
Existing	0.0006	0.9994	0.000568	-3.24537
Improved	0.0002	0.9998	0.000182	-3.74104

$$ALOR = \text{logit } P(A) - \text{logit } P(B) = -3.74 - (-3.25) = -0.5$$

The output of interest is the probability of a casualty. This is obtained by summing the relevant endpoint probabilities in each model. Note that there are two different scenarios here: an existing and an improved scenario. The improvement is considered to be maintenance dredging to increase the controlling dept of the channel. This alters several input values between the two scenarios, but it does not affect the possibility of a casualty.

Note that the model ends if the controlling depth of the channel is not a binding constraint. The assumption is not that these vessels have no casualties, but that the number and nature of the casualties will not be affected by dredging the channel. Note also that the only change captured in this model is the change in the probability that the controlling depths will be exceeded and the effect of this change on subsequent calculations in the models.

To calculate the $\Delta LOR = \text{logit } P(A) - \text{logit } P(B)$, the values shown in [Table 17.7](#) are obtained from the model. The probabilities of a casualty are sums of two model endpoints. The ratio of $P(\text{Casualty})/P(\text{No Casualty})$ is given in column 4. The log of these ratios is found in the last column. Subtracting the two produces the $\Delta LOR = -0.5$. The negative value means that dredging the channel, thereby decreasing the probability of a vessel exceeding the controlling depth, reduces the probability of a casualty.

In this simple computational example there is no other input to change to produce another ΔLOR value to compare to this one. In a more complex problem or model, there might be multiple model inputs to change that would influence the output probability of interest. Finding the control variable that has the largest desirable effect on the probability output via the ΔLOR is potentially a significant help to the risk manager. The largest absolute value of the ΔLOR would identify the sensitive input with the greatest impact by this method.

17.3.2.3 Break-Even Analysis

This mathematical method applies the familiar concept of breaking even to sensitivity analysis. The notion, borrowed from economics, is that at the break-even point we are indifferent to producing or not producing a good or service. The important idea here is to look for a break-even/cutoff/threshold value for a parameter or decision variable, i.e., a point where something interesting happens, such as, something goes negative, turns good, turns bad, equals zero, and the like. In a decision context, the break-even point is any value where a decision could change.

Applied as a sensitivity method, break-even analysis requires one to find values of inputs that provide a model output for which the risk manager is interested in the so-called break-even point. Such a breakeven point could influence the choice between accepting the risk or managing a risk, choosing option A or option B, and so on. Alternatively, a threshold might indicate a point at which the risk manager has a strong preference for one course of action over another.

The input value or combination of input values for which the risk manager is indifferent is called the switch-over or break-even value. Once the break-even input value(s) is determined, the risk manager must judge whether the most likely input values will lie above or below these break-even values. If an input's range of uncertainty includes the break-even point, that input is instrumental for decision making. In other words, it will not be clear which is the best decision because the switch-over point may or may not be exceeded. In that case, additional research or efforts to reduce the uncertainty may be necessary for a more confident decision. Conversely, if the uncertainty about an input does not include the break-even point, a decision can be made more confidently.

Finding these break-even values is a unique endeavor for each risk assessment; there is no generalized technique applicable to all models. It can be difficult to find these values when the number of sensitive inputs increases. There is also no clear ranking to be obtained from this method. Frey and Patil (2002) provide an example of a patient choosing between a medication and an operation that produces an iso-risk line for the utility of the medication versus the probability of success for an operation. The application of this technique can be sophisticated.

We can simplify here to aid understanding by returning to the dredging cost estimate. Suppose this project was to be constructed under a government program with a \$20-million budget cap. A modified application of this break-even method would be to calculate what the dredging quantity in reach 1, for example, would have to be before the threshold (break-even point) is passed. If dredging in that reach exceeds 846,972 cubic yards,* costs will exceed \$20 million. If our uncertainty about this input value is, say, from 500,000 to 900,000 cubic yards, then this quantity alone is sufficient to exceed the budget constraint, and the project may not be able to proceed. Risk assessors may be motivated to estimate the probability that the dredging quantity will equal or exceed this amount.

Risk managers would be well advised to do all they can to improve the estimate of the required dredging in this reach. It is not difficult to imagine that this technique can become tedious when multiple inputs are considered. It also does not lend itself readily to considering multiple inputs without the use of iso-risk lines.

17.3.2.4 Automatic Differentiation Technique

The automatic differentiation (AD) technique is a mathematical method that relies on the use of partial derivatives of outputs with respect to small changes in sensitive inputs to calculate local sensitivities. It is usually reserved for larger models. Because

* Costs are \$858,424 below the cutoff. At \$3.17 a CY (\$2.78 plus 14% for AED and CM), the dredging quantity would have to rise by $\$858,424/\$3.17 = 270,865$ CY to exceed the budget cap. The current estimate of 576,107 CY would rise by this amount.

these models are not always well-behaved systems of equations, differentiation often relies on numerical techniques that can be time consuming and difficult to calculate. In addition, they may yield inaccurate results. What makes mathematical AD techniques different is that they rely on precompilers that analyze the code of the model and then compile algorithms for computing first or higher order derivatives in an efficient and accurate manner.

This is a software-intensive technique that is not going to be available to most risk assessors. For more information on this technique, see the work of Bischof et al. (1992, 1994, 1996). Applications also can be found in the work of Carmichael, Sandu, and Potra (1997); Issac and Kapania (1997); Ozaki, Kimura, and Berz (1995); and others.

17.3.3 STATISTICAL METHODS FOR SENSITIVITY ANALYSIS

17.3.3.1 Regression Analysis

Regression analysis is one of the more common sensitivity methods used because simple linear regression sensitivities have been built into some of the commercially available risk assessment software packages. This statistical method can be a useful probabilistic sensitivity analysis technique.

There are many standard econometric textbooks that explain regression analysis techniques. In best practice, the assessor will specify a functional form for the cause-and-effect relationship between the output (dependent variable) and the relevant inputs (independent variables) based on sound theory. In a probabilistic risk assessment, a random sample of values for these variables will be obtained through some probabilistic analysis like a Monte Carlo simulation.

Using data from the simulation for inputs and outputs, a multiple regression model of the form

$$Y_i = \beta_0 + \beta_1 X_{1,i} + \dots + \beta_m X_{m,i} + \varepsilon_i \quad (17.4)$$

is estimated. The $X_{m,i}$ are the inputs, where m indicates the number of the individual input variable and i indicates the i th input data point. The Y_i indicates the i th output data point.

The beta values, β_m , are regression coefficients. Because they are estimated from a random sample, they are themselves random variables. When the beta coefficients are statistically significantly different from zero they provide a measure of the effect of the particular input variable X_m on Y , all other input variables being held constant. In fact, the β_m value shows the effect of a one-unit change in X_m on the output variable, when all the other input variables in the regression equation have been accounted for. This makes regression coefficients similar to the nominal range sensitivity technique in terms of interpretation, although it is a more sophisticated technique that can account for some nonlinearities in the model, if they can be transformed to a linear form. It also can handle variation among multiple assessment inputs.

Input variables with beta regression coefficients that lack a statistically significant difference from zero relationship with the output variable are not sensitive. Those with significant regression coefficients indicate a sensitivity. The regression coefficients

can be normalized over the [-1,1] interval to eliminate dimensional effects and to allow ranking based on the absolute value of the coefficient.

Some of the popular risk assessment software generates simple linear regressions as part of their sensitivity analysis package. A simple linear regression has only one independent (X) variable. The software will regress each input value against the same selected output using the ordinary least squares (OLS) estimation technique and rank them by normalized regression coefficients (β). If the output (dependent variable) is actually a function of several inputs (independent variables), this technique could violate one or more classical assumptions for OLS estimators (Studenmund 2006) and provide misleading results. Consequently, one should be wary of these built-in regression results.

Multiple regression techniques allow evaluation of the sensitivity of individual model inputs, taking into account the influence of other inputs on the output. The cost estimate model does not provide a very interesting example for this technique because it is so linear, so let us switch examples again for the moment. The example used for this demonstration is based on an FDA (2001) risk assessment entitled “The Human Health Impact of Fluoroquinolone Resistant *Campylobacter* Attributed to the Consumption of Chicken.” Fluoroquinolone (FQ) drugs had been administered to some domestic U.S. poultry at subtherapeutic doses. There was some evidence to suggest this was causing an increase in antibiotic resistance of *Campylobacter* to this drug. The risk hypothesis suggested that some consumers who were made ill by FQ-resistant *Campylobacter* in chickens would seek medical care and subsequently be prescribed FQ drugs, which would be ineffective against their illness. The FDA conducted a risk assessment to learn how many people may have been affected in this way.

Five input variables are used to estimate the number of people affected by this problem. They are the independent variables in the regression and are listed in Table 17.8. A sample of $n = 500$ values for each input and the output was obtained through a Monte Carlo simulation using the FDA model. A multiple regression was run with this sample using the number of people with *campylobacteriosis* seeking the care of a doctor and being administered FQ drugs for the dependent variable. The result in Table 17.8 shows all independent variables, but the proportion of sick people seeking care from a doctor have effects that are statistically significantly different from zero. The beta coefficients have not been normalized over the [-1,+1] interval because all inputs have the same metric units, so the usual coefficients provide a ranking.

TABLE 17.8
Regression Results

Regression	Coefficient	p-Value
Constant	-25,523	<0.0001
Proportion of <i>Campylobacter</i> cases associated with chicken	171	<0.0001
Proportion of FQ resistant <i>Campylobacter</i> infections from chicken	538	<0.0001
Proportion sick seeking care	129	0.1164
Proportion treated with antibiotic	91	0.0029
Proportion receiving FQ treatment	189	<0.0001

Table 17.8 shows that a 1% increase in the proportion of FQ-resistant *Campylobacter* infections from chicken has the potential to affect an average of 538 people, with all other inputs held constant. This makes it the most sensitive input of those investigated.

Using simple (one independent variable) linear regression can produce less reliable results. In addition, the built-in software features may fail to select important intermediate calculations as inputs. In general, these software features identify inputs as those spreadsheet cells that have been assigned a probability distribution. We will return to this simple regression technique and the cost estimation example when we consider graphical sensitivity analysis techniques.

17.3.3.2 Correlation

Correlation is a statistical method used to determine whether two variables (an input and an output) tend to move together. If above-mean values of one variable are associated with above-mean values of the other, and vice versa, there is a positive correlation. A negative correlation results when above-mean values of one variable are associated with below-mean values of another variable.

The Pearson correlation coefficient is a numerical value between -1 and 1 . The sign of the coefficient indicates whether the association is a positive one or a negative one. The size of the coefficient indicates the strength of the association. The top row of Figure 17.7 shows negative correlations with coefficients of -1 , -0.5 , and -0.25 . The bottom row shows positive correlations of 0.8 , 0.5 , and 0.25 . Note that as the absolute value approaches 1, the cloud of points approaches a straight line.

Data from a simulation that produces a sample of input and output values can be used to calculate correlation coefficients. This is a feature on some simulation software. Correlation is not causation, and correlation coefficients are best understood when accompanied by a scatter plot like those in Figure 17.7. In general, inputs that are highly correlated with the output are of potential interest in a sensitivity analysis.

For a correlation example, let us return to our cost estimate example. A 10,000-iteration simulation of costs produced the characterization of the possible costs of dredging the waterway and creating wetlands with the dredged material seen in Figure 17.8.

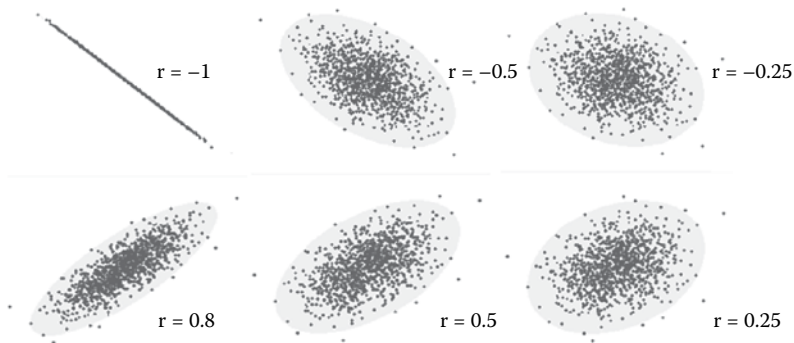


FIGURE 17.7 Selected scatter plots and Pearson correlation coefficient examples.

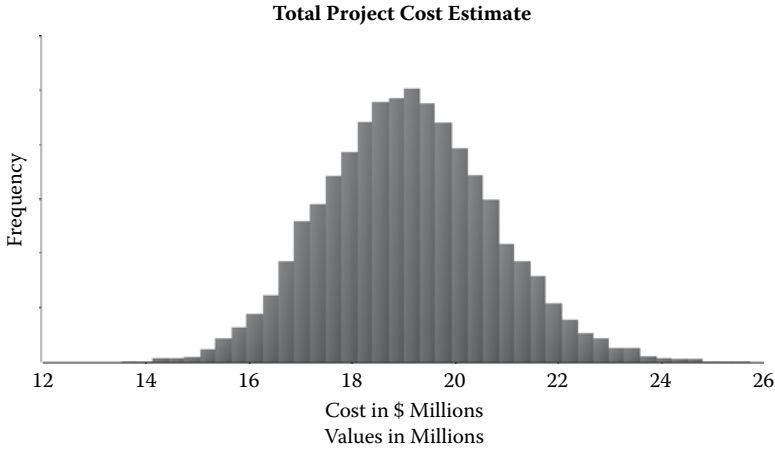


FIGURE 17.8 Distribution of dredging cost estimates.

The simulation had 20 variable inputs and a single output. @RISK 7.5’s built-in simulation sensitivity produced Spearman rank correlation coefficients for each input-output pair as shown in Table 17.9.

This technique indicates that the total project cost is most highly correlated to the price of 45-foot diameter geotubes in reach 1, followed by the dredging quantity to be removed from reach 3A. Thus, any efforts to reduce uncertainty in these variables would produce a more reliable cost estimate. This sensitivity analysis can be equally useful at times in identifying variables that are of no special concern. Variables with low correlation coefficients can be treated as point estimates with no loss of fidelity. You need not develop probability distribution estimates for every uncertain input.

TABLE 17.9
Importance Analysis of Cost Estimate Inputs Using Spearman Rank Correlation Coefficient

Rank Four Output	Cell	Name	Spearman Correlation Coeff.
1	E26	Price of Reach 1 45’ Geotube	0.529
2	C22	Quantity Pipeline Dredging, Reach 3A	0.406
3	E24	Price of Reach 1 Scour Pad	0.4
4	C21	Quantity Pipeline Dredging, Reach 2	0.325
5	E22	Price per CY Reach 3A	0.297
6	E21	Price per CY Reach 2	0.208
7	C20	Quantity Pipeline Dredging, Reach 1	0.164
8	E23	Price per CY Reach 3B	0.145
9	E20	Price per CY Reach 1	0.133
10	C23	Quantity Pipeline Dredging, Reach 3B	0.091

The cruel irony is that you may not know this until after you have done so and conducted this kind of sensitivity analysis.

17.3.3.3 Analysis of Variance

Analysis of variance (ANOVA) is another statistical method that is a model-independent probabilistic sensitivity analysis method. It is used to determine if there is a statistical association between an output and one or more inputs. Unlike regression analysis, ANOVA requires no assumption about the functional form of the relationships between inputs and the outputs.

Inputs are called “factors.” Values of quantitative factors and categories of qualitative variables are called factor levels. The output is called a “response variable.” Single-factor and multifactor ANOVA are options for the analyst. ANOVA is used to determine if values of the output vary in a statistically significant manner associated with variation in values for one or more inputs. If variation in the output is not statistically significant with respect to the input(s), then it is considered random. There are somewhat stringent assumptions required to validate the ANOVA process. If these assumptions are violated, corrective measures must be taken to address the problem. ANOVA is a technique preferred by certain disciplines. It is a topic that can be found in most standard statistics texts. Warner (2008) has an especially detailed and helpful treatment of the topic.

17.3.3.4 Response-Surface Method (RSM)

The response-surface method (RSM) is a statistical technique used to estimate the relationship between a response variable (output) and one or more explanatory inputs. It is a complex method. Think of it as the graph of a surface in n -space that identifies curvatures in this space by accounting for second-order effects that enable assessors to observe the effect on the output given selected effects in one or more inputs.

It is best to limit the number of inputs so as to limit the size of n -space. Therefore, RSM is best used after other sensitivity screening methods have identified the most important inputs. Frey and Patil (2002) suggest Monte Carlo simulation methods can be used to generate multiple values of each model input and the corresponding output, and then a least squares regression method is used to fit a standardized first- or second-order equation to the data obtained from the original model. If the classic assumptions of least squares regression are not satisfied, other techniques such as rank-based or nonparametric approaches should be used (Khuri and Cornell 1987, Vidmar and McKean 1996).

A response surface can be linear or nonlinear. Think of it as a “model of a model.” Once generated, it is often easier to conduct sensitivity analysis of the response surface than it is of the original model. The sensitivity analysis of the response-surface analysis is often simpler and faster to execute than sensitivity analysis of the original model. This means that computationally intensive sensitivity analysis methods, such as Mutual Information Index (Finn 1993) or others, may be more readily applied to the response surface than to the original model. Applications of the RSM can be found in Gardiner and Gettinby (1998); Moskowitz (1997); Hopperstad et al. (1999); Williams, Varahramyan, and Maszara (1999); and others. This is not a technique that many risk assessors are likely to use due to its complexity.

17.3.3.5 Fourier-Amplitude Sensitivity Test

The Fourier amplitude sensitivity test (FAST) is a statistical method that can be used for both uncertainty and sensitivity analysis (Cukier et al. 1973, 1975, 1978). It is not for beginners. FAST is used to estimate the contribution of individual inputs to the variance of the output. It is independent of any assumptions about model structure. Assessors can study the effect of single or multiple inputs using FAST.

Frey and Patil (2002) describe the method as relying on a transformation function used to convert values of each model input to values along a search curve. The transformation specifies a frequency for each input, and using Fourier coefficients, the variance of the output is evaluated. The contribution of each input observation (x_i) to the total variance is also calculated based on the Fourier coefficients, fundamental frequency, and higher harmonics of the frequency, as explained by Cukier et al. (1975). The ratio of the contribution of each input to the output variance and the total variance of the output can be calculated and used to rank the inputs (Saltelli, Chan, and Scott 2000).

The model needs to be evaluated at enough points in the input parameter space that numerical integration can be used to determine the Fourier coefficients (Saltelli et al. 2000). For applications, see Lu and Mohanty (2001), Helton et al. (2000), and Rodriguez-Camino and Avissar (1998).

17.3.3.6 Mutual Information Index

The mutual information index (MII) is a statistical sensitivity analysis method that produces a measure of the information about the output provided by a specific input. The MII is based on conditional probabilistic analysis. The magnitude of the MII for different inputs can be compared to determine which inputs provide useful information about the output. This is a computationally intensive method typically used for models with dichotomous outputs.

Frey and Patil (2002) describe MII as typically involving three steps: (1) generating an overall confidence measure of the output value; (2) obtaining a conditional confidence measure for a given value of an input; and (3) calculating sensitivity indices (Critchfield and Willard 1986a, 1986b). The cumulative distribution function (CDF) of the output is used to estimate the overall confidence in the output, where confidence is the probability of the dichotomous outcome of interest. The conditional confidence is estimated by holding one input constant at some value and varying all other inputs. The new resulting CDF of the output is a measure of the assessor's confidence in the output conditioned on the particular value of the input used to generate it.

The mutual information between two random variables is the amount of information about a variable that is provided by the other variable (Jelinek 1970). In other words, it is a quantity that measures the mutual dependence of the two variables. A description of the calculation of the MII is found in Frey and Patil (2002).

Critchfield and Willard (1986a, 1986b) devised and demonstrated the application of the MII method using a decision-tree model. MII includes a more direct measure of the probabilistic relatedness of two random variables than correlation coefficients, and it can account for the joint effects of all inputs when evaluating sensitivities of an input. It is computationally complex and difficult to apply. It is not one of the more commonly applied sensitivity analysis methods.

17.3.4 GRAPHICAL METHODS FOR SENSITIVITY ANALYSIS

17.3.4.1 Scatter Plots

Scatter plots, shown earlier in [Figure 17.7](#), can be used to visually assess the influence of individual inputs on an output. A Monte Carlo simulation, for example, can generate many input-output pairs, which when plotted can reveal potentially sensitive associations between these variables. Linear or nonlinear patterns, which may be observed, could depict potential dependencies between an input and an output.

There need to be enough points to show a pattern but not so many as to obscure the variability in the scatter. Pattern detection methods can be applied to help identify relationships between inputs and outputs (Kleijnen and Helton 1999, Shortencarier and Helton 1999). Applications are found in Sobell et al. (1982); Rossier, Wade, and Murphy (2001); Hagent (1992); Fujimoto (1998); Helton et al. (2000); and others.

When you have completed a probabilistic risk assessment, it can be helpful to plot the scatter plot for each input-output relationship as a first step in the sensitivity analysis of your statistical sample. It is a useful screening mechanism, but it can become quite tedious if the model has large numbers of inputs and outputs. When a pattern is evident, more rigorous sensitivity analysis is warranted.

For an example, consider the cost estimate again. Earlier, the Spearman rank correlation coefficient identified the price of 45-foot diameter geotube as a significant source of variation in the output. A plot of 500 data points from the 10,000-iteration simulation in [Figure 17.9](#) shows a clear positive relationship between geotube cost/ft. and total project cost. Note that this correlation coefficient is a Pearson correlation and that it differs from the Spearman value often produced by commercial software packages.

17.3.4.2 Tornado Plots

Tornado graphs are a variation of a bar graph. They are used to show the relative sensitivity of an output to uncertain (or variable) inputs. They normally display a vertical zero-point axis when sensitivity is measured by a correlation or normalized regression coefficient. Bars extending to the right of this axis indicate a positive relationship with the selected output; bars extending to the left of the zero axis indicate a negative relationship.

The length of the bar indicates the relative strength of the positive or negative relationship. It is often measured as a normalized regression coefficient, when the sensitivity is based on a normalized simple linear regression between an individual input and the selected output, or it may be measured by a correlation (Spearman or Pearson) coefficient.

The example shown in [Figure 17.10](#) begins with the distribution of total project costs. There is about a \$12-million range in the cost estimate outputs. To learn what contributes most to this variation, a regression analysis or correlation sensitivity method must first be completed and its results plotted, as shown in the bottom graph of [Figure 17.10](#). This tornado plot is based on normalized beta coefficients from a sequence of simple linear regressions. There are no inputs that decrease cost.

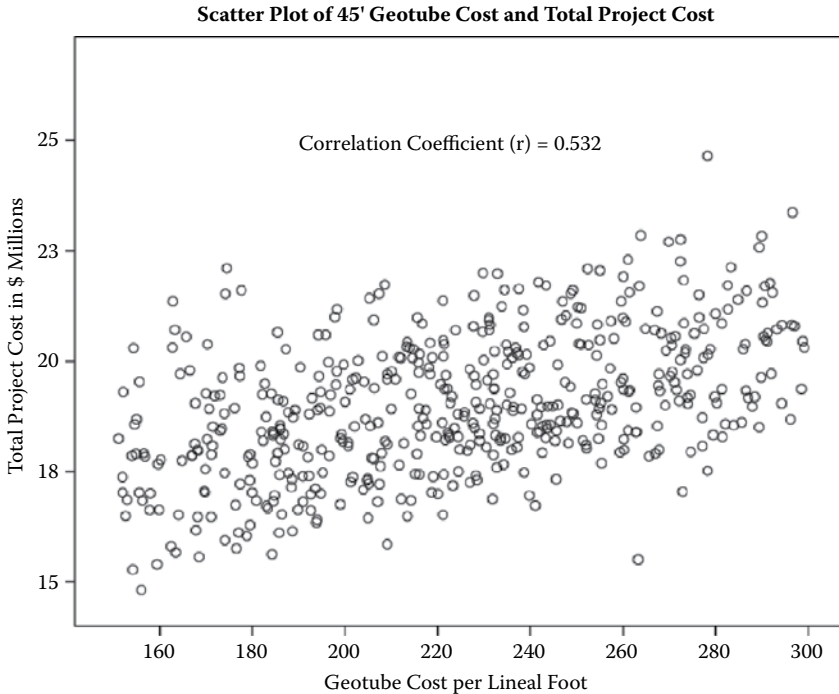


FIGURE 17.9 Scatterplot of total project cost and the price of a 45-foot-diameter geotube.

In this instance, the price of 45-foot geotubes is at the top of the list.* A tornado chart can be prepared for each model output of interest to risk managers. This statistical sensitivity analysis, which is based on data from a Monte Carlo process, yields different results than our initial OAATA did, as we should expect. These are all tools that require professional judgment. The price of 45-foot geotubes was not the most significant input during the OAATA analysis, although it was near the top. Had an assessor decided not to pursue the quantification of the uncertainty around that value, it would have been an error. We need to take into account not only the structure of the model, which OAATA did reasonably well, but also the magnitude of the uncertainty. As it turned out, the cost estimators were less certain about the price of the large geotubes than about most other inputs, i.e., the input varied by more than $\pm 20\%$.

Let us return, briefly, to our OAATA analysis and consider another form of the tornado graph. Figure 17.11 shows a tornado graph prepared using a nominal range sensitivity (one-way what-if analysis) based on point estimates rather than a Monte Carlo process using probability distributions for the inputs.

* If you are curious why these results are different from the OAATA results, recall that that is a mathematical method based on point estimates for each input. This is a statistical one that is based on the expression of each input value as a probability distribution. The actual uncertainty among the inputs is more variable than the $\pm 20\%$ used for each input in the OAATA.

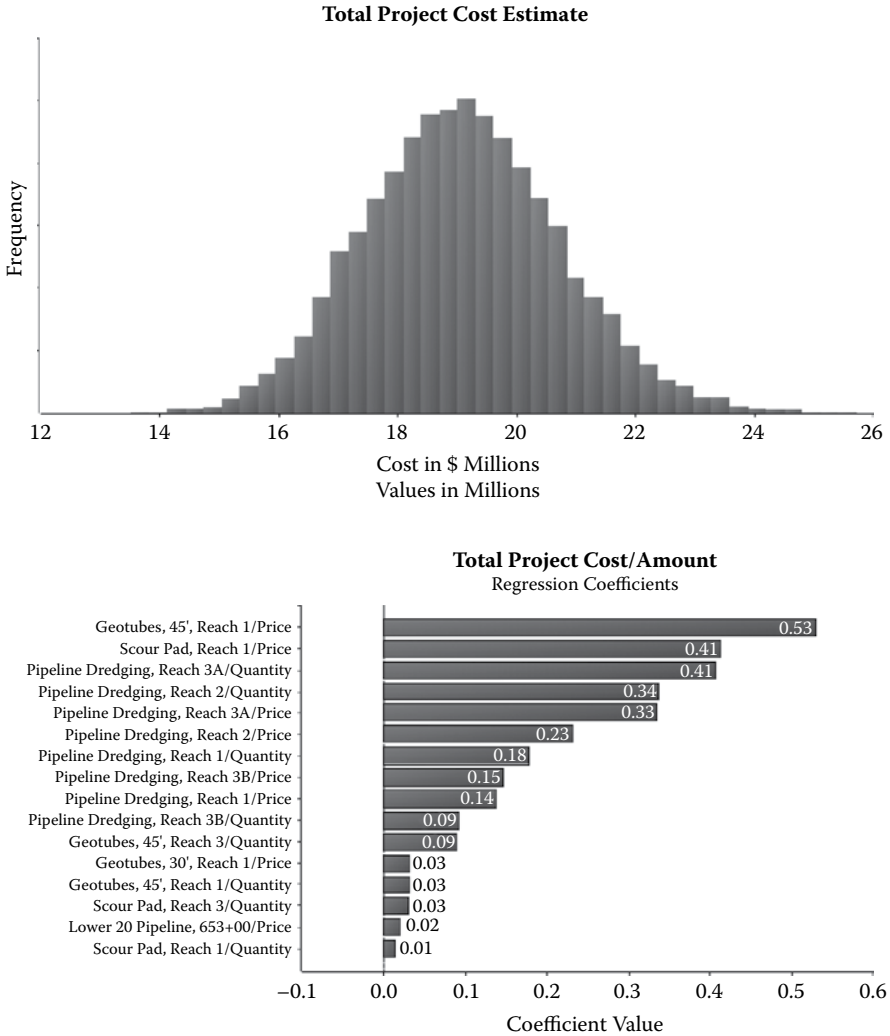


FIGURE 17.10 Total project cost distribution with a regression-based tornado chart.

In this particular graph, the inputs on the left were allowed to vary by $\pm 20\%$. The impact of this variation on total project costs is shown on the horizontal axis of the graph. In this graph, the impact is measured as a percentage. It could have just as easily been measured in actual costs, with the deterministic cost estimate as the center of the graph instead of 0%. The length of the bar indicates the amount of change the input caused to the output measured as a percentage. The input with the largest effects (and longest bar) is shown at the top, and those with less impact are shown below. The diminishing influence of less significant inputs produces the tornado shape. Note that geotube prices are listed third on the tornado chart.

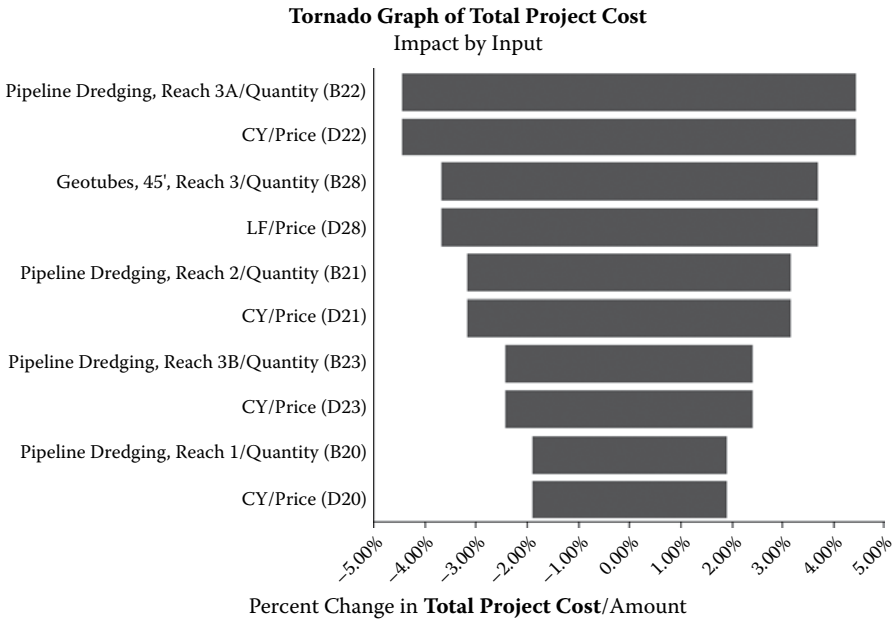


FIGURE 17.11 OAATA tornado graph for total project cost.

17.3.4.3 Spider Plot

Figure 17.12 shows a sensitivity graph. It shows the relationship between the quantity of dredged material in reach 3a and total project cost. The horizontal axis shows input changes of -20% , -10% , 0% , 10% , and 20% . The vertical axis shows the corresponding effect on total project costs. This is essentially the data from an analysis like that in Table 17.5.

A spider plot is a collection of multiple sensitivity graphs. The spider plot is an alternative way of visualizing effects of inputs on outputs that is useful for models with fixed-point inputs. It relies on the nominal range sensitivity method to generate data for the plot. Variation in input effects often creates a spiderlike spread of effects about the no-change point (0% , 0%). An example is shown in Figure 17.13.

For each input, the percentage change in its value from the fixed-point estimate (base case) is plotted on the x -axis, and the percentage change in the output is plotted on the y -axis. Lines that are higher to the right of the no-change (0%) point indicate inputs with a greater impact on the output under investigation. Conversely, lines that lie highest to the left of the no-change point have the least impact on the output. This figure is showing that a 20% change in the cost of dredging in reach 3a causes over a 4% change in total project cost, making it the most sensitive input in the spider plot. This is the same result reported numerically earlier in the chapter.

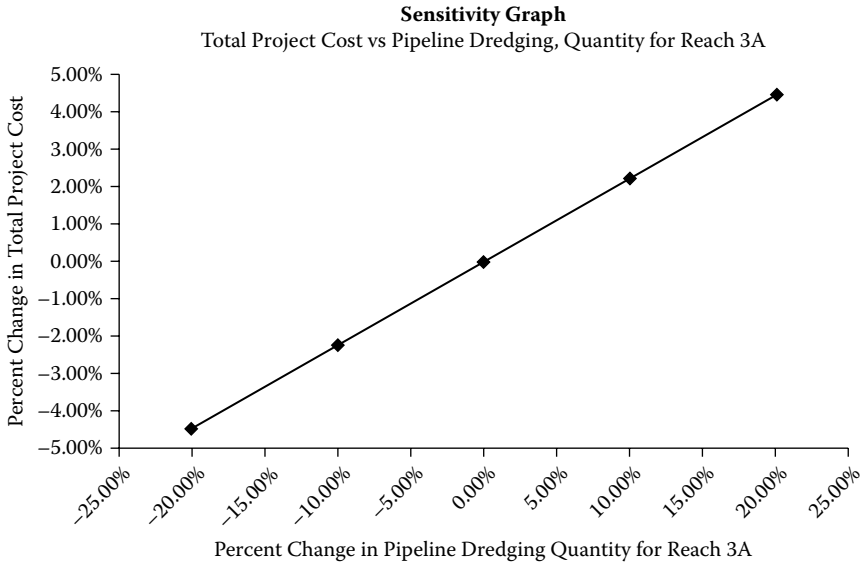


FIGURE 17.12 Sensitivity graph.

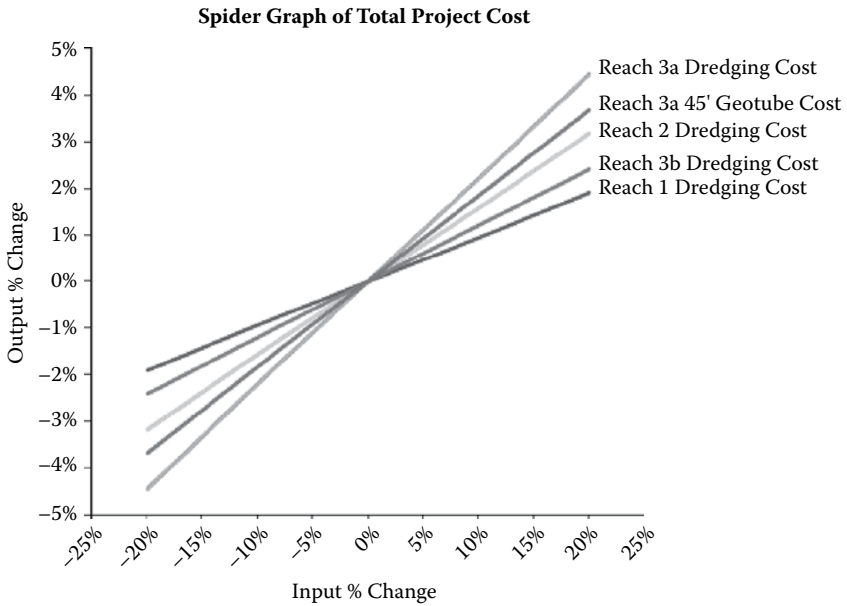


FIGURE 17.13 Spider plot for total project cost.

17.4 THE POINT

The point of doing sensitivity analysis does not end with the identification of your most sensitive inputs. Finding out what your most significant uncertainties are is an important part of a sensitivity analysis. The real purposes of a sensitivity analysis, however, are to help develop a plan for addressing the instrumental uncertainty to inform decision makers about the significance of uncertainty for decision making.

Nominal range sensitivity, for example, can be used early in a risk assessment to help identify those variables for which the most effort should be made to describe the uncertainty. It is not always necessary, as mentioned earlier, to enter every uncertain input as a probability distribution. Some of these techniques can suggest which variables to concentrate on.

When risk managers are presented with output distributions like the one in [Figure 17.14](#) for costs, it is helpful to be able to explain why there is so much variation in the output upon which they will base their decisions. Furthermore, if we can present risk managers with options for further reducing the instrumental uncertainties, the sensitivity analysis adds even more value to the risk assessment. If we assume a budget cap on project cost of \$20 million we see a 28.3% the cap will be exceeded. Sensitivity analysis can be used to identify the circumstances most likely to result in a cost over \$20 million. Managers then can choose to reduce the uncertainty or to make a decision based on the available information.

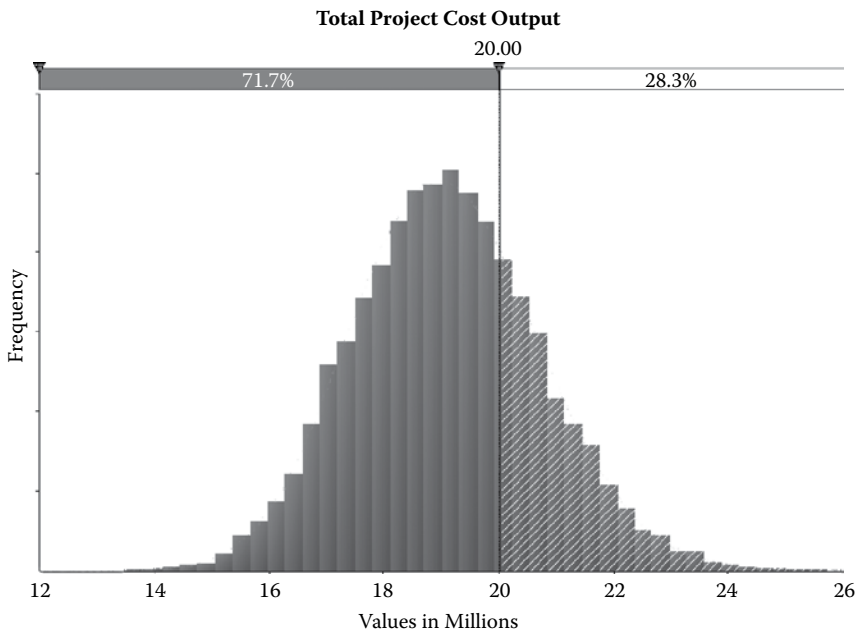


FIGURE 17.14 Distribution of total project cost estimates.

The best risk assessments will be subjected to sensitivity analysis that will discover the most important input variables. This helps everyone understand what contributes most to good and bad outcomes. Once these important variables have been identified, risk assessors should address the uncertainty systematically, by varying assumptions and examining their effects on outcomes, using one or more of the techniques here, or of course, by doing a probabilistic risk assessment. Good risk assessment fixes what can be fixed and addresses what can be addressed. If variation due to knowledge uncertainty can be reduced, risk managers may choose to do so. To the extent that the variation in output is attributable to natural variability, sensitivity analysis can help assessors describe that variability.

Risk managers need to understand the instrumental uncertainties that could influence their decisions. When a decision is sensitive to changes or uncertainties within the realm of possibility, then more precision and additional information may be required. In addition, they need to understand the potential quality of the risk management options they are considering. Thus, it is helpful, when conducting a sensitivity analysis, to identify sensitive inputs that are controllable, especially decision variables. When sensitivity analysis identifies those inputs with the greatest positive and negative effects on outputs as well as which of those we can influence, it adds value to risk assessment.

Consider a sensitivity analysis that suggests that the price of 45-foot geotubes is a significant source of output uncertainty. This could provide the impetus for an estimator to contact manufacturers of these tubes for a more reliable price quote. Sometimes sensitivity analysis can suggest new risk management options. For example, the uncertainty attending this cost estimate might be managed through an innovative futures contract arrangement. The responses to a good sensitivity analysis can influence both risk assessment and risk management.

17.5 SUMMARY AND LOOK FORWARD

Good risk assessment, whether qualitative or quantitative, must include some sensitivity analysis. Examining the effects of varying the assessor's assumptions should always be included in every sensitivity analysis. Qualitative sensitivity analysis has often been overlooked, and it should not be. A three-step process was suggested in this chapter. It includes identifying sources of uncertainty, identifying instrumental uncertainties and characterizing their effects on decision parameters.

Quantitative sensitivity analysis has a much larger toolbox available to it. Some of these tools can be quite sophisticated. My personal bias is to use the simplest quantitative technique you legitimately and usefully can. The purpose of sensitivity analysis is to support decision making that is better informed about the instrumental uncertainties in an assessment. Not only are complex techniques more difficult to execute properly, they are often much more difficult for others to understand. There will no doubt be circumstances when the most sophisticated and robust techniques are warranted by the goals of the risk management activity, but when a good job can be done with simpler methods, use the simpler methods.

By now we have discussed a good many sophisticated analytical techniques capable of generating a great deal of decision-critical information. The next question

is, “How do we best present this information to risk managers, and how do they use them to support decision making?” These are the topics covered in the next chapter.

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18 Presenting and Using Assessment Results

18.1 INTRODUCTION

What do risk managers want from a risk assessment? In best practice, they want answers to their questions in a form they can understand and use for decision making. They want to understand the instrumental uncertainty and how it could affect the decisions they must make. In general, risk managers want the “answer.” What they may not always understand is that we may not know the answer or that the answer can be one of any number of possibilities.

What we all want are good decisions that yield desirable outcomes. Patrick Leach (2006) masterfully describes the irresistible tendency to focus on a single number for decision making in his book *Why Can't You Just Give Me the Number?* Numbers, once generated and used, have a way of becoming part of an organization's gospel. An overreliance on single numbers in decision making means that managers are ignoring uncertainty, errors, variability, and ranges of possibilities and that can lead to damaging misjudgments.

Howard Wainer (2009), in his book *Picturing the Uncertain World* said, “The road to advancing knowledge runs through the recognition and measurement of uncertainty rather than through simply ignoring it.” If risk analysis is ever to realize its promise, assessors must begin to help managers probe and understand the uncertainty that attends the answers to their questions. Risk managers should learn to explore the possibilities, rather than to rely on “the” number.

Information reduces uncertainty. If it does not improve a decision, it is worthless (Savage 2009). Risk assessment is an evidence-gathering activity. For risk managers, reading the results of a risk assessment is a very different kind of information-gathering activity. Your risk assessment results need to present information that is observable, treats the relevant uncertainty, can impact a decision, and does not cost the manager more time to find and understand than it is ultimately worth for decision making.

The goal in this chapter is to present methods that can be used to move risk managers, who must make decisions in an uncertain world, away from reliance on a single value. This chapter proceeds by discussing ways to understand and present the results of risk assessments. It considers how to examine quantities, probabilities, and relationships in the data and how to use them to answer risk manager's questions. [Chapter 19](#), *Decision Making Under Uncertainty*, a companion to this chapter offers a practical approach for addressing uncertainty in the decision-making process.

18.2 UNDERSTAND YOUR ASSESSMENT OUTPUT DATA BEFORE YOU EXPLAIN IT

A risk assessor needs to understand the data before explaining it. Lest this sound simplistic or condescending, it is absolutely essential that the assessment team explore their data thoroughly and understand its full information content before they begin to present and explain it. The concern is not that assessors do not understand their data so much as they might not appreciate all it has to reveal.

Data can be described narratively or visually. It must be organized in ways that make sense to its audiences. That is likely to mean descriptions at various levels of detail. Different reports are going to be needed for different audiences. Media, the public, peers, decision makers, politicians, stockholders, bosses, and stakeholders all are going to desire different levels of detail. To focus this discussion, we will consider the risk manager as the intended audience for our assessment results.

Summarizing data for others is essential. But there is no substitute for setting out the full details as clearly as can be easily managed by an audience that is charged with decision-making responsibilities. In that delicate balance, rests the secret to successfully presenting and using risk assessment results. Too much data can become as much of a hurdle to good decision making as too little.

Learning how to analyze a distribution and extract managerial insights is an art well worth practicing. There are two dimensions to risk data of particular interest: the quantities we are interested in and their probabilities of occurring. It is often easier to get a good sense of the data if you focus first on one, then on the other. It can make understanding the information easier for both assessors and managers.

Those experienced in data analysis will likely have developed their own methodologies for unlocking the secrets to the data. This discussion of how to understand and explain risk assessment data comprises four simple, almost obvious, considerations. All assessors who work with risk data and need to convey their relevant information content to managers should learn to:

1. Examine the quantities
2. Examine the probabilities
3. Examine the relationships
4. Answer the manager's questions

18.3 EXAMINE THE QUANTITIES

We will discuss output quantities in three stages. First, we will consider categorical quantities. Second, will consider nonprobabilistic quantities. Third, and finally, we will look at probabilistic quantities. Our discussion begins with the consideration of categorical data.

18.3.1 CATEGORICAL QUANTITIES

We begin by considering the case of categorical data. The first example considers the categorical data produced when considering the vulnerability of dairy

production plants to intentional attack on their products. The CARVER + Shock vulnerability assessment tool* (Catin and Kautter 2007; USFDA 2009a,b) can be used to determine how well various food processing plants are prepared to resist an intentional contamination threat by an internal (employee) or external (terrorist) attacker. Each processing point (node) in the production facility is categorized from 1 (low susceptibility) to 10 (high) for each of seven CARVER + Shock elements (see sidebar) through a series of incisive questions.

CARVER + SHOCK

Criticality – assessing the public health and economic aspects of an attack.

Accessibility – evaluates the attackers’ ability to reach the target and get away unseen.

Recognizability – is the ease of identifying a target.

Vulnerability – analyses whether an attack will be successful.

Effect – estimates the direct loss from an attack, as measured by loss of production.

Recuperability – is the ability of a system to recover from an attack.

Shock – is a measure of the combined health, economic and psychological effects of an attack within the food industry.

Imagine that vulnerability assessments have been conducted for a number of dairy plants and their specific processing steps in the production process, such as receiving materials, storage, mixing, pasteurizing, bottling, distribution, and so on, have been assessed.[†] Now imagine, for the sake of simplicity, that we are initially interested in the ratings (categories) for the accessibility and vulnerability of the 144 production nodes assessed across half a dozen or so dairy processors, i.e., we now have 144 categorical estimates of accessibility and 144 estimates of vulnerability for a variety of production nodes in a number of facilities. Accessibility describes the ease with which an attacker can gain access to a node or target. Vulnerability describes the ease with which an attack can be successfully executed once an attacker gains access to the target. A node with high accessibility and high vulnerability is a soft target. Nodes with low accessibility and vulnerability are hard targets. Most nodes are spread between these two extremes.

With this example in mind, let us consider how to examine and present the categorical data produced by a CARVER + Shock vulnerability assessment. When working with categorical or nominal data, a first question to consider is, “Does the order of the data matter?” Explaining why it does or does not is the second logical

* CARVER was a tool developed by the Department of Defense to identify the most vulnerable enemy targets during the cold war period. Post-9/11, the tool was adapted to help antiterrorist strategists to “think like the bad guys” and identify the most vulnerable food sectors in the United States. The tool was subsequently modified to enable food processors to evaluate the steps in their own production process that are most susceptible to attack.

[†] This example is based on an actual assessment. The data have been modified to protect the confidentiality of the dairy plants.

TABLE 18.1
Frequency Tables for the Accessibility and Vulnerability Elements of 144
Potential Food Processing Targets in Dairy Processing Facilities

Valid	Accessibility			Valid	Vulnerability		
	Frequency	Percent	Cumulative Percent		Frequency	Percent	Cumulative Percent
1	5	3.5	3.5	1	53	36.8	36.8
2	1	0.7	4.2	2	3	2.1	38.9
3	6	4.2	8.3	3	5	3.5	42.4
4	6	4.2	12.5	4	35	24.3	66.7
5	9	6.3	18.8	5	43	29.9	96.5
6	6	4.2	22.9	6	2	1.4	97.9
7	3	2.1	25.0	7	0	0	97.9
8	13	9.0	34.0	8	0	0	97.9
9	7	4.9	38.9	9	1	0.7	98.6
10	88	61.1	100.0	10	2	1.4	100.0
Total	144	100.0		Total	144	100.0	100.0

step. When the order of the risk assessment output data matter, such as when there is a sequential logic compelling the results, the simple techniques described here may be of limited value. In the current instance, the order of the data does not matter.

When the order does not matter, one can begin to understand the data better by counting categorical values and calculating percentages. Are there interesting patterns in the data? How many elements fall into each category? What percentage of the total falls in each category? Are the elements evenly distributed across the categories? Do any patterns appear in the distribution of elements across the categories? Are there groupings of elements that are interesting?

Numerical displays and tables can be effectively used to summarize qualitative data. [Table 18.1](#) presents frequency tables for the two variables of interest. These typically provide counts, percentages, and cumulative percentages for all relevant categories for a variable. A quick glance at these tables informs risk managers that most (61%) of the production nodes are highly accessible with a maximum score of 10. On the other hand, about 2% of all the potential targets have vulnerability scores above 6. The percentages of nodes in each rated category together with the cumulative distribution of categorical ratings provide a quick overview for the individually rated elements of accessibility and vulnerability. These tables can be supplemented with graphical displays like the dot plot of accessibility scores seen in [Figure 18.1](#). Tree maps are convenient for providing a “big picture” view of how the whole of a thing is divided into categories.

The dot plot is one of the simpler graphs you will find. It shows all the data in a readily understood fashion. It is ideally suited to categorical data where the categories are relatively limited and the data set is not too large. Here the number of nodes with a maximum accessibility score of 10 threatens to dwarf the other data points.

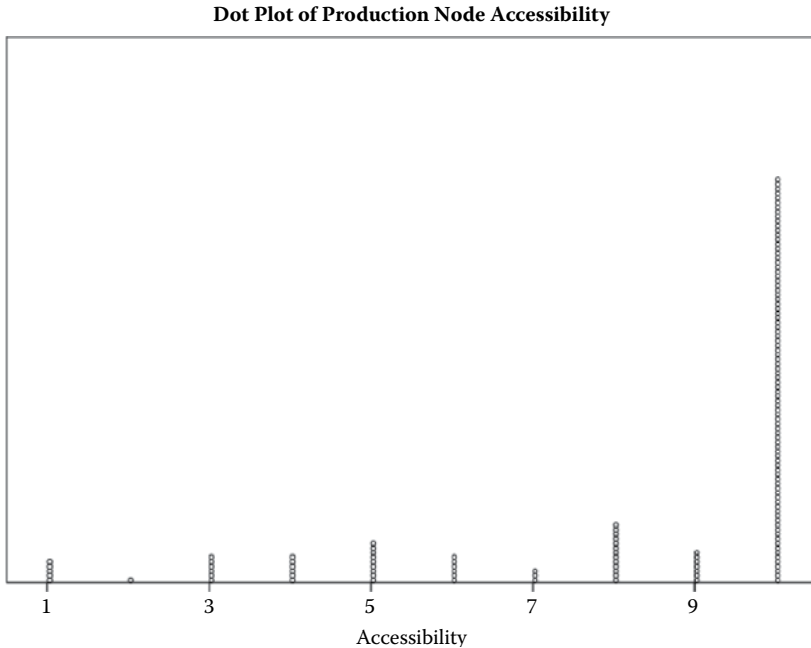


FIGURE 18.1 Dot plot of accessibility categories for dairy production nodes.

When elements fall into more than a single category, as is the case with the accessibility and vulnerability of production nodes, more questions arise. What are the numbers and percentages of elements in each pair of categories? Are there interesting pairs of categories to consider? Are there relationships between any pairs of categories? Do the numbers of elements in any combinations of categories stand out for any reason?

Cross tabulations or contingency tables are useful displays that enable us to explore relationships among categories for more than one variable. Table 18.2 shows a contingency table for accessibility and vulnerability of production nodes. The lower right-hand corner of the table will show those nodes that are at greatest risk of attack. Likewise, the upper left-hand corner would identify targets that are at very low risk of attack. We see a large number of production nodes that are highly accessible, i.e., many data points fall in the bottom row of the table. Yet 37 of these accessible nodes are virtually invulnerable (the (10,1) cell in the table). About half (78) of the nodes fall in vulnerability categories 4 and 5. Risk managers can use this kind of information to aid in their resource allocation decisions by protecting those nodes that are at greatest risk. We see few node targets in obvious need of hardening.

The same questions posed here can be adapted for quantitative data, and more questions can always be added, such as: Are their groupings of data? Are the data symmetrical or do they tail off, in which direction and why? Are there unexpectedly popular (common) or unpopular (uncommon) values? Where do the data center? How widely do they spread? Which values are most likely? How are the data shaped? Are

TABLE 18.2
Cross Tabulation of Production Node Accessibility and Vulnerability

Accessibility	Vulnerability								Total
	1	2	3	4	5	6	9	10	
1	0	2	0	0	3	0	0	0	5
2	0	0	0	0	1	0	0	0	1
3	2	0	0	0	4	0	0	0	6
4	1	0	1	1	3	0	0	0	6
5	2	0	0	4	3	0	0	0	9
6	3	1	0	0	1	0	1	0	6
7	0	0	0	2	1	0	0	0	3
8	6	0	2	0	4	0	0	1	13
9	2	0	0	3	1	0	0	1	7
10	37	0	2	25	22	2	0	0	88
Total	53	3	5	35	43	2	1	2	144

there any significant thresholds? Can you identify pairs of explanatory (independent) and response (dependent) variables? And what does all of this mean for understanding the risks and managing them? Separating the discussion of quantities based on the qualitative/quantitative distinction is largely artificial. Answers to some of these questions will be found in the discussions that follow.

Figure 18.2 offers a simple three-dimensional graphic that is useful for showing how categorical data tend to be grouped across variables. A third variable, recognizability

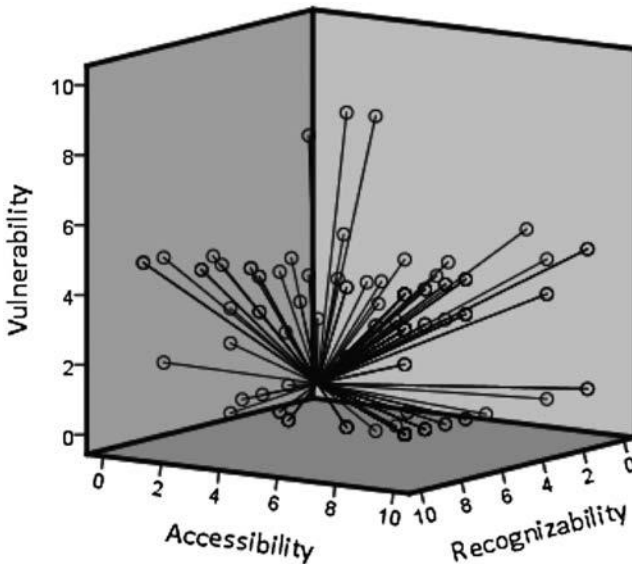


FIGURE 18.2 Three-dimensional plot of recognizability, accessibility, and vulnerability of dairy production nodes.



FIGURE 18.3 Sample tree map showing distribution of accessibility ratings for nodes with vulnerability equal to one

(see previous sidebar), has been added. A target that is easily recognized, accessible, and vulnerable provides the most attractive target for an attack. The origin point of the figure is recessed into the page, and the data reach out toward the reader. There are three rather clear clusters of vulnerability (the vertical dimension of the figure): one low, one in the middle range, and one small cluster that lies above the others. Within these clusters we find a spread of the other two variables without the same obvious clustering. The points farthest from the origin are those that represent the greatest risk of attack. Only a few nodes stand out as easy targets.

Although these examples do not exhaust the tools available, frequency tables, contingency tables, dot plots, and three-dimensional plots are useful tools for exploring and displaying categorical information. Histograms, scatter plots, and other tools can be equally useful. Examples of these using quantitative data follow later in the chapter. Tree maps allocate a 100% space proportionately to the subcategories that comprise the space. Figure 18.3 presents an example of a tree map for the varying accessibility levels for all nodes with a vulnerability rating of 1. A separate map could be prepared for each vulnerability level or a more complex tree map could display all the nonzero entries in Table 18.2.

18.3.2 NONPROBABILISTIC AND PROBABILISTIC QUANTITIES

Let us quickly address nonprobabilistic quantities (point estimates) before turning primarily to probabilistic risk assessment data. If statements about means, medians, and other selected statistical measures or point estimates are presented without a description of the relevant uncertainties attending them, they should be accompanied by narrative descriptions of the risk assessment results so as to expand their utility for decision making. In general, it is wise to avoid presenting quantitative results with no discussion of the uncertainty that attends their estimation. Even in the absence of probabilistic data, a sincere effort should be made to convey the limitations of numerical estimates, which may appear to have more credibility than they in fact have. Do what you can to properly convey the degree of confidence you have in all nonprobabilistic data.

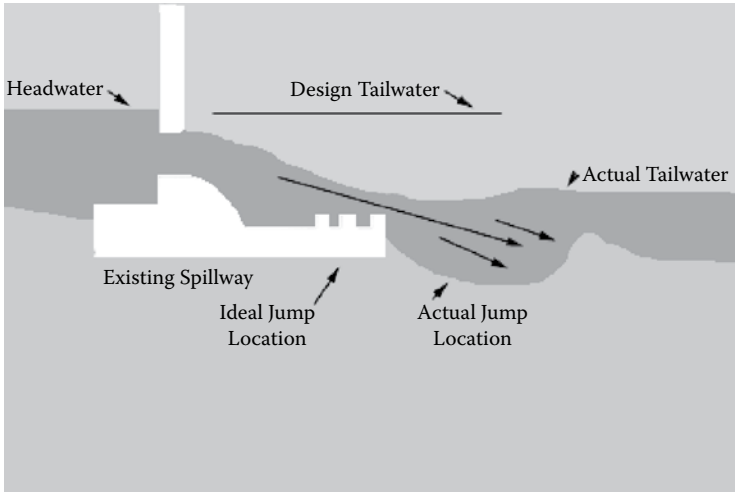


FIGURE 18.4 Existing design flaw in a water control structure.

Different point estimates may have different levels of uncertainty and, therefore, confidence associated with them based on model assumptions, available data, calculation methods, and other factors. These differences should be conveyed to the risk manager. The WHO (2006) addresses the importance of wording in communicating assessment results and has suggested sample phrases to communicate the uncertainty attending point estimates. Following the WHO guidance would generate statements like this: “Taking into account the uncertainty that has resulted from the lack of sufficient data, we assume that the exposure of the highest exposed individuals in the population is lower than X with about 66% confidence.” When discussing uncertainty of nonprobabilistic numbers, it is virtually impossible to avoid words that express probability in some way. Although there is a great deal more that can be said about nonprobabilistic quantities, it will be more convenient to include that in the discussion of probabilistic graphics and numbers.

A new example is introduced to facilitate the probabilistic discussion for the remainder of this chapter. This example is based on a probabilistic risk assessment of a proposed rehabilitation of a water control structure in need of repair. The design discharge for this structure jumps beyond the end of the stilling basin and has caused severe erosion, as shown in the actual jump location in [Figure 18.4](#). The erosion has undermined the structure and threatens to cause it to collapse. If the structure fails, unregulated flows will cause extensive erosion and loss of valuable agricultural lands in the project area.

The costs of this project are the costs of correcting this design flaw. This would be done by adding a new weir downstream of the structure, as shown in the proposed modification seen in [Figure 18.5](#). The benefits are equal to the value of the adjacent land erosion that would be prevented.*

* For simplicity this calculation is omitted from the example.

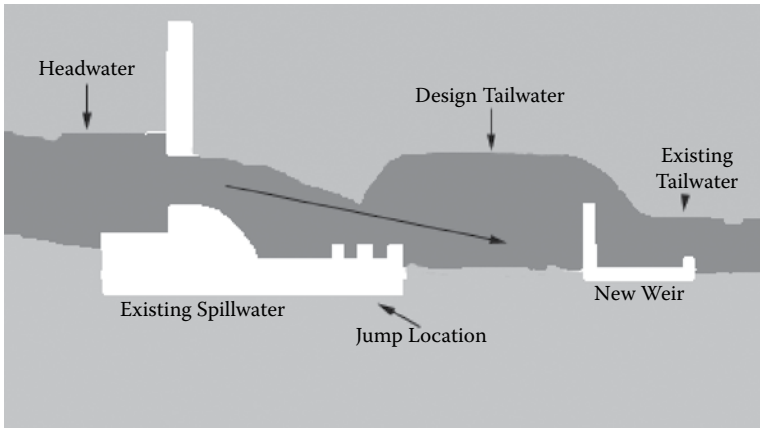


FIGURE 18.5 Proposed modification to water control structure.

While the details need not concern us, there is substantial uncertainty about every element of this project at the preliminary level of investigation. All costs and quantities are subject to some uncertainty, as are the benefits.

Imagine that risk managers are interested in the answers to the following questions:

1. What is the probability that project costs will exceed \$1 million?
2. Identify the cost estimate that has no more than a 20% chance of being exceeded.
3. Identify the cost estimate that has no more than a 10% chance of being exceeded.
4. What is the maximum exposure to cost overruns associated with these costs?
5. What are the most significant contributors to the variations in cost?
6. What is the probability that this project will be economically feasible, i.e., net benefits equal or exceed zero.
7. What is the most likely level of net benefits?

Although each question is answered in Section 18.6, we will focus on the answer to question 7 in the example to avoid the tedium of repeating the attending discussion for each answer. All dollar values for this example are present values at a constant price level. Keep in mind that risk assessments can yield a wide range of outputs, and that the simulation results used here focus narrowly on costs and net benefits. This example, chosen for the common familiarity with the costs and benefits of decisions, does not produce all the types of data assessors may encounter in their work. Nonetheless, the approach and methods described are valid for most kinds of risk data.

18.3.2.1 Graphics

Many of us like to begin with numerical measures of our data: means, medians, minimums, maximums, and the like. An alternative approach is to begin by trying to

get a feel for what the data are like. Because this latter approach may be less familiar, let us begin there. To get a feel for the data, you must first see the data, all the data. Look at it from several perspectives to get a sense of it. Then convey that to decision makers.

How are the data alike? Where do they tend to cluster? How are the data different? How spread out are they? Look at points when you can. Use a scatter plot or a time trend when appropriate but do not automatically connect the points, if you connect them at all. Suppress grids and use only a few numbered ticks while you get a feel for your data. Let the evidence speak.

Graphs can be both useful and friendly. When well chosen, they can help us to note the unexpected, and little is more important to understanding one's data. There is no more reason for us to expect one graph to tell all about our data than there is reason to expect one number to reveal all. Be prepared to use multiple graphs. Robert L. Harris (1999) provides an excellent reference for choosing innovative graphics in his book *Information Graphics: A Comprehensive Illustrated Reference*.

A histogram is an obvious place to begin. How do the data appear? Is there one large single peaked group, or do your data separate into groups or clusters? The net benefits in Figure 18.6 show two different distributions of net benefits. The first is single peaked and roughly symmetrical; it tends to center around \$40,000 – \$50,000 with a range of about \$400,000. The second distribution has a much wider spread

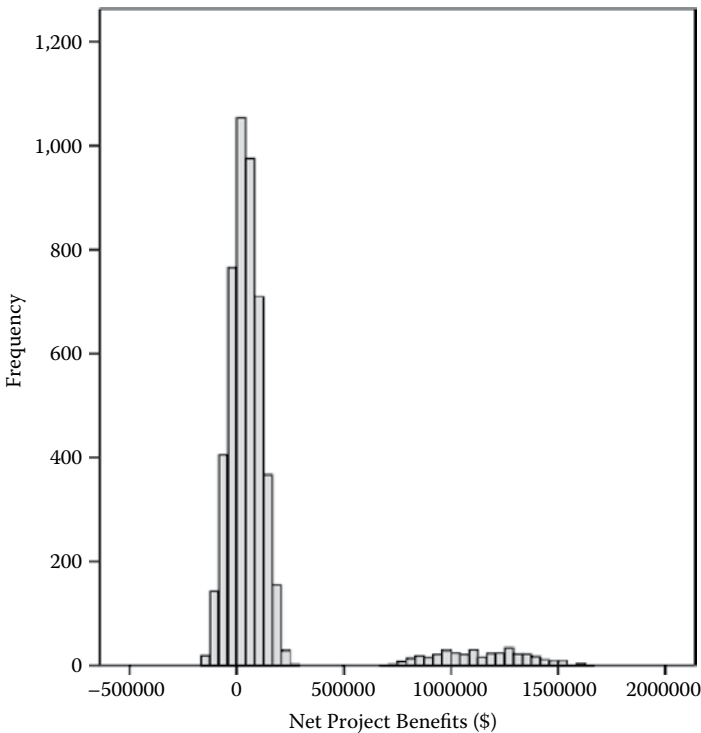


FIGURE 18.6 Histogram of project net benefits showing two distinct clusters of data.

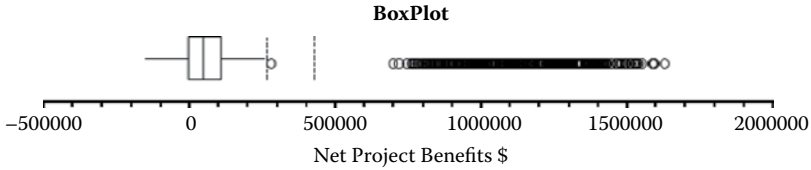


FIGURE 18.7 Box plot of project net benefits.

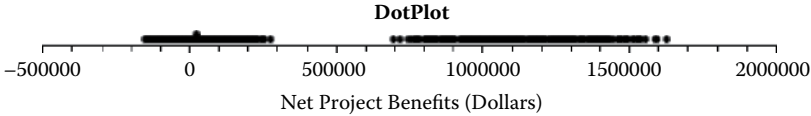


FIGURE 18.8 Dot plot of project net benefits.

with a range of about \$800,000 or so. It tends to center at about \$1.2 million in net benefits.

This distribution strongly suggests two distinctly different kinds of outcomes. We need to learn why that is so. In the present case, the reason for this dual distribution outcome stems from uncertainty about the value of the adjacent land that is being eroded. Values from the left distribution are based on the land staying in agricultural use. Values from the right are associated with a relatively small (10%) chance that the land will receive a zoning change and come into more valuable commercial usage in the near future. Preventing the loss of commercial land produces larger benefits than does preventing the use of agricultural land.

Keep in mind that a histogram can be deceptive, depending on the number of bins or bars used to display the data. Alternative views of the 5,000 simulated values are provided in [Figures 18.7](#) and [18.8](#).

The box plot clearly shows two distinct clusters of data. The median value (vertical line in box at left) is quite small compared to the potential range of benefits. The dots in the box plot show outliers. These values, which comprise what is effectively the second cluster of data, lie well outside the range of most of their “colleague” points, which represent 90% of the likely outcomes.

The dot plot adds no real insight beyond the two distinct clusters of points, each with their own centers and their own spread of values. The dots here have no vertical dimension with one exception. Dot plots are often more effective with categorical data, as noted previously. Nonetheless, they do effectively show there are some “unpopular” values between the two clusters. They also reveal the lack of any specific “popular” values, a fact not as readily observed in the histogram.

At this point, the assessor may want to decide whether to separate these outputs into two distinct data sets for analysis or not. We know that the cluster on the left corresponds to the prevention of agricultural land loss and the cluster on the right corresponds to the prevention of commercial land loss. Separating them for analysis is a decision that would be made in consultation with the risk manager. It is a simple matter to filter and separate the data using most spreadsheet and data analysis software.

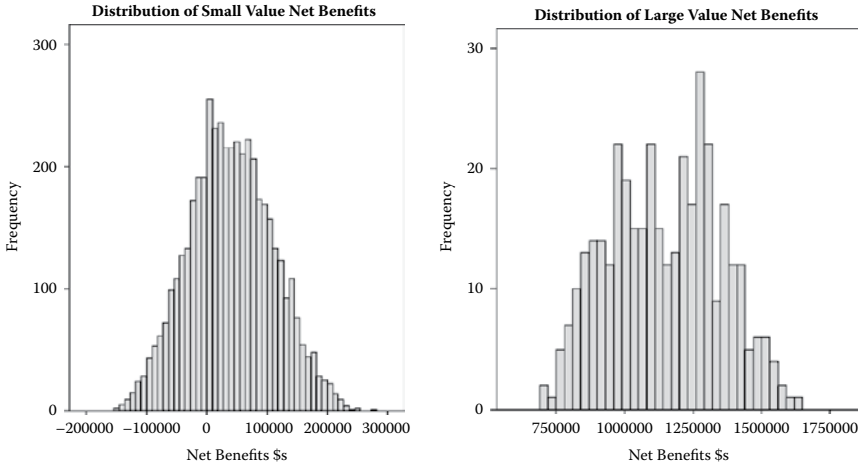


FIGURE 18.9 Two separate histograms showing small-value and large-value clusters of net benefits.

Histograms of the two distributions, obtained by separating the data into its two clusters, are shown in [Figure 18.9](#). Note that the vertical scales differ by an order of magnitude. The distribution of small values is reasonably normal; the other distribution, with a smaller sample, is less obviously so.

Stem-and-leaf plots provide a histogram-like perspective that also shows the data. The plot of the smaller net benefit values in [Figure 18.10](#) shows a histogram in a horizontal orientation. The individual data values are easier to pick out. For example, note how easy it is to find negative values and to observe the actual frequency with which these values occurred.

The far-left column shows the actual number of observations in a row. The first value after the frequency is the stem. Note that its value is in units of \$100,000. Each leaf, denominated in \$10,000 increments, represents 6 individual cases. Consider the row with a frequency of 460. The stem is 0; this means the dollar value is less than \$100,000. There are 6 values in the \$60,000s for each leaf of 6 in the plot. Likewise, a leaf of 7 means there are 6 values in the \$70,000s for each 7 in the plot. An & means there are observations but not enough (i.e., under 6) to complete a leaf.

The cluster of large net benefit values are shown in the stem-and-leaf plot of [Figure 18.11](#). Notice each leaf now represents only one case. The minimum value is about \$700,000 and the maximum value is about \$1,600,000. The distribution shown in this way suggests less jaggedness than the histogram showed. This is an artifact of the number of bins used in the two different plots, a point to always bear in mind when using histograms.

These figures are generally not well suited to the needs of the general public. However, when communicating complex information to risk managers, it is always useful to show the data if we are going to move decision making away from overreliance on a single value. Risk managers must understand why a single value is inadequate to describe the assessment outputs.

Large Value Net Benefits Stem-and-Leaf Plot		
Frequency		Stem & Leaf
1.00	6..	9
11.00	7..	14566778899
40.00	8..	000111222233344555555556677777888889999
55.00	9..	000001111222223333444455556666667777777788888999999
57.00	10.	000000011111444433333333444555566667777778888999999999
47.00	11.	0000000111111112223333444455556666777777889999
73.00	12.	00000000001111222222333344444444555566666677777788888888888999999
48.00	13.	00000000011112233344445555556666677778888899
28.00	14.	000001111222223334455667888
13.00	15.	1111223335889
1.00	16.	2

Stem width: 100000.0
Each leaf: 1 case(s)

FIGURE 18.11 Stem-and-leaf plot of large-value net benefits.

The five-number summary provides an easy and concise summary of the distribution of the observations without resorting to using the mean. Consistently reporting these five numbers avoids both anchoring to a mean as well as the need to focus on any one summary statistic. The five-number summary is useful because it provides information about the location of the data with the median. The data’s spread is described by the quartiles, and extreme values are estimated by the minimum and maximum observations. The data range and interquartile range (middle 50% of all observations) are easily calculated from the five-number summary.

Each of the five numbers is an order statistic. This makes it easier to imagine data sets, as we see in the table. Look at the medians. It is easy to quickly see how the central location of the three data sets varies. The median and quartile values are resistant statistics, i.e., they are not much influenced by outliers. Nonresistant statistics, like the mean and standard deviation, are heavily influenced by outliers.

TABLE 18.3
Five-Number Summary for Net Benefit Values

Item	Small Values	Large Values	All Data
Minimum	\$(152,036)	\$696,575	\$(152,036)
1st quartile	\$(8,238)	\$979,164	\$(3,604)
Median	\$38,347	\$1,141,616	\$45,938
3rd quartile	\$88,447	\$1,294,851	\$103,078
Maximum	\$276,460	\$1,627,013	\$1,627,013

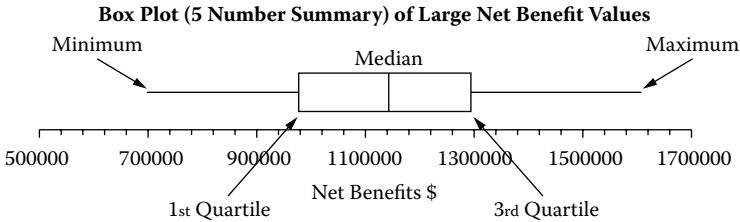


FIGURE 18.12 Box plot and five-number summary of large net benefit values.

These five numbers constitute the values needed to define a box plot, as shown in [Figure 18.12](#).

Describing how the data are alike is sometimes a desirable task. We want to summarize the most frequently occurring characteristics of the data using a few numbers that are easily understood and agreed upon. The mean, median, and mode are the most popular measures of your data's central tendency. Try not to rely on the mean and encourage the five-number summary.

[Table 18.4](#) adds a few more commonly calculated descriptive statistics to the previous table. Notice how the extreme values can affect the mean and standard deviation. The overall mean is \$123,000 while the separated means are \$40,000 and \$1,143,000. The overall mean is almost three times as large as the median. Extreme values can have this effect on means. That can make these familiar but nonresistant statistics somewhat misleading to decision makers. Consider relying more on resistant order statistics than on more traditionally reported values.

CHEBYSHEV'S THEOREM AND THE EMPIRICAL RULE

Theorem: The fraction of any data set lying within k standard deviations of the mean is at least $1 - (1/k^2)$ where $k =$ a number greater than 1. This theorem applies to all data sets, which includes samples and populations.

The empirical rule gives more precise information about a data set than Chebyshev's Theorem, but it only applies to a data set that is bell-shaped. The empirical rule says:

- 68% of the observations lie within one standard deviation of the mean.
- 95% of the observations lie within two standard deviations of the mean.
- 99.7% of the observations lie within three standard deviations of the mean.

The standard deviation is useful for helping others understand what constitutes an unusual value for your output of interest. Adding ± 2 standard deviations to the mean provides a first cut at identifying unusual values for a single-peaked symmetric distribution; ± 3 standard deviations defines a rough cutoff for identifying very unusual values. Calculate these values and use them to examine and explain your data.

TABLE 18.4
Selected Descriptive Statistics for Net Benefits Data

Item	Small Values	Large Values	All Data
Minimum	\$(152,036)	\$696,575	\$(152,036)
1st quartile	\$(8,238)	\$979,164	\$(3,604)
Median	\$38,347	\$1,141,616	\$45,938
3rd quartile	\$88,447	\$1,294,851	\$103,078
Maximum	\$276,460	\$1,627,013	\$1,627,013
Mean	\$40,228	\$1,143,208	\$122,731
Standard deviation	\$69,871	\$203,235	\$302,998
Interquartile range	\$96,685	\$315,686	\$106,682
Range	\$428,495	\$930,439	\$1,779,049
Count	4,626	374	5,000

Another obvious set of values an assessor must understand includes significant thresholds. These will vary depending on the decision context and the questions risk managers have asked, of course, but a few are predictable. Separating good/desirable values from bad/undesirable values will always be important. Minimums and maximums are likely to be important. Values set in policy, zeros, and unusually large or unusually small values may all be important. Converting data points to z-scores provides a good first indication of how “usual” such a result is in your distribution. Z-scores within ± 2 would be considered within the usual range of observed values. The greater the absolute value of the z-score the farther it is from its mean and the more unusual it is.

If point estimates of any risk measure are used, they should be identified, explained, and their locations in the distribution(s) of results shown. [Figure 18.13](#), for example, shows the three different means of [Table 18.3](#).

In the current case, zero is a significant threshold, separating negative net benefits from positive ones. It is important to know that this project could produce a net loss in the magnitude of \$150,000. Likewise, it is useful to know that if the land does get rezoned commercial, there is no chance the project will result in a net economic loss. The maximum gain under the agricultural land use scenario is about a quarter of a million dollars compared to \$1.6 million for the commercial land-use scenario. For simplicity we have considered only one output from this model. Similar sorts of analyses should be conducted for other outputs as well.

18.4 EXAMINE THE PROBABILITIES

Once you understand the quantities you are ready to tackle their probabilities. Let us begin with a brief review of the ways probabilistic data can be presented graphically, as seen in [Figure 18.14](#). The vertical axis of the probability density function (PDF) measures density and has no convenient probability-related interpretation. Probabilities are calculated as areas under this curve. The PDF shows the relative likelihoods of the

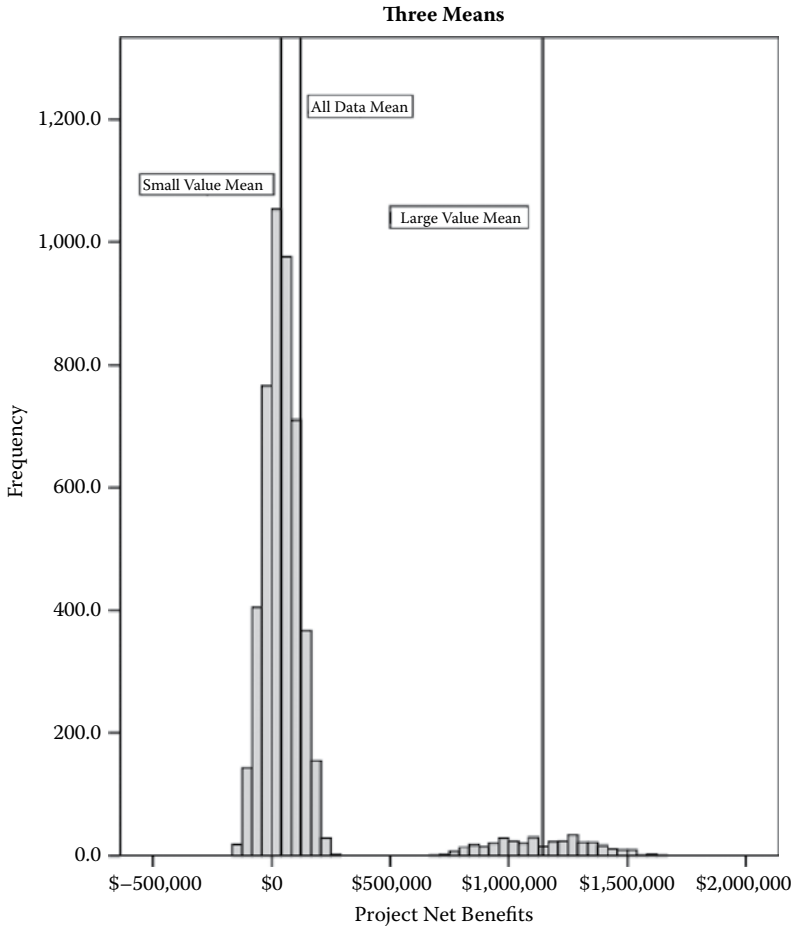


FIGURE 18.13 Locating important risk estimates in a distribution.

different values in its skew, kurtosis, and overall shape characteristics. It effectively reveals the most likely values and the scale of the output.

The vertical axis of the ascending cumulative distribution function (CDF) shows the probability that a specific value or less will be realized. The CDF shows quantile and median values. It is useful for estimating probability intervals or for making confidence statements. When comparing two or more CDFs, stochastic dominance is easier to see. The survival function, sometimes called the exceedance distribution or descending CDF, shows the probability that a specific value or more will be realized. Different people find one curve easier to understand than another. Experience suggests that the cumulative distribution function may be favored more often than the other two forms, but the best choice will depend on the quantities you are examining and the people with whom you work. The EPA (1997) has suggested that it is useful to display both the PDF and CDF, one above the other, with identical horizontal scales.

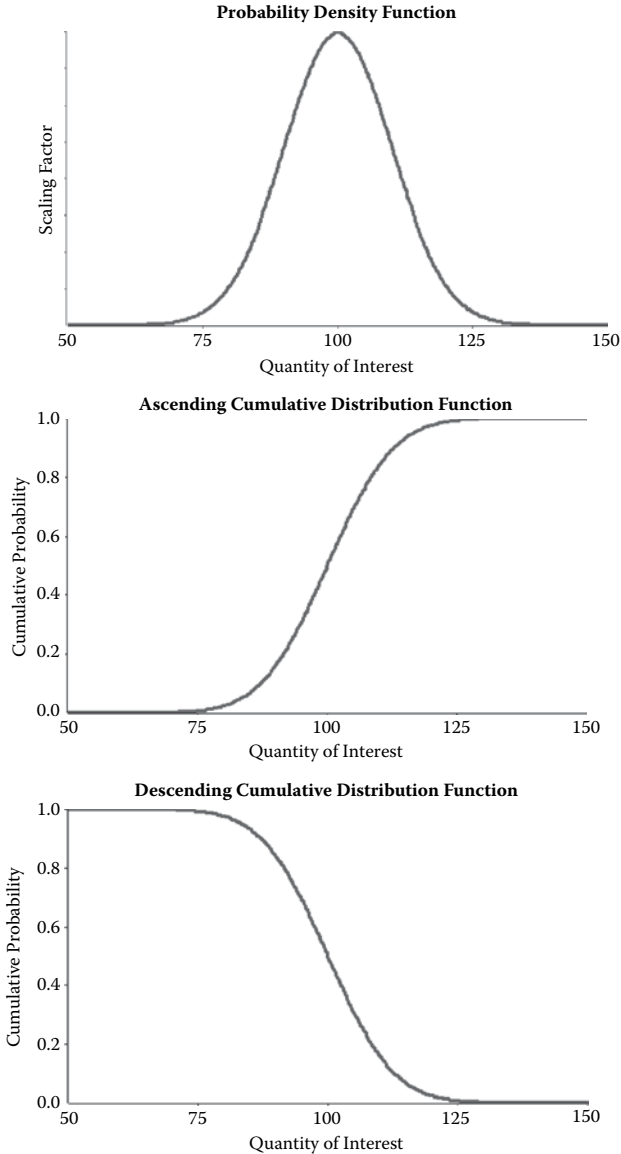


FIGURE 18.14 Review of three common ways to display a distribution of hypothetical values.

18.4.1 QUARTILES

The simplest way to begin to address probabilistic information is by using the quartiles developed for the five-number summary. [Table 18.3](#) provides all four quartile values, with the median being the second quartile and the maximum the fourth quartile value. These four values represent four standard points on the cumulative distribution function.

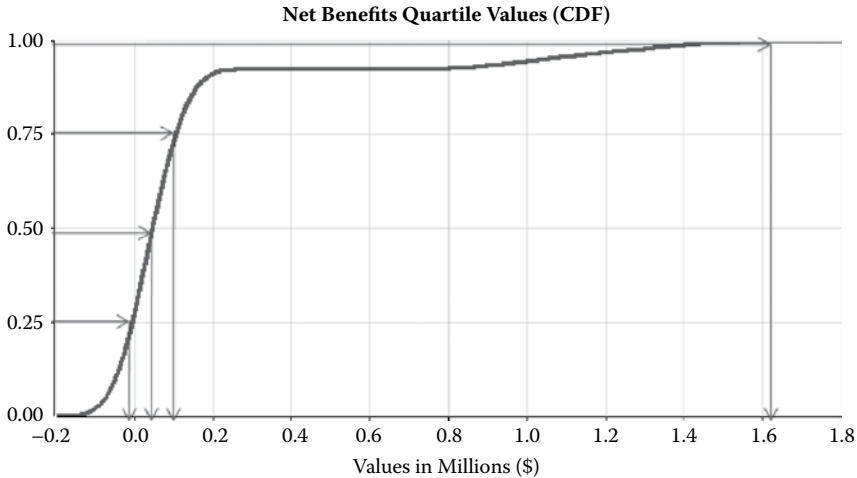


FIGURE 18.15 Quartile values for project net benefits.

The four quartiles are shown for project net benefits in [Figure 18.15](#). Each quartile comprises one-fourth (1,250) of the observations. There is a 25% chance that net benefits will be $-\$4,000$ or less; a 50% chance they will be below $\$46,000$; and a 75% chance they will be below $\$103,000$.

The more sharply the CDF rises, i.e., the steeper the slope, the more densely concentrated the values are. That is, the scale of the distribution is smaller. When the CDF flattens out, the spread of the distribution is greater. Imagine that the CDF casts a shadow on the horizontal axis. The shorter the shadow, the more concentrated is the distribution.

18.4.2 PROBABILITIES OF THRESHOLDS

One category of quantities to consider, mentioned previously, was that of significant thresholds. It is often important to know the likelihood that a threshold will be missed, attained, or exceeded. When there are specific quantity values that we do not want to exceed or fall below, or ranges of values we need to hit, it is useful to estimate the probabilities of these events.

With probabilistic risk assessment, this is relatively simple to do. An obvious threshold for the example project would be the break-even point of $\$0$ net benefits. In a world of limited maintenance resources, risk managers would be very interested in the probability of this particular rehabilitation project producing negative net benefits. The distribution of outputs in [Figure 18.16](#) shows that 27.3% of all the simulated values are negative; thus, we estimate the probability this project will not produce a positive net return as 27.3%.

Let us, for the sake of an additional illustration, assume that a higher budget authority is considering funding a number of projects, but it cannot fund them all, so they are interested in projects with $\$1$ million or more in net benefits. [Figure 18.16](#) shows that this project has a 5.3% chance of meeting or exceeding that threshold.

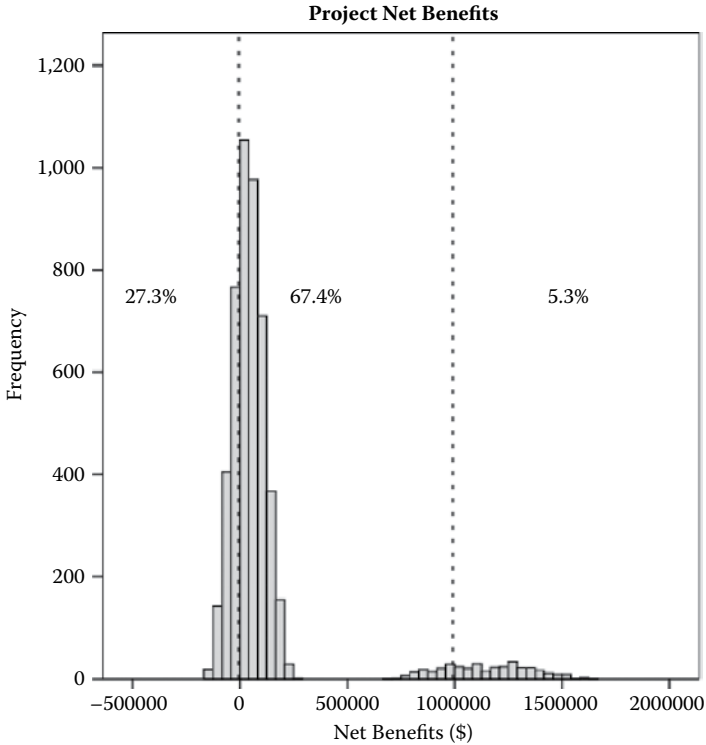


FIGURE 18.16 Project net benefit threshold values in a frequency distribution.

Risk managers sometimes find it easier to understand the CDF view of a distribution. The quantity of interest is shown on the horizontal axis with a reasonably intuitive vertical axis that shows percentile/quantile data for the simulation results, which lend themselves well to likelihood estimates. Thus, we can point to the lower arrow in [Figure 18.17](#) and explain that the likelihood of the quantity being 0 or less is given by the cumulative probability, 27.3%, on the vertical axis, which is also shown in the delimiter bar at the top of the graphic. Likewise, the probability of net benefits less than \$1 million is 94.7%. Using the complementary law of probability, we know the probability of being more than \$1 million is $100\% - 94.7\%$, or 5.3%. It is a simple matter to run a simulation with thousands of iterations and then to analyze, sort, and count outputs to estimate the likelihood of virtually any imaginable threshold being met, exceeded, or fallen short of as well as the probability of any interval of values occurring.

18.4.3 CONFIDENCE STATEMENTS

One of the strengths of risk assessment is its ability to cope with uncertainty. Probabilistic risk assessment techniques enable us to cope with uncertainty and to express our confidence in our results in a quantitative way.

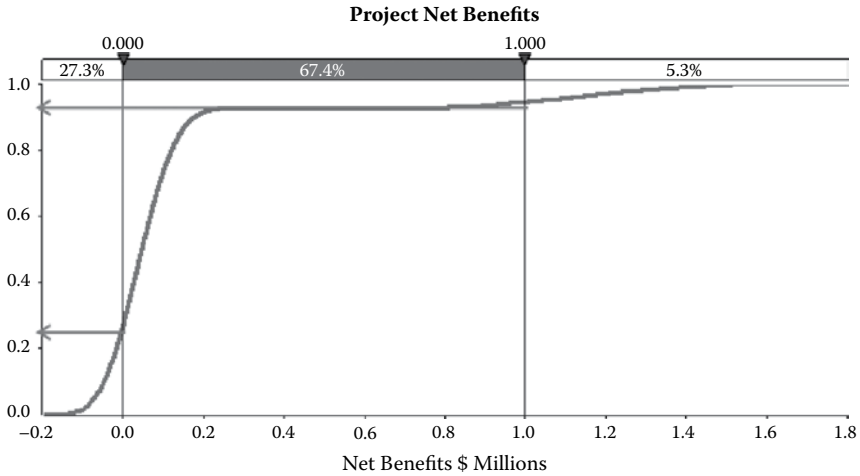


FIGURE 18.17 Project net benefit threshold values in a CDF.

After reporting on quantities of particular interest, it is important to convey to risk managers the degree of confidence that assessors have in their estimates. This can be done qualitatively in the narratives of reports and meetings. It is, however, important to convey quantitative messages about quantitative values. Information like that in [Table 18.5](#), for example, enables risk assessors to tell risk managers that we are 90% sure that the eventual value of net benefits lies between $-\$70,000$ and $\$1,030,000$.

Alternatively, we are 95% sure that the true value of net benefits will lie between $-\$90,000$ and $\$1,240,000$. This gives the risk manager a much more vivid understanding of the effects of uncertainty than if you begin by saying our best estimate of net benefits is $\$123,000$. Confidence ranges are probabilistic statements that help diminish overreliance on a single estimate of the output.

The confidence ranges described here are not the same as the confidence intervals calculated for sample statistics. When we speak of being “sure,” as we do here, this is used in a rather loose sense. It literally means that 90% (or 95%, etc.) of our results fell between these two numbers. Thus, this confidence statement is based on the assessor’s best data and efforts. It is a subjective quantitative measure. The ranges presented should meet the communication needs of the risk assessor and the decision-support needs of the risk manager. If the risk manager is dismayed because the confidence range is too broad for his purposes, this should lead to a discussion of practical options for further reducing the existing uncertainty. In the current example,

TABLE 18.5
Confidence Statements for Project Net Benefits

Minimum	(\$152,036)	5th percentile	(\$71,162)	2.5th percentile	(\$90,395)
Maximum	\$1,627,013	95th percentile	\$1,031,349	97.5th percentile	\$1,238,284
Range	\$1,779,049	90% confidence range	\$1,102,511	95% confidence range	\$1,328,679

the obvious choice is to find out what is happening with the rezoning appeal in an effort to pin down the value of the land that could be lost.

18.4.4 TAIL PROBABILITIES AND EXTREME EVENTS

Dealing honestly with uncertainty means moving away from single-value estimates of complex phenomena. Expected values are rarely going to be the only number relevant to risk managers and other decision makers. The value of probabilistic risk assessment is found in the way that its results contribute to our understanding of the problems we face, our understanding of the complex systems that produce them, and the characterizations of the effects of uncertainty and variability. All of this is propagated through the range of results generated by our probabilistic models.

The current example provides an ideal illustration of one of the problems of dealing with expected values. They are not resistant statistics. As noted earlier, the expected value of net benefits is \$123,000. Compare that to the median of \$46,000 and we can see the influence of extreme values on the mean. Decisions based on the mean may well distort expectations about a project's actual performance.

Let us shift our focus now from net benefits to project costs to facilitate a simpler consideration of distribution tails and extreme events. Total project construction costs are distributed as seen in [Figure 18.18](#).

We see that costs span from \$750,000 to \$890,000, a range of \$140,000. If our only interest is in the mean cost estimate, that is \$812,000. That cost will only occur in the extremely unlikely event that all of our "best estimates" are realized. The purpose of identifying and addressing uncertainty, however, is to learn what the actual truth might be and what might happen if our best estimates are not realized. How low might costs be, and how high could they rise? This information is embedded in the tails of the distributions.

Costs appear to have an asymmetric distribution, with more values to the left of the single peak than to the right. The tails seem a bit unevenly defined by the

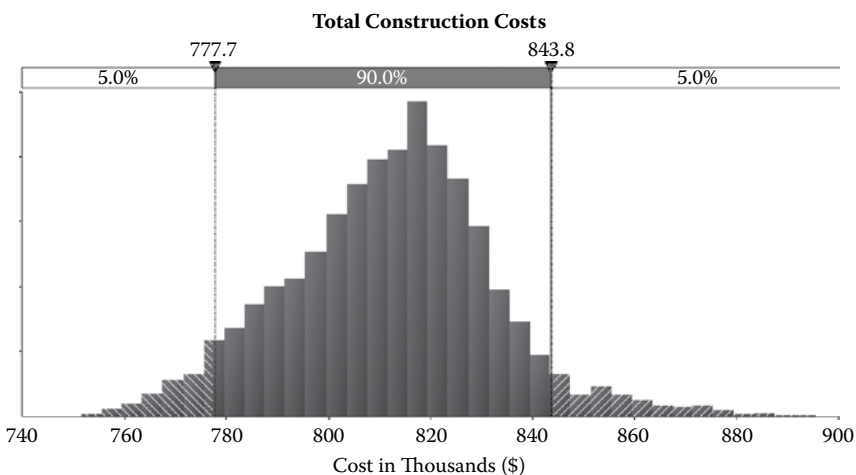


FIGURE 18.18 Distribution of total construction costs.

5,000-iteration simulation. If tails values are of interest, it is generally wise to do iterations in the magnitude of 10^4 , and if extreme events are of interest at least 10^5 .

There are several options for discussing and presenting tail values. Deciding how to define the tails is the starting point. We previously discussed the importance of threshold quantity values, whether high or low. Here we define the tails by percentages and suggest the highest and lowest 5% as starting points.

The threshold values, the 5th and 95th percentiles, for our example are \$778,000 and \$844,000, respectively. Using the filter feature of your spreadsheet software, it is a simple matter to isolate these clusters of data to analyze and summarize the tail data.

Let us consider the lowest 5% of cost estimates as shown in [Figure 18.19](#). Assessors can now explain to risk managers that if all the uncertainties resolve themselves “favorably” (i.e., producing a lower cost), we are looking at a range of costs roughly from \$750,000 to \$780,000, with a conditional expected value of about \$771,000.

This sort of information is conditional on the fact that actual costs will be somewhere among the lowest 5% of all possible costs, i.e., an optimistic scenario. The distribution shown in the histogram is a new conditional distribution. It isolates and magnifies the tail portion of an assessment output distribution. Conditional information can be informative for risk managers when tail values are important to decision making. This kind of partitioned analysis can be done for any size left or right tail.

Extreme values can also be important to risk managers, especially when loss of life, human health, and safety are among the outputs of concern. In the case of a cost estimate, the extremes in this example are not quite so compelling as they might be for

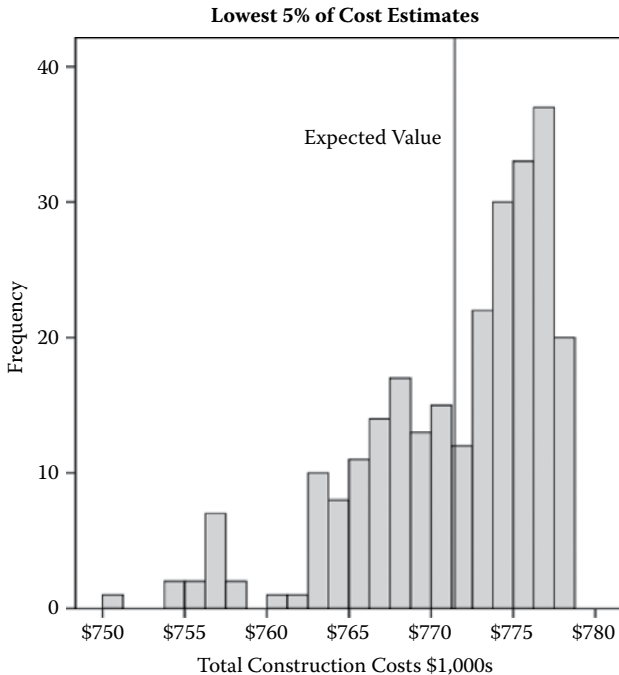


FIGURE 18.19 Distribution of the lowest 5% of cost estimates.

TABLE 18.6
Extreme Value Estimates of Cost with Varying
Numbers of Iterations

Iterations	Minimum	Mean	Maximum
5,000	\$750,959	\$811,951	\$886,142
10,000	\$745,355	\$811,952	\$887,159
100,000	\$743,097	\$811,926	\$903,757

human life and safety. However, it is a relatively simple matter to explore the potential extremes of any given situation with your probabilistic risk assessment model.

Doubling the number of iterations provides a better chance of capturing a more extreme set of high or low input values. The reductions in the low extreme cost estimate going from 10,000 to 100,000 iterations, shown in Table 18.6, are relatively modest. This indicates that we are likely to be zeroing in on a reasonable estimate of this extreme value. Note that high extremes are a little further from the mean than low extremes. The additional iterations add no real precision to the estimate of the mean.

18.4.5 STOCHASTIC DOMINANCE

Stochastic dominance, as used here, refers to a form of ordering for probability distributions. It is a concept developed in decision theory that sometimes enables one to call one distribution better or more desirable than another. To illustrate this concept, let us revert to some hypothetical outputs associated with two hypothetical risk management options, A and B. Let $F_A(x)$ and $F_B(x)$ be the cumulative distribution functions for these two options, and let larger values of x be preferable.

Figure 18.20 demonstrates first-order stochastic dominance, i.e., where $F_A(x) \leq F_B(x)$ for all x . Let the horizontal axis show a hypothetical assessment output where higher values are preferable to lower values. For any given x -value, option A provides a lower probability of that value or a smaller one being realized. Likewise, for any given probability (percentile), option A yields a higher outcome. That means for any potential value of the outcome and for any cumulative probability, option A is preferable to option B, and so it dominates option B at all points of the curve. Had the example been reversed, with lower values preferable to higher values (such as lives lost, illnesses, damages sustained, or costs), we would say option B dominates A and is preferable.

What happens when the CDFs intersect and there is no first-order dominance? Is it still possible to call one distribution preferable to another? In Figure 18.21, option A (dashed line) has second-order stochastic dominance over B (solid line). To calculate second-order dominance we consider a function, $D(z)$, that is the cumulative difference between the two CDFs. The function is defined as follows:

$$D(z) = \int_{\min}^z (F_B(x) - F_A(x))dx \geq 0, \quad \forall z \tag{18.1}$$

then A is said to have second-order stochastic dominance over B.

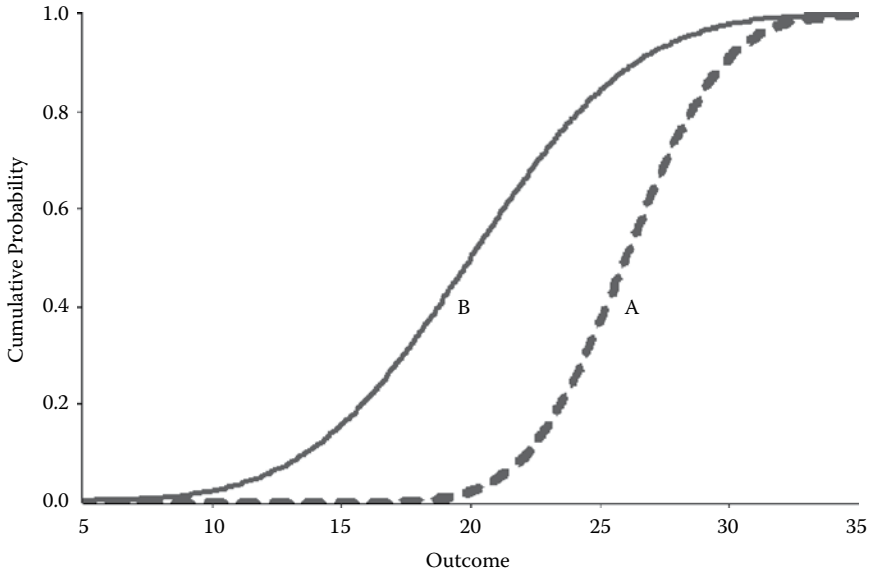


FIGURE 18.20 First-order stochastic dominance.

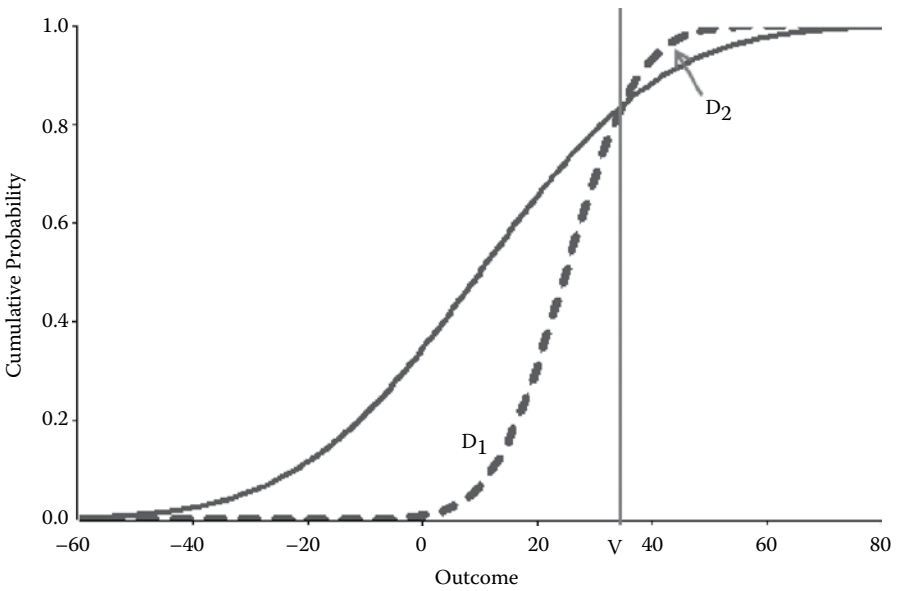


FIGURE 18.21 Second-order stochastic dominance.

The figure shows that A dominates B up to the value, V . From this point on, B dominates A. The areas between the curves is calculated as D_1 and D_2 . D_1 is a positive value because $F_B(x)$ is the greater cumulative probability up to V . D_2 is a negative value. The sum of D_1 and D_2 is positive, and so A is said to hold second-order dominance over B. While first-order dominance is rather unambiguously superior, second-order dominance is not; it is based on the assumption that the decision maker has a risk-averse utility function. Option A offers the best chance of a preferred outcome. Second-order dominance does not take into account different preferences for large or small outcomes. It is not always convenient to calculate second-order stochastic dominance.

18.5 EXAMINE RELATIONSHIPS

So far, we have considered how to explain the quantities and probabilities of individual variables and outputs. Explaining relationships between variables is sometimes more important. Dose-response relationships in hazard characterizations for human health risks, for example, are a common example of a two-variable relationship that is critically important to some risk assessments. Contingency tables, discussed earlier, can be an effective tabular display of relationships between and among variables. In this section we examine tools and methodologies to help you understand and explain relationships between two variables.

18.5.1 SCATTER PLOTS

The single best, simple graphic device for exploring relationships between two variables is the scatter plot. Think in terms of exploring relationships between:

- Outputs
- Inputs and outputs
- Significant inputs

Bear in mind that scatter plots do not reveal cause and effect but simple correlation. Consider a few scatter plots* from our example, beginning with the relationship between project costs and net benefits, two outputs of interest shown in [Figure 18.22](#). The plot reveals the two distinct clusters that we identified previously. There appears to be no obvious association between construction costs and net benefits in the top cluster, beyond a vague suggestion of a negative slant to the cloud of points, despite the very obvious fact that benefits – construction costs = net benefits. The bottom cluster, with more data points, does exhibit the expected negative relationship although it is more subtle than dramatic. As costs get larger, net benefits decline.

Now we will look at two more outputs: gross benefits and net benefits. [Figure 18.23](#) shows a positive relationship: as gross benefits increase so do net benefits. The

* Plotting all 5,000 points obliterates a lot of the detail. A random sample of 500 output points was used to create these scatter plots.

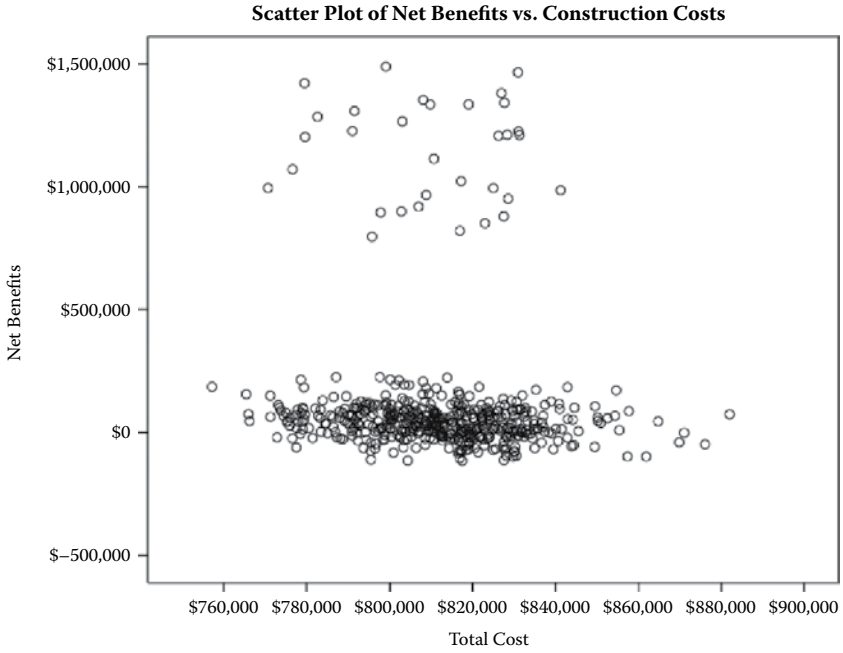


FIGURE 18.22 Scatter plot of project net benefits and construction costs.

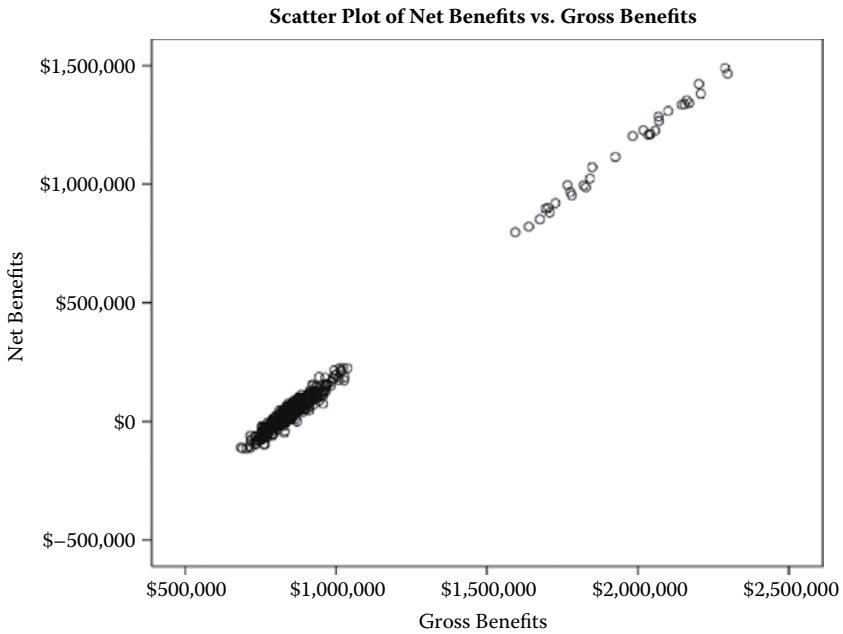


FIGURE 18.23 Scatter plot of project gross benefits and net benefits.

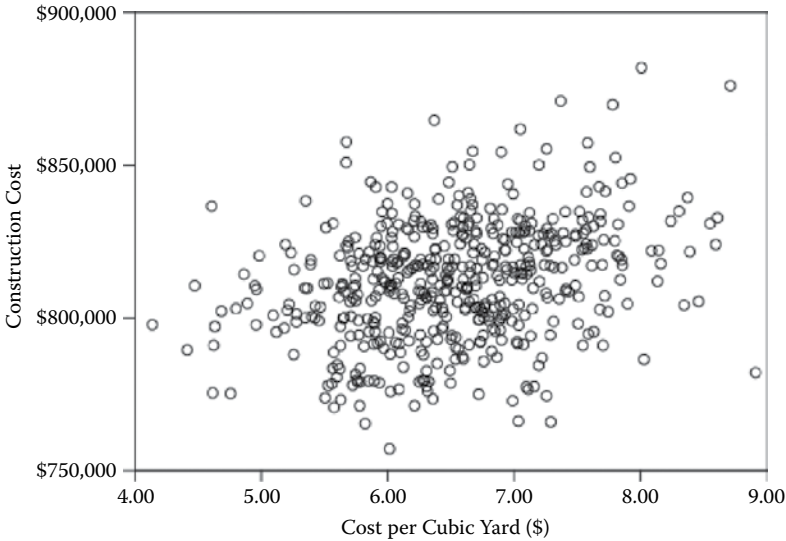


FIGURE 18.24 Scatter plot of excavation costs per cubic yard and excavation quantity in cubic yards.

relationship is also very tight, indicating a very close association between these two values. Figure 18.23, although far from surprising, was generated to demonstrate the scatter plots' ability to reveal a range of relationships.

To illustrate a relationship between an input and an output, let us examine the relationship between the cost per cubic yard of excavation and the total cost estimate. The slight upward sloping circular pattern of Figure 18.24 indicates the absence of a strong correlation. A weak positive relationship is confirmed by the correlation coefficient of 0.284. There are enough other cost factors that this one does not exhibit an especially strong association with construction costs. Scatter plots can be one of the more effective tools for identifying sensitive inputs in a risk assessment model. Multiple-minis,* a page with a large number of relatively small graphics, can provide a useful summary of the assessor's investigation of the relationships among inputs and outputs.

An example of a scatter plot for two inputs is shown in Figure 18.25. Excavation cost and excavation quantity were treated as independent inputs by cost estimators. This assumption is borne out by the scatter plot. If they were associated, that relationship would have to be reflected in the model. Thus, checking pairs of inputs can be informative not only in surfacing relationships that exist, but in revealing expected relationships that do not exist. If excavation cost and quantity are, in fact, related, this figure would reveal they are not related in the model. Recall from Chapter 11 that sketching the relationships between variables is an important part of model building.

* The International Shark Attack File provides an excellent example of multiple-minis at <http://www.flmnh.ufl.edu/fish/sharks/statistics/pop2.htm>.

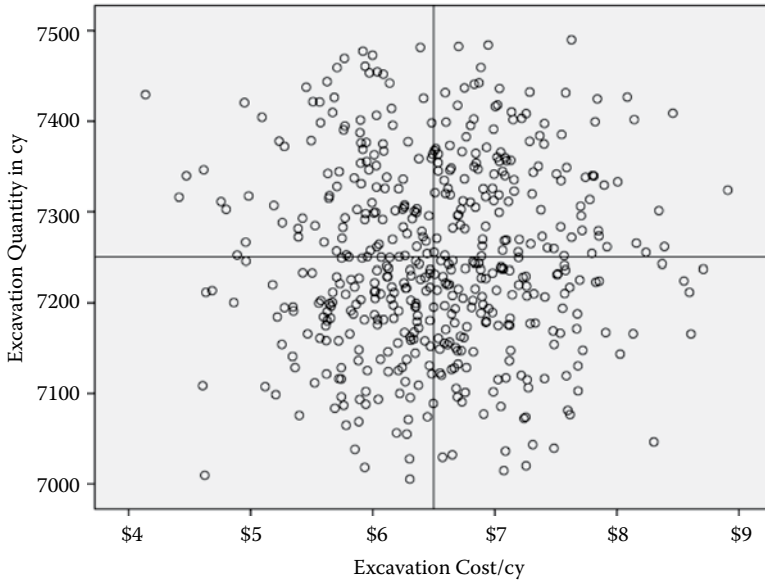


FIGURE 18.25 Scatter plot of excavation quantity and excavation cost.

Examining the scatter plots of simulation results (inputs and outputs) to verify those relationships can provide a good reality check for model results.

Scatter plots can help reveal overall patterns of relationships between variables. Lines and curves, with their tightness and direction, quickly reveal facts about relationships. It is easy to see how individual points differ from the averages when the averages are identified on the graphs. Unusual points and subclusters are also easy to identify. When clusters of points are found, this invites the assessor to explore what “membership” in the group may be based upon. Use scatter plots to explore, understand, and then explain relationships to risk managers. Remember that not every detail of the exploration and analysis needs to be documented in the main report. However, all important details should be captured either in support files for the assessment or the assessment’s technical appendices if it is formally documented.

18.5.2 CORRELATION

Correlation coefficients measure the strength of a relationship between a pair of variables. We see changes in variables all of the time in risk assessment. When two variables are changing at the same time, there are three possible relationships among the variables. When higher-than-average values of one variable tend to occur with higher-than-average values of the other variable and lower-than-average values of one variable are associated with lower-than-average values of the other, the variables covary and have a positive correlation.

TABLE 18.7
Pearson Correlation Coefficient for Scatter-Plot Variables

	Construction Cost	Gross Benefits	Net Benefits	Cubic Yards	Cost/CY
Construction Cost	1.000	.014	-.052 ^a	.026	.284 ^a
Gross Benefits		1.000	.998 ^a	.016	.025
Net Benefits			1.000	.014	.006
Cubic Yards				1.00	-.031 ^b
Cost/CY					1.000

^a Significant at the 0.01 level (two-tailed).

^b Significant at the 0.05 level (two-tailed).

The second kind of correlation is a negative one. This means the two variables vary inversely or oppositely. Higher-than-average values of one variable occur with lower-than-average values of the other variable and vice versa. The third possibility is that there is no discernible pattern among higher or lower values of one variable with another variable's values.

The correlation coefficient takes a value between -1 and $+1$. A scatter plot for variables with these minimum and maximum correlations would be perfect straight lines. The sign indicates the direction of the association, and the size of the correlation indicates the statistical strength of the relationship. A coefficient of 0 indicates the absence of a statistical association. Coefficients with an absolute value close to 0 are weak; absolute values closer to 1 indicate strong relationships.

Two commonly used coefficients are the Pearson and Spearman rank correlation coefficients. The Pearson coefficient is based on the differences from means between paired raw-data values. The Spearman rank coefficient is based on differences between the ranks of paired raw-data values.

The Pearson correlation coefficients (r) for the relationships shown in the preceding scatter plots are shown in Table 18.7. Costs and net benefits have a very small negative relationship, with $r = -0.052$. The relationship between gross and net benefits is almost a perfectly linear one, as indicated by a coefficient of 0.998 . There is a positive relationship between construction costs and the cost of excavation of 0.284 . The correlation between excavation quantities and costs is almost 0 , with $r = -0.031$.

Correlation tables are easy to produce with most commercial software packages, and they can provide a handy first screening tool to identify potential linear dependencies and independencies among model inputs and outputs.

18.5.3 RE-EXPRESSION

It can sometimes help to express the data in different ways in order to see relationships. It helps to straighten out the dependence or point scatter as much as possible; it is usually easier to see what is going on in linear relationships. If you have a curvilinear

plot, try converting your data using logarithms or roots. This can sometimes make data more linear and easier to understand.

Whatever the reasons, most of us do better understanding addition rather than multiplication. “This plus this” rather than “that times that” is just easier for most people to comprehend. Use logs to convert data and change multiplicative relationships to additive ones. Logs, although foreign to many audiences, sometimes enable you to examine a linear relationship between variables. That is often a more successful way to examine and explain data. Be aware that most people will still need help interpreting data in a log scale.

18.5.4 COMPARISON

Comparisons are often appealing to less quantitatively oriented people. Sometimes saying Sue is a head taller than Sarah, or Joe is twice as heavy as Rich, is more revealing than the actual numbers. So, when you consider comparisons use the analogy: What can you do mathematically to one person (i.e., variable of interest) to make him like another (variable of interest)?

Comparisons are often a matter of difference or ratio. Find out what is different about your two variables. To compare things, explore whether there is anything that can be added or subtracted from the data to make them comparable. Add or subtract a value to compare a value. For example, you might subtract a background illness or mortality rate from your risk estimate to show how much worse (or better) it is from the background level. Alternatively, you might add or subtract some baseline costs or revenues from financial outputs to place them in a more user-friendly perspective. This option will cost \$x more than average cost or earn \$y more than average revenues.

Ratios can sometimes support useful comparisons. Comparing the largest value to the smallest value can sometimes help. Construction costs in our example yield the following ratio $\$882,142/\$750,959 = 1.18$. This means the smallest cost estimate plus 18% covers all the potential cost possibilities. Other times ratios are not so useful; for example, net benefits range from $-\$152,035$ to $\$1,627,013$ and this ratio does not have the same easy interpretation.

18.6 ANSWER THE QUESTIONS

The reason for understanding and explaining one’s results is to answer questions and provide information useful for decision making. At the outset of this chapter we posed the following seven hypothetical questions for the example.

1. What is the probability that project costs will exceed \$1 million?

The maximum cost estimate was \$886,142. There is no chance the cost of this project will exceed \$1 million. [Figure 18.26](#) shows the distribution of costs with \$1 million, as well as the 80th and the 90th percentiles identified.

2. Identify the cost estimate that has no more than a 20% chance of being exceeded.

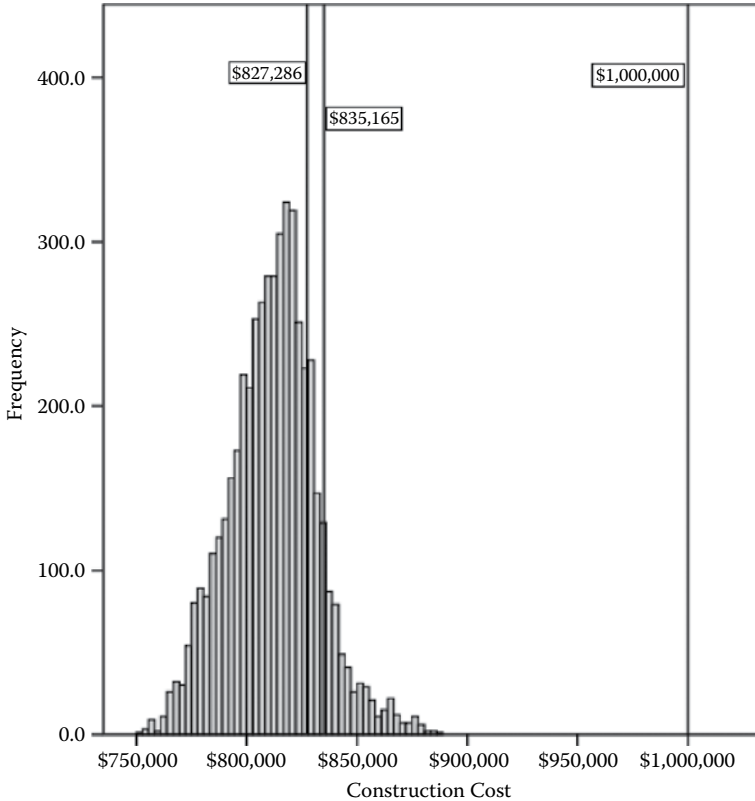


FIGURE 18.26 Distribution of project costs with selected thresholds identified.

The 80th-percentile value in the simulation is \$827,286. Because 20% of all the simulation values exceeded this amount, we assume there is a 20% chance that costs will exceed this value, as shown in [Figure 18.26](#).

3. Identify the cost estimate that has no more than a 10% chance of being exceeded.

The 90th-percentile cost estimate is \$835,165, as seen in [Figure 18.26](#). There is a 10% chance that costs will exceed this amount. Thus, faced with a decision of which of 5,000 possible cost estimates to use in the budget process, risk managers would decide the probability of a cost overrun they are willing to tolerate. If they can tolerate a 20% chance of a cost overrun, they will use \$827,000. If they want to reduce that risk to 10%, they will use \$835,000 as the cost estimate.

Costs are rather trivially different in the example. In fact, the comparison here indicated that the maximum cost estimate (based on 5,000 iterations) is only 18% more than the minimum. In projects with larger price tags or more significant uncertainties, the difference between a 20% and 10% chance of an overrun might be substantial.

TABLE 18.8
Uncertainty Rankings Based on Simple Linear Regression Standardized Coefficients

Cost Input	Standardized Regression Coefficient
Number of pieces of sheet pile	0.695
Lands and damages cost	0.489
Cost of mobilization and demobilization	0.297
Excavation cost/CY	0.293
Tremie concrete cost	0.184
Tremie concrete quantity	0.160

4. What is our maximum exposure to cost overruns associated with these costs?

The maximum cost estimate was \$886,000, and the 20% and 10% overrun risk costs are \$827,000 and \$835,000, respectively. Therefore, the exposure to cost overruns is \$59,000 and \$51,000, respectively, if either of these values is used as the estimate of record. If the consequences associated with these chances of an overrun are unacceptable, we will have to refine our analysis.

5. What are the most significant cost uncertainties?

Borrowing from lessons learned in [Chapter 17](#) on sensitivity analysis, we can list the most significant uncertainties using simple regression analysis, as shown in [Table 18.8](#). To improve the cost estimate and reduce the variation in cost, we are best advised to improve our estimate of the amount of steel sheet pile needed, followed by getting a better idea of real estate costs. If we examined contributions to the variation in net benefits or any other assessment output, we might expect a different list of significant inputs.

6. What is the probability that this project will be economically feasible, i.e., net benefits equal or exceed zero.

We have seen from the previous analysis that there is a 27.3% chance that this project will produce negative net benefits. Thus, there is a 72.7% chance that the project is economically feasible.

7. What is the most likely level of net benefits?

We are 90% sure net benefits will be between $-\$71,000$ and $\$1,031,000$, as seen in [Figure 18.27](#). Notice, this questions forces us to select a point estimate. Our best estimate is the median value, $\$46,000$. The range in possible outcomes is substantial. We have learned from our analysis of the data that the single greatest uncertainty in this project evaluation is whether the adjacent eroding land will be in agricultural use, which will result in lower net benefit estimates or if the land is rezoned it will result in larger net benefits with no probability of a negative return. In short, the project may be worth doing to protect commercial land but it is not as clear that it is worth doing to protect agricultural land. The single most useful thing we could do to reduce significant uncertainty is try to learn whether this land will be rezoned or not.

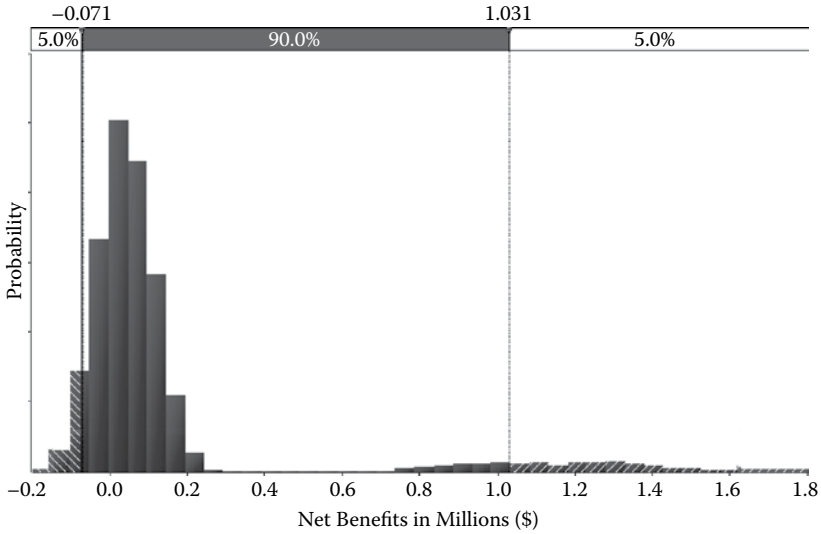


FIGURE 18.27 Distribution of project net benefits with a 90% confidence level.

18.7 DATA VISUALIZATION

Technology offers exciting and promising new ways to help convey the information embedded in data. Data visualization is concerned with the visual representation of information obtained from data. Friedman (2008) describes the main goal of data visualization as communicating information clearly and effectively through graphical means. He goes on to argue that conveying ideas effectively requires both aesthetic form and functionality to go hand in hand, providing insights into a data set by communicating its key aspects in a more intuitive way. Designers often fail to achieve a balance between design and function, creating gorgeous data visualizations that fail their main purpose, which is to communicate information.

DATA GRAPHICS

“Data graphics visually display measured quantities by means of the combined use of points, lines, a coordinate system, numbers, symbols, words, shading, and color. The use of abstract, non-representational pictures to show numbers is a surprisingly recent invention...”

“At their best, graphics are instruments for reasoning about quantitative information. Often the most effective way to describe, explore and summarize a set of numbers—even a very large set—is to look at pictures of those numbers. Furthermore, of all methods for analyzing and communicating statistical information, well-designed data graphics are usually simplest and at the same time the most powerful.”

Source: Edward R. Tufte, Introduction to The Visual Display of Quantitative Information.

This balance between design and function opens some exciting possibilities for risk assessors to both convey the meaning of their work and to support decision making. Finding new ways, like interactive graphics, to make data available to people so they can examine it themselves in ways that are meaningful to them may be the greatest promise of data visualization and its related fields of information graphics, information visualization, scientific visualization (a three-dimensional variation), and statistical graphics. Inventing interesting and innovative visual displays of complex data, information, and knowledge that can be easily and quickly understood is one of the most promising fields for aiding risk assessors in communicating their work to risk managers and the public.

Edward Tufte (1983, 1990, 1997) has written a well-received series of books on information graphics. His principles of graphical excellence and integrity are summarized here.

Graphical excellence:

- Well-designed presentation of interesting data is a matter of substance, of statistics, and of design.
- Communicates complex ideas with clarity, precision, and efficiency.
- Gives the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space.
- Almost always is multivariate.
- Tells the truth about the data.

Tufte's six principles of graphical integrity are:

- The physical representation of numbers on a graph should be directly proportional to the numerical quantities represented (use consistent size for all numbers).
- Avoid graphical distortion and ambiguity with clear, detailed and thorough labeling. Explain the data on the graph itself. Label important events in the data.
- Show data variation, not design variation.
- In time-series displays of money use constant dollar amounts unless you have a specific reason not to.
- The number of information carrying (variable) dimensions depicted should not exceed the number of dimensions in the data.
- Graphics should never depict data out of context.

Tufte is also quite passionate in his views about data ink, i.e., the ink on a graph that represents data. He says good graphics maximize data ink and erase as much nondata ink as possible. He offers these five points:

- Above all, show the data.
- Maximize the data-ink ratio.
- Erase nondata ink.
- Erase redundant data ink.
- Revise and edit all graphics.

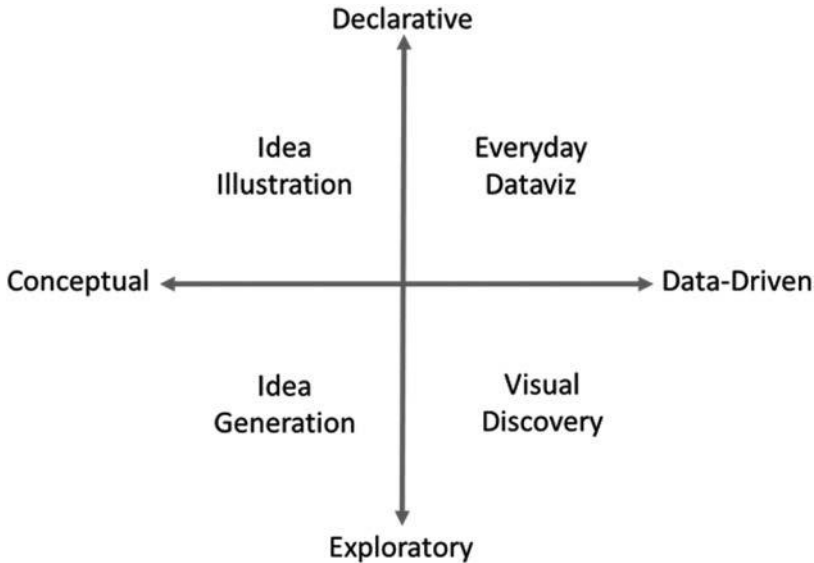


FIGURE 18.28 Four types of data visualizations. (Adapted from Berinato, Scott. 2016. *Good Charts*. Boston: Harvard Business Review Press.)

Scott Berinato (2016) offers an extremely useful typology for chart making that is the subject of this section. His typology is derived by answering two questions. First, is the information conceptual or data-driven? Next, are you declaring something or exploring something? The first question tells us what you have, the second question tells us what you are doing. The answers to these two questions yield four types of visualization as depicted in [Figure 18.28](#). Conceptual information focuses on ideas, data-driven information focuses on statistics. The goal of conceptual information is to simplify or teach. “Here is how the risk can be mitigated.” The goal of data-driven information is to inform or enlighten. “Here are the historical damages caused by this risk.”

Thanks to the growing number of affordable tools, creating visuals is easy and cheap, regardless of one’s data or design skills. As a result, this reinforces the tendency to turn on the computer, create a bunch of charts, then choose the one that appeals most to its creator, without ever thinking about the purpose and goals of the chart. Berinato says convenience has become a tempting replacement for good. This convenience can lead to charts that are adequate at best and ineffective or misleading at worst. His four visualization types are summarized below.

Idea illustration clarifies complex ideas by drawing on our ability to understand metaphors and simple design conventions. Organizational charts, hierarchies, decision trees, processes, pyramids, concentric circles, relationships, and the like are examples as is the 2×2 matrix of [Figure 18.28](#). The focus should be on clear communication, simple structures, and the logic of the ideas. The ability to pare things down to their essence is a useful skill for preparing these visuals. The goals of idea illustrations are learning, simplifying and explaining ideas.

Idea generation is used to find new ways of seeing things and to answer complex management challenges: generating the sequence of events in a risk chain, brainstorming risk management options, restructuring an organization, designing a new business process, codifying a system for making risk management decisions as found in [Chapter 3](#), are all examples suitable for idea generation graphics. These visuals also rely on conceptual metaphors. The goal of idea generation is problem solving, discovery, and innovation. Think of a white board covered with conceptual, exploratory doodles and drawings aimed at rendering fuzzy, muddled ideas crisp and clear. These begin as rapid sketches that may evolve into refined designs.

ICONS OF DATAVIZ

Rene Descartes is credited with inventing the Cartesian coordinate graph with x and y axes in the 17th century. This was used for graphing mathematical equations. It was not until the late 18th century that William Playfair used this graph system to communicate quantitative data. Playfair is also credited with inventing bar and pie charts. In the second half of the 20th century, John Tukey's invented field of exploratory data analysis introduced the world to the power of data visualization. Edward Tufte later pointed out that there were effective ways of displaying data visually and then there were the ineffective ways that most people were doing it.

Visual discovery is the most complicated quadrant. Its goals are making sense of things, spotting trends, and deep analysis. Visual discovery has two dimensions: visual confirmation and visual exploration. Visual confirmation attempts to answer questions like, is what we suspect actually true, and what are some other ways of depicting this idea? Confirmation relies on common chart types, but the work is usually done informally as one searches for the best way to demonstrate confirmation of a point.

Visual exploration is much more open-ended and data-driven. This is used when analysts seek new truths in the data. Data plots are more complex and multivariate. Charts may include multiple data sets or load dynamic, real-time data into a system that updates automatically. Complex data may suit specialized and unusual visualization. Statistical modeling can benefit from such exploration.

Analytical, programming, data management, and business intelligence skills are more important than the ability to create presentable charts for visual exploration. If you use experts to prepare visualizations, they will be found on the right-hand side of [Figure 18.28](#).

Everyday dataviz comprises the basic charts and graphs you normally see, like line charts, bar charts, pies, scatter plots, and the like. The goals of these charts are to affirm and to establish a context. The keys to these charts are simplicity, clarity, and consistency. Most such visualizations communicate a single message. Additional data and a more comprehensive view are not appropriate for these charts. An everyday dataviz that cannot stand on its own, has failed.

18.8 BIG DATA AND RISK MANAGEMENT

Marr (n.d.) says “Big data” is a concept that is continually evolving and being reconsidered, even as it drives many of the ongoing waves of digital transformation, including artificial intelligence, data science and the Internet of Things. Big data starts with the explosion in the amount of data generated since the rise of computers, the Internet and technology capable of capturing data from this digital age. Data, of course, are not new. We have always had data. It used to be kept in ledgers, paper, customer records, physical spreadsheets, textbooks, files and in other physical manifestations. It is the way we store, organize and access data that are new. Information is now available at the click of a mouse.

More data now cross the internet every second than were stored in the entire Internet 20 years ago. Every two days we create as much data as we did from the beginning of time until 2000 (Marr, n.d.). By 2020, the digital information available will have grown to 50 zettabytes. A zettabyte is 1,000,000,000,000,000,000,000 bytes. The problem, or opportunity, depending on one’s perspective, is that almost every digital action we take leaves a trail. We generate data when we shop, whenever we go online, with our GPS-equipped smartphones, and when we communicate with friends through social media. Now add to this the data our devices generate when they communicate with each other, then factor in the data generated by industrial machinery around the world and we can begin to understand zettabytes. Big data is the collection of all these data as well as our ability to use it to our advantage.

Marr says, “Big data works on the principle that the more you know about anything or any situation, the more reliably you can gain new insights and make predictions about what will happen in the future. By comparing more data points, relationships begin to emerge that were previously hidden, and these relationships enable us to learn and make smarter decisions.”

The first question a risk-driven organization needs to ask itself is not “What do we think?” but, “What do we know?” Big data has the potential to change the answer to that question. With big data, risk assessors can measure and risk managers can manage more precisely than ever before. Assessors can make better predictions and managers can make smarter decisions. Risk managers can target more-effective interventions in areas that so far have been dominated by gut and intuition rather than by data and rigor.

The evidence-based decision-making practices of risk management are tailor made for big data. Risk management can become more agile. Nearly real-time information in an increasing number of arenas can transform the intervention algorithms, interventions, and intervention results obtained by risk management. Once the risk community embraces big data we will know radically more about the risks we face as a society, as an organization, as an individual. That knowledge can then be translated into improved decision making and performance. Big data has the potential to change long-standing ideas about the value of experience, professional judgment and expert opinion, hallmark methods of addressing the uncertainty encountered in risk analysis. Big data promises a management revolution and part of that will be a risk management revolution.

Three attributes distinguish big data from analytics.

Volume. About 2.5 exabytes (10^{18} bytes) of data have been created each day since about 2012. Walmart collects more than 2.5 petabytes (10^{15} bytes) of customer transactions data every hour.

Velocity. The speed of data creation can be even more important than the volume. Real-time information, or close to it, makes it possible for a company to be more agile than its competitors.

Variety. Big data include all the traditional forms of data plus the deluge of data that comes from new applications and devices. Twitter data began in 2006, for example. Each next generation cell phone creates new databases.

Source: McAfee & Brynjolfsson, 2012.

The U.S. Army Corps of Engineers has decades worth of inspection reports from many hundreds of water resource projects across the country and unknown amounts of sensor data. If they could harness the information in these data it would certainly provide an invaluable aid to understanding and forecasting future problems. The food industry has gargantuan amounts of food inspection data. If these data are ever shared they would provide tremendous advances in our ability to prevent foodborne illness and unintentional contamination of foods. As smaller businesses develop the ability to harness some of the big data sources they will be forever changed by the data revolution. Imagination and inertia are the only real impediments to great leaps forward in risk analysis as a result of big data.

With recent advances in storage and analytics we can capture, store and work with different types of data such as databases, photos, videos, sound recordings, written text and sensor data. With advanced analytics we can take some of these big data and run millions of simulations until we find a pattern or an insight that helps us solve the problem we are working on. This capability is revolutionizing the world of business. A 2017 survey of business executives (Bean, 2017) showed a near majority, 48.4%, say their firms are achieving measurable results from their big data investments. They are using big data to decrease expenses, find new innovation avenues, launch new products and services, add revenue, increase the speed of current efforts, transform business for the future and establish a data-driven culture. For example, companies can now predict with incredible accuracy what a specific segment of the public will want to buy and when.

Big data offers a great deal of potential for assessing and managing risks. Big data are being used to improve healthcare and police protection. Earthquake prediction comes closer to being a reality and storm track forecasting gets better each storm season. Marr reports that patterns of human behavior help organizations give relief to survivors of natural disasters. Marr (2017b) identified 10 areas where big data were being used to excellent advantage. These are:

1. Understanding and Targeting Customers-big data is used to better understand customers and their behaviors and preferences to create predictive models
2. Understanding and Optimizing Business Processes-stocks, supply chain, delivery route, talent acquisition, and the like become more efficient because of big data
3. Personal Quantification and Performance Optimization-individually we can benefit from data generated by smart watches, bracelets and armbands that collect data on our calorie consumption, activity levels, and our sleep patterns
4. Improving Healthcare and Public Health-we can decode DNA strings that allow us to find new cures and better understand and predict disease patterns, phones are used for biomedical research, we can better predict the developments of epidemics and disease outbreaks
5. Improving Sports Performance-we can track the performance of every player in team sports, sensor technology in sports equipment provides feedback on our game and how to improve it
6. Improving Science and Research-the computing power of big data could be applied to any set of data, opening up new sources to scientists
7. Optimizing Machine and Device Performance-helps machines and devices become smarter and more autonomous
8. Improving Security and Law Enforcement-improving security and enabling law enforcement to foil terrorist plots, to detect and prevent cyber-attacks, to catch criminals and even predict criminal activity and to detect fraudulent transactions
9. Improving and Optimizing Cities and Countries-optimize traffic flows, creating Smart Cities to operate transport infrastructure and utility processes
10. Financial Trading-High-Frequency Trading (HFT)-uses big data to make trading decisions

Along with the potential to improve the assessment, management and communication of so many risks, big data bring new risk challenges in the form of data privacy, data security, and data discrimination (Marr, 2017a). Big data contains a lot of information about our personal lives that we have a right to keep private. We are being challenged to strike a balance between the amount of personal data we divulge and the convenience that big data offers.

18.9 SUMMARY AND LOOK FORWARD

Quantitative risk assessments, especially probabilistic ones, produce a great deal of data. The starting point for explaining these results to risk managers is understanding the results. Risk assessors must carefully avoid overreliance on any one numerical result. The best way to understand and then explain one's data is to examine the quantities, their probabilities, and the relationships between and among key variables, and then to answer the risk manager's question as clearly, concisely, and completely as possible while accounting for the remaining uncertainty.

There are a great many numerical and graphical tools to aid the presentation and understanding of data to risk managers. Be sure to look for ways to convey the nonexistence of “the number.” Refuse to give it! The five-number summary is a convenient way to do this. Technology is making a great many new opportunities for displaying the data available to assessors and managers. Big data analysis offers a great deal of promise to the advancement of the risk analysis sciences.

Conscious attention is a scarce resource for decision makers so they tend to be selective about the information they use for decision making. If risk management is to succeed, we simply must find practical and effective ways to help decision makers become aware of and to account for uncertainty and the risks they give rise to in decision making. The next chapter, *Decision Making Under Uncertainty*, presents practical ways to do just that. It also includes an overview of several popular decision analysis techniques that are commonly applied in uncertain situations.

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19 Decision Making Under Uncertainty

19.1 INTRODUCTION

Judgments and decisions are often made intuitively rather than analytically. Decision makers draw upon personal memories, experiences, and associations that are supplemented by vast repositories of unconscious material that include the cognitive biases and heuristics of [Chapter 14](#). They weave these materials together into explanatory stories that support their judgments and decisions.

Daniel Kahneman's (2011) work offers an explanation for how we formulate explanatory stories that we tell ourselves to give our world shape and meaning. We "humans," he argues, strongly prefer "fast" stories to "slow" logical processes and analytical judgments. He describes two discrete mental systems, System 1 and System 2, to explain this phenomenon. System 1 represents our fast, intuitive, and typically story-based decision-making and judgmental processes. It is also the dominant system that draws upon a blending of memories, associations, and quickly retrieved information to produce causal and associational thinking, which we use to create coherent explanatory stories upon which we base our judgments and decisions.

Unfortunately, System 1, although very fast and quite good at constructing compelling stories, is also prone to mistakes and systemic errors, especially so when we rely on biases and heuristics. System 2, by contrast, takes effort. It relies on laborious algorithms, probability, science, and evidence. System 2 can be used to monitor and "check" the accuracy of System 1 thinking, but it does not control System 1. The faster and intuitive System 1 typically dominates, and it often prevails when the two systems are at odds.

If decision making does not change with risk analysis, then we have found its Achilles heel. It makes no sense to focus so much attention on the evidence and uncertainty in risk assessment if decision makers do not intentionally and carefully consider them during decision making. Risk analysis can be said to represent an effort to replace System 1 decision making with System 2 decision making.

In risk analysis, decision makers cannot count on the outcomes of their decisions. There is a range of outcomes, and decision makers need to understand that. Risk is an important decision-making criterion. When risk is the only criterion, decisions are risk-based. When risk is an influential member of a set of decision criteria, decisions are risk-informed. In risk-based decision making, risk estimates and risk narratives form the basis for decisions. Unacceptable levels of risk trigger action. By contrast, risk-informed decision-making trades off levels of risk with other criteria to arrive at a decision.

Risk analysis is a paradigm shifting decision-making framework. Analysts take great care to account for and document the potential effects of uncertainty on decision

outcomes. Uncertainty is the engine of change here. In a decision-making context it arises in one of two fundamental ways. First, the decision maker may not know the true values of one or more decision criteria because they are uncertain as a result of knowledge uncertainty, natural variability, or model uncertainty encountered while estimating those values. In these cases, decision makers must understand the resulting range of potential outcomes, what can cause those outcomes to occur, and their relative likelihoods. Second, the decision maker may understand the uncertainty inherent in the decision and just not know what to do in the face of that uncertainty.

Despite the best efforts of risk analysis, there is a mismatch between the clarity we hope the evidence can provide and the degree of certainty the evidence actually delivers. There is no shortage of methodologies for decision making under uncertainty. They range from elegant simplicity to impenetrable complexity. What the risk management community of practice needs is a practical approach, one that can be applied by decision makers with no special qualification beyond their interest in better decisions and better decision outcomes.

This chapter begins by considering the use of several decision-making strategies. The notion of risk analysis as evidence-based decision making is revisited in order to address one of the more perplexing paradoxes of decision making under uncertainty: how much evidence is enough to make a decision?; or, stated differently, how much uncertainty can a decision maker accept? Residual uncertainty is introduced as a formal topic to be considered by decision-makers and to be communicated to decision makers. The chapter then turns its attention to offering a practical approach for decision makers who must decide under uncertainty. Finally, some more conventional approaches to decision making under uncertainty are presented before it concludes.

19.2 DECISION-MAKING STRATEGIES

Heuristics and bias research is usually said to have begun in the 1970s with the work of Tversky and Kahneman (1974). The research originally focused on the field of prediction under uncertainty and the estimation of probabilities and frequencies (Keren and Teigen, 2004), consequently, those heuristics were introduced in [Chapter 14](#). It did not take long for the research to be generalized to the whole area of judgment and decision making. This is why the idea is revisited again here.

[Figure 19.1](#) presents the central elements of a decision process. There are the characteristics of the decision problem, which can be divided into the complexity of the decision task and the complexity of the decision context, the decision maker's goals and preferences, the decision strategy used, and the decision that is made.

The complexity of the decision task refers to the number of alternatives from which to choose and the number of attributes upon which to judge. The complexity of the decision context is affected by such things as the nature of the trade-offs among the alternatives, the range of attribute metrics (alternatives with more similar metrics tend to be more difficult for decision makers to differentiate), the quality of the alternatives, and their similarities or differences.

The decision maker's goals can include such things as maximizing the accuracy of a decision, minimizing the cognitive effort required for the decision, minimizing the

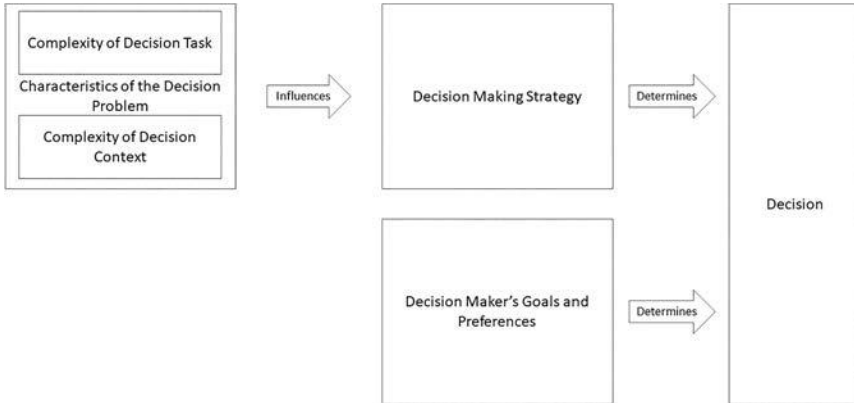


FIGURE 19.1 Central elements of a decision-making process. (Adapted from Pfeiffer, 2012.)

negative emotions experienced while deciding, and maximizing the ease of justifying a decision (Bettman et al., 1998). The decision maker's preferences are important for determining attribute importance or weights, aspirational levels, that is, cutoff-values that identify thresholds or acceptable levels of an attribute, and value functions.

Decision making strategies vary by such characteristics as the amount of available information that is processed, whether trade-offs are considered explicitly or not, whether decision makers process information by alternative or attribute, the use of weights and/or aspiration levels, whether alternatives are screened in or out, the use of quantitative or qualitative data, and the like. All of these elements contribute to the decision that is made.

Risk analysis is evidence-based decision making under conditions of uncertainty. Classical economics relies on the notion of a rational decision maker, who possesses complete knowledge and has a stable set of preferences that are known well, along with sufficient computational skill to make decisions that achieve objectives, such as utility maximization, cost minimization, and profit maximization. Decision researchers increasingly see an alternative decision maker, one who constructs preferences and beliefs on the spot when needed rather than drawing on known, well-defined, and stable preferences (Payne and Bettman 2004). These preferences are based on the use of a variety of decision heuristics. If we are going to influence decision making under uncertainty in a positive direction, it is incumbent upon us to understand something about the ways that decision makers process information.

Conscious attention is “the” scarce resource for decision makers (Simon, 1978). This means that decision makers will be selective about the information they use for decision making. Payne and Bettman (2004) point out that this highly selective decision processing does not necessarily mean poor decisions are being made. However, to the extent that decision makers attend to irrelevant information or neglect instrumental information, poor decisions can be made. Thus, it is crucial to help decision makers focus on instrumental information.

Simon (1955) introduced the idea that limited cognitive capacity requires the use of decision strategy heuristics that rely on selective and simple use of information to

solve decision problems. These heuristics are a different set than those introduced in [Chapter 14](#). The information processing approach to judgment and decision making assumes an individual possesses a set of such strategies, acquired through experience and perhaps formal training. Payne and Bettman conclude that heuristic methods for solving complex problems with limited information generally produce satisfactory outcomes. However, they can and do produce decision errors that tend to be systematic and predictable. So, let us examine some of the more common strategies people use to solve the classic multiattribute choice problem.

A multiattribute problem typically has a goal, such as to choose the best alternative and multiple ($n > 2$) alternative solutions from which to choose. The decision is based on each alternative's contribution to a set of multiple ($n > 2$) attributes. Different people use different strategies. Some process information on multiple attributes for one alternative before moving to the next alternative, that is, they have an alternative focus. Others will examine the values of several alternatives for a single attribute before moving to another attribute, that is, they have an attribute focus.

Several such strategies are introduced in [Table 19.1](#). Each is summarized in turn. The weighted additive strategy is often considered a normative rule for decision making. Each attribute measurement for an alternative is assigned a utility value, and those values are weighted by subjective weights assigned to each attribute and summed. The alternative with the maximum sum of utilities is the preferred option. This is a variation of the equal weight heuristic in which all attributes have the same weight; this is equivalent to a simple sum of the unweighted utilities. Multicriteria decision analysis methods would include the weighted additive method.

In the lexicographic heuristic, decision makers first consider the attribute with the highest importance. They select the alternative with the highest or an acceptable value for that attribute. If this produces more than one alternative, they iteratively compare the remaining alternative for the next most important attribute. This process continues until there is only one alternative left. A related heuristic is the minimum difference lexicographic rule. The distinction here is that attribute values for two alternatives are

TABLE 19.1
Comparison of Characteristics of Four Information Processing Decision Strategies

Characteristic	Weighted Additive Strategy	Lexicographic Heuristic	Satisficing Heuristic	Elimination by Aspects Heuristic
Information used	All	Some	Some	Some
Explicit consideration of tradeoffs	Yes	No	No	No
Basis for information processing	Alternative-based	Attribute-based	Alternative-based	Attribute-based
Attribute Weights	Explicit	Implicit	None	Implicit
Aspiration levels	No	No	Yes	Yes
Elimination of alternatives	No	Yes	No	Yes

considered to be equal if their difference is less than a value determined by decision makers. That value is based on a threshold above which a decision maker notices a difference between two attribute values. Thus, for example, cost estimates within \$1,000 of one another might be considered equal costs; in another context costs within \$1,000,000 of each other might be considered equal.

With the satisficing heuristic, decision makers consider alternatives in the order in which they occur in the choice problem. The attributes of the first alternative are compared to the corresponding aspiration levels set by the decision makers for each attribute. Decision makers stop evaluating alternatives as soon as one of them meets all aspiration levels. If no alternative meets this criterion, the aspirational levels are reduced or new alternatives are formulated. With the satisficing-plus strategy decision makers consider a subset of the attributes, and the first alternative to meet their aspiration levels is chosen. The conjunctive strategy is based on the elimination of alternatives if they fail to meet the aspirational threshold of one or more attributes. Satisficing screens alternatives, conjunction screens them out.

The elimination by aspects strategy begins with decision makers sorting the attributes from the most important (highest weight) to the least important. Starting with the most important attribute, alternatives are removed if the value of the alternative for that attribute does not meet the aspiration level. Those alternatives that pass the first round of evaluation are iteratively removed from consideration by considering the next most important attribute. The strategy continues until one alternative is left. If a unique choice is not reached, the aspirational levels can be adjusted.

It is clear that some of these heuristics conserve cognitive efforts. The lexicographic strategy is highly selective in the information it uses. Stopping after a satisfactory alternative is identified, in the satisficing heuristic, and can save a lot of information processing. It is not uncommon to see decision makers use a combined strategy, beginning with an alternative eliminating strategy and then analyzing the remaining alternatives in more detail.

Payne and Bettman (2004) found that decision heuristics can be highly accurate with substantial reductions in cognitive effort but no one heuristic is accurate across all environments. Their research showed that decision makers increase their use of decision heuristics as the decision task becomes more complex. For example, when a decision offers many alternatives decision makers tend to try to eliminate some of them as soon as possible. However, that strategy may shift to a more complex strategy as the number of alternatives decreases. Heuristics are especially useful when the decision maker is under time pressure. Most heuristics offer significant time savings over strategies like the weighted additive. In summary, they found that individuals use a variety of strategies to make multiattribute decisions, including heuristics that rely on highly selective information processing.

Payne and Bettman (2004) argue that our limited cognitive capacity requires us to use these mechanisms that involve the selective and simple use of information to solve decision problems. They further argue that we use these heuristics because they generally produce satisfactory outcomes. We may use them because there is no other option when our limited cognitive capacity or limited time for processing information act as constraints on our decision-making options. We may choose to use them

because of the cost in time or effort of using our scarce resource of computational capacity or we may use them because they have worked in the past.

What we do know is that the rational decision maker of economic theory who follows the laws of logic, knows the calculus of probability, and is equipped with perfect information does not describe the way we make decisions. Most risk problems are intractable computationally, that is, we neither know the optimal solution nor a method for finding it. This opens the door to the use of fast and frugal heuristics. Fast means it can solve the problem quickly, within seconds even, and frugal means it requires little information. The early literature concluded that heuristics generally lead to second-best choices at best and irrational choices at worst. More recent literature suggests heuristics may do better than was once thought.

This chapter offers examples of rational decision making in Section 19.11. It should be used whenever possible. However, you are cautioned to bear in mind that real decision makers often rely on heuristics and biases that can influence judgments and decision making. This is especially true because decision making under uncertainty leads back to the roots of heuristic and bias research. Thus, it is important to get the most instrumental information in front of decision makers and to do a good job early in the risk management process of identifying decision criteria.

19.3 EVIDENCE-BASED DECISION MAKING

Everyone agrees that public policy should be based on the best available scientific and technical information. Most people would agree that private sector decisions are, likewise, enhanced by facts and sound evidence. The central role of evidence in effective decision making is unassailable. Even so, it is not unusual for experts and decision makers to decide based on heuristics and bias or to have different interpretations of what the evidence means. The Council of State Governments (2013) offers six reasons why these differences in interpretation seem to emerge:

Lack of Information—Despite our access to vast and growing amounts of data and information, we rarely face policy problems with an obvious solution. Problems include not enough data; too much data to absorb; outdated data; restricted access to certain data; inconclusive data; data irrelevant to the decision at hand; existing studies have different objectives, assumptions, or methods of data collection and analysis; and insufficient analysis of the existing data.

Lack of Agreement—There can be fundamental disagreements about the information needed to inform a particular decision. Different parties may define the problem and objectives differently resulting in different conclusions about the information needed.

Lack of Incentives—The paradigm risk analysis would displace in public policy is an adversarial one that can pit science against politics and one interest group against another. Adversarial advocates cherry-pick their evidence in order to prevail in the process. There is little interest in resolving their differences in an evidence-based manner. Adversaries are adept at exploiting existing uncertainty and incomplete understanding is often touted as a

reason for delaying decisions. The adversarial use of science can undermine trust in science, experts, and the decision-making process.

Lack of Capacity—Some stakeholders may lack access to data due to the lack of scientific and technical resources or because of data confidentiality. Stakeholders differ in their expertise and ability to understand the data. Different stakeholders can be expected to have different tolerances for risk and uncertainty.

Lack of Communication—A fundamental lack of communication and understanding among experts, decision makers, and advocates can give rise to disputes. Scientists may be interested in different issues than decision makers and stakeholders. Participants may have unrealistic expectations of the experts, science, and the ability to predict the future.

Media Hyperbole or Oversimplification—Conflict sells. Some media may overemphasize minor disagreements and make the issue look out of proportion. Writers may lack the technical background necessary to discern details or nuance when summarizing a story or gathering information on a debate.

In light of these reasons for regarding the evidence in different ways, let us consider the nature of evidence and what makes for good evidence. Evidence has been summarized here as anything that helps assessors discern the truth about a matter of concern to them. Evidence, then, is factual information that helps the risk manager or other decision maker reach a conclusion and form an opinion about something. Evidence-based decision making embodies the modern view of scientific policy advice in which science informs policy by producing objective, valid, and reliable knowledge (Funtowicz 2006).

Figure 19.2 presents an evidence hierarchy. The predictive power of the decision increases as the supporting evidence moves up the hierarchy. Decision Innovations (<http://www.decision-making-solutions.com>) defines the evidence hierarchy categories as follows:

- Analogical evidence is a weak form of evidence that suggests something true about one thing is also true about another thing due to its similarity.

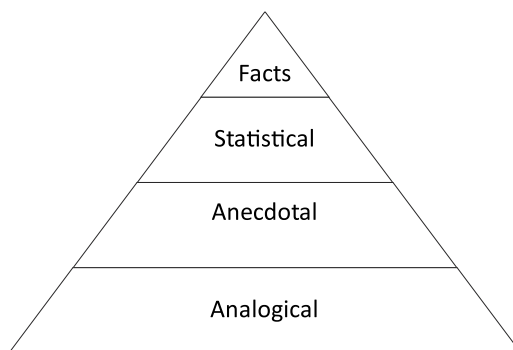


FIGURE 19.2 Evidence hierarchy.

- Anecdotal evidence arises from small sample sizes that are frequently not representative of typical experience. Anecdotal evidence indicates possibility without establishing likelihood.
- Statistical evidence provides evidence of causality, but it does not prove causality. Statistical inference helps establish causal relationships.
- Facts represent verifiable actual occurrences. They include empirical and historical evidence as well as scientific facts that can be confirmed with repeatable experiments.

The legal system, which has already done a great deal of careful thinking about evidence, provides a second way to consider evidence. In general, it identifies four types of evidence:

1. Real evidence, which includes tangible things
2. Demonstrative evidence, which may include a model of what likely happened at a given time and place
3. Documentary evidence, like reports, letters, and other documents
4. Testimonial evidence, which comprises witness testimony

The basic prerequisites for admissible evidence are that it be relevant, material, and competent. These are also reasonable requirements for risk analysis. Evidence is relevant if it has a tendency to make a fact more or less probable than it would be without the evidence (Federal Rules of Evidence, Rule 401, <https://www.law.cornell.edu/rules/fre>). Evidence is material if it is offered to prove a fact that is at issue in the case. Evidence is competent if it tends to prove the matter in dispute. These are qualities decisions makers would value as the judiciary would.

EVIDENCE AND CONFIDENCE

When making decisions under uncertainty, decision makers should take care to understand and appreciate the strengths and weaknesses of the evidence upon which a decision will be based. Relevant material and competent evidence free the decision maker to rely more confidently on the facts than they can absent such evidence.

There are several other terms that can be profitably borrowed and adapted from the legal field. Evidence that tends to prove a factual matter by proving other events or circumstances from which the occurrence of the matter can be reasonably inferred is called circumstantial evidence. Evidence that is independent of and different from, but that supplements and strengthens evidence already presented as proof of a factual matter is called corroboratory evidence. Hearsay evidence can be described as a statement offered as proof that what is stated as true is true. Hearsay is usually deemed inadmissible as evidence. There is a rule of evidence, the exclusionary rule, that excludes or suppresses evidence obtained improperly.

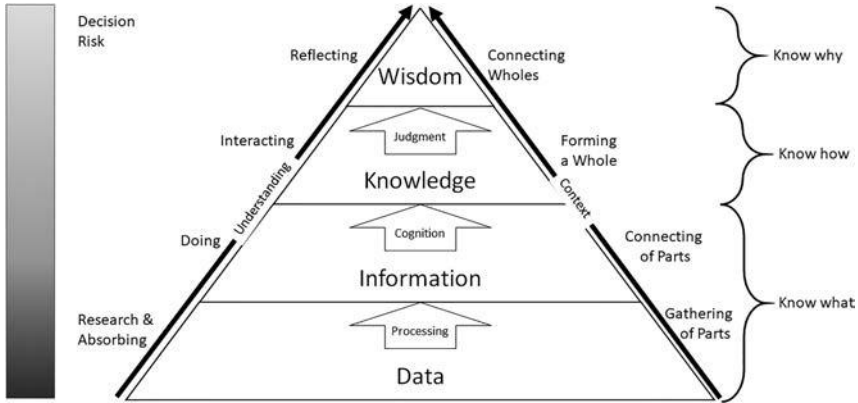


FIGURE 19.3 DIKW pyramid mashup of two other pyramids.

Although these notions were developed for a different field of inquiry, this is not a bad lexicon for risk assessors to borrow from. Examine each bit of information to assure its provenance and use only evidence that are relevant, material, and competent.

Now, let us turn our attention to the nature of this evidence and how it becomes useful for decision makers. Russell Ackoff (1989) is credited with being among the first to represent the knowledge hierarchy as a pyramid. Figure 19.3 presents a stylized data, information, knowledge, wisdom (DIKW) pyramid that is a mash-up of a U.S. Army Knowledge Managers pyramid (Wikipedia, 2018a) with a pyramid developed by Karim Vaes (2013).

Data are raw facts that have no meaning of themselves. Data simply exist in a usable or unusable form. Ackoff (1989) describes data as symbols that represent the properties of objects and events. Rowley (2007), who studied the DIKW definitions provided in textbooks, describes data as “being discrete, objective facts or observations, which are unorganized and unprocessed and therefore have no meaning or value because of lack of context and interpretation.” Truth and objectivity are fundamental properties of data and facts, so incorrect facts or false data are precluded from this definition. A spreadsheet database full of peak daily streamflow measurements at a specific gage location is an example of data. Data are gathered through research or absorbed from the world around us.

Ackoff (1989) says information consists of processed data where the data have been processed specifically to increase its usefulness. Thus, information is data that has been given meaning by way of some relational connection. Rowley (2007) describes information as “organized or structured data, which has been processed in such a way that the information now has relevance for a specific purpose or context, and is therefore meaningful, valuable, useful and relevant.” In contrast to Rowley’s structural definition of information, Henry (1974) defined information as “data that changes us.” Using the streamflow data to produce a flow-frequency curve is information. Information is gained by doing something with data.

Knowledge is the collection of relevant information with the intent to be useful (Wikipedia, 2018b). It can also be described as the synthesis of multiple sources of information over time. Thus, knowledge is a deterministic process. Someone must put forth effort to acquire knowledge, and this knowledge has useful meaning to the seeker. Knowledge is sometimes described as information connected in relationships. Using the information from flow-frequency and depth-flow curves, analysts can develop knowledge about the depth and frequency of flooding in a town. Knowledge is gained by combining information in interactive ways.

Ackoff (1989) describes wisdom as the ability to increase effectiveness. Wisdom requires judgment and it adds value. Knowledge and understanding are commonly conflated in discussions of the DIKW pyramid. The values implied by knowledge are inherent to the analyst and are, therefore, unique and personal. Wisdom can ask questions to which there are no easily-achievable answers. Wisdom is the process by which we discern, or judge, between right and wrong, good and bad, ethical and unethical. Knowledge of a flood risk can lead to wisdom in managing that risk and preventing similar risks in the future through flood risk management measures and land use controls.

Understanding is a cognitive and analytical process that runs throughout the wisdom building process; it includes processing, cognition, and judgment. It facilitates movement from one tier to the next. Understanding is the process by which we recognize information in data; it is how we construct knowledge from information, and, perhaps most importantly, it is how we take existing knowledge and synthesize new wisdom from it. Understanding facilitates useful action.

Risk analysis would aspire to turn as much evidence into wisdom as possible. Decisions are not made based on data. The pursuit of data for the sake of its completeness is the equivalent of a false god for those who pursue evidence-based decision making. What risk managers need is wisdom. What risk assessors can best provide is the information, knowledge and understanding necessary to give birth to that wisdom. When we speak of gaps or holes in our data, the real concern is how those holes affect the information that is available to us to construct the knowledge required to give birth to wise decisions.

When making decisions under uncertainty, decision makers are well-advised to understand where the decision critical evidence rests in the DIKW pyramid. Proven knowledge is more valuable than raw data and speculation.

19.4 HOW MUCH EVIDENCE IS ENOUGH?

Gathering information in the face of uncertainty is a rational response by decision makers. Information gathering includes reading newspapers, books and journals, doing research, consulting experts, taking a class, conducting surveys, doing additional analysis of the available data, and the like. The common sense behind

this approach is obvious. If we can reduce uncertainty about future outcomes we can make better choices (Clemen and Reilly, 2014).

Our minds are not comfortable with uncertainty. Most of us experience uncertainty as a threat that needs to be reduced, resolved, or overturned, the less uncertainty the better. Uncertainty implies doubt and danger. It is random and volatile. When information is missing, our brains say, “Uh-oh, what if this is important?” Risk assessors and analysts must be able to differentiate between questions worth exploring and questions best left unasked or at least unanswered. It is easy, even natural, to overestimate the value of missing data. Some individuals and organizations are obsessed with filling information gaps and that obsession can lead them astray, especially today, when so much information is so accessible.

Decision making under uncertainty is best served by a systematic and consistent approach to risk management. This begins by carefully establishing the decision context. That means identifying problems and opportunities, specifying objectives and constraints, formulating questions that risk assessment or other analyses need to answer, and identifying decision criteria. All of these tasks are best done at the outset and iteratively throughout a risk management process. A strong foundation in the decision process goes a long way in defining the questions that are necessary to answer. Limiting the questions a risk management activity pursues is the first and best way to limit the amount of data and information collected.

This brings us to the crux of one of the most important issues related to uncertainty. For the questions you need to answer, how much information is enough? Stated equivalently, how much uncertainty is too much? Or, when is the best time to make a decision?

Assessors may, at times, struggle with the appropriate level of detail in a risk assessment. Reducing uncertainty always has a cost. So, what is the appropriate level of detail? The answer is at once simple, elegant, and not terribly pragmatic; the level of detail shall be sufficient to make the decision at hand. Do not pay to gather evidence that is not needed to make a good decision. Built into this concept of an appropriate level of detail is an implicit notion that the risks associated with not reducing the uncertainty further have been considered.

Decision making needs to be grounded in reality. It cannot be based on default positions, consensus, what the boss believes, unsubstantiated opinions, whim, or fancy. “What is the evidence of that?” is an important question to ask repeatedly throughout the decision process. We live in a world of resource constraints and we cannot do everything. Thus, we must make choices about what evidence we will and will not pursue in a risk assessment.

Figure 19.4 demonstrates the basic trade-off between the costs of reducing uncertainty through evidence gathering and the amount of uncertainty that remains.* A good evidence gathering strategy is to gather only the evidence needed to make the risk management decision. The shape of the curve makes it clear that the only way to reduce evidence-gathering costs is to live with more uncertainty. The only way to

* The figure, as drawn, suggests zero uncertainty may be possible. This is not always the case.

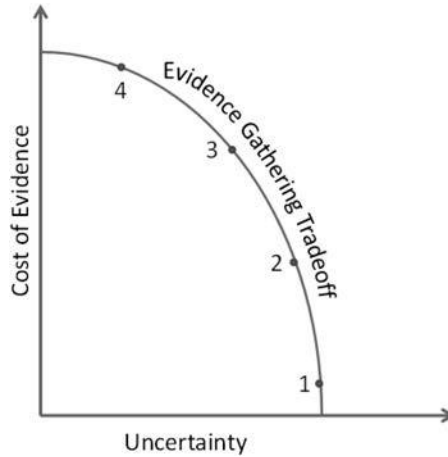


FIGURE 19.4 Trade-off between evidence-gathering cost and uncertainty remaining. (From Yoe, C. 2017. *Principles of Risk Analysis for Water Resources*. U.S. Army Corps of Engineers, Institute for Water Resources.)

reduce uncertainty is to devote more resources to evidence gathering. A good risk management process that establishes realistic expectations of the risk assessment and other analyses is the best way to address this trade-off.

Gathering data is wasted time, money, and effort if it does not add relevant evidence in the form of information, knowledge, and wisdom to our decisions. We call a piece of information relevant if it could impinge on the decision in some, even subtle, way. Relevant information may make one RMO look more appealing than another, or it might make a stakeholder happier. Relevant information can be categorized as instrumental or noninstrumental (Bastardi and Shafir, 1998). The ability to distinguish between the two is essential to both good risk assessment and good risk management. To be faithful to the language of Bastardi and Shafir’s argument, “information” is used below, but “evidence” would work as well.

Instrumental information is a piece of information that can alter the decision that is made or the outcome of a decision. This would include decision criteria and other things one needs to know in order to make a decision. Noninstrumental information refers to information that would have no instrumental value if it were directly available. That is, these data may be, in some way, relevant and of interest but they would not affect the decision to be made or its outcome once it is made.

The contradictory conundrum is that noninstrumental information can come to acquire instrumental mystique once it has been sought. Analysts are rarely aware of pursuing noninstrumental information; instead, they may pursue this information because it appears or is believed to be relevant to the decision at hand. Then, having spent time, money, and effort pursuing the data, analysts or decision makers treat the information as instrumental and may even proceed to make their decision partly on the basis of this noninstrumental data. Bastardi and Shafir (1998) point out that

whereas the information would have had no impact on the decision had it been directly available, the act of pursuing it can lead people to make choices they would not otherwise have made.

Thus, some individuals and some organizational cultures are prone to gather too much data, data that do not produce higher levels of knowledge on the pyramid or data that produce information that is not needed for decision making. In a world of scarce resources and limited budgets it makes sense to only gather the information that is needed to make a decision and to accept the remaining uncertainty as relevant noninstrumental information.

A former student offered the following example. I do not know the height of my vehicle, it is uncertain. I do know I am about six feet tall and my vehicle is just below my shoulders. So when I approach a bridge that is 14' high I do not have to do any more work to figure out the height of my vehicle, it is uncertain but reducing it further will not affect my decision. However, if I am driving a truck and I guess its height to be between 13 and 15 feet, it is going to be well worth my time to stop and measure as I approach that bridge.

Having more evidence may reduce your anxiety, but, unless it changes your decision, it is not worth the cost of obtaining it. Ask yourself, “Could this additional evidence affect the decision?” If the answer is no, forget it. If the answer is yes, then ask how likely it is to change the decision? If the possibility is remote, you may not need the evidence. Do not pursue evidence to perfect your decision; pursue it when it might affect your decisions.

19.4.1 THERE IS A BEST TIME TO DECIDE

How much evidence do you need to make a decision? Let us reframe that question for the moment as “What is the best time to make a decision?” and consider it further. Some decisions, like whether to read a journal article or not, require minutes to make; others, like what is the proper scale of a risk management response to a major social problem, may take years to make.

Consider [Figure 19.5](#) to help visualize the competing forces at work. Imagine a perfectly scalable relationship. As analysts spend time and money to increase their evidence base and knowledge they are adding value to decision making as they increase their confidence. If analysts take too much time and spend too much money, the value of the additional information decreases.

The point to take from this conceptual figure is that there is a best time to make a decision and that time comes before all the evidence has been collected and weighed. The image helps us visualize the competing forces at work when trying to find the best time to reach a decision. Too little time, and the decision is made without knowledge that could have enabled a more informed and confident choice. Too much time, and the benefits from the alternative solutions may be

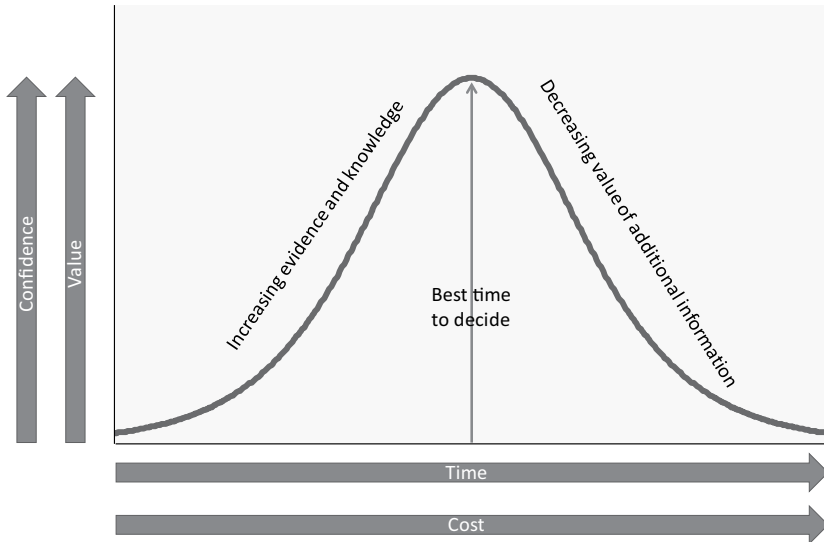


FIGURE 19.5 Optimal time to make a decision. (Adapted from Decision Innovation, <http://www.decision-making-solutions.com/decision-timing.html>)

delayed, costs might rise, and in the case of some problems, losses or pain may continue to increase.

Risk managers may decide too soon by falling into one or more of the following traps (Decision Innovation, <http://www.decision-making-solutions.com/decision-timing.html>):

- Impulsive decision making or shooting from the hip
- Planning fallacy—underestimating how long it takes to get things done
- Primacy effect—weighing initial events, for example, decisions made in early iterations, more than later ones
- Risk neglect—the inclination to ignore risk when making uncertain decisions
- Herd instinct—the common bias of adopting the views of the majority
- Reliance on heuristics, rules-of-thumb, and other shortcuts (see [Chapter 14](#))

On the other hand, risk managers may decide too late by falling into these traps:

- Paralysis by analysis—seeking information that cannot affect the outcome
- Focusing on the analytical process rather than on its result
- Review anticipation—trying to preempt negative comments by trying to provide every bit of information conceivable
- Procrastination—waiting too long to begin actually deciding
- Risk register complacency—failing to actively manage high and medium risks to prevent their occurrence

- Maintaining the status quo—doing this analysis the way past analyses were done
- Job security—analysts continue analysis for as long as possible
- Lack of experience—results in mistakes and delays that delay the schedule and expand the budget
- Fear of litigation—drives the desire to gather additional information
- Normalcy bias—failing to respond effectively to an event, delay, or failure that has not happened before or that was not incorporated
- Fear—someone will criticize a mistake or missing data so information gathering is prolonged
- Vertical team failure—decisions previously made by the team are not subsequently honored, resulting in delay

Figure 19.5 shows the optimal point for making a decision occurs at the balance point between taking sufficient time to obtain the required knowledge to decide effectively and avoiding the loss in information value due to delaying the decision. As you might suspect, finding this optimum in practice is more art than science.

Difficult and highly complex decisions often lead to information gathering efforts that can have a serious negative impact on decision timing. The key is to gather enough information to get as close to the conceptual optimum decision-making data point as possible. This means reducing uncertainty strategically and gradually and deciding not when all uncertainty is reduced but when confidence and evidence enable a reasonable decision. Decision Innovation (<http://www.decision-making-solutions.com/decision-timing.html>) offers three specific strategies to help strike this balance. First, begin with lower cost exploratory efforts for decision options with high levels of knowledge uncertainty. Do not necessarily set out to eliminate uncertainty, begin by reducing it to the point where a decision can be made with a tolerable risk. Second, make the decision and proceed along the preferred decision path, but put checkpoints in place that would enable a new or revised decision based on knowledge gained through decision execution. Third, take actions to reduce the undesirable consequences of delaying a decision.

Too much emphasis on information gathering may interfere with effective decision making. Knowing enough to decide is critically important but knowing too much can clog up our cognitive processes. A complex set of regulations, such as some organizations rely upon, may cause decision makers to manage to the rules, if only for fear of falling afoul of them. Abundant policy and guidance documents can induce professionals to act defensively, focusing on the small print at the expense of the bigger picture. These defensive actions reduce risks to the decision makers but they are potential risks to decisions and the stakeholders they were intended to serve. Bloated budgets and swollen time frames can threaten the implementation and efficacy of risk management options.

We need information to both reduce the risk of decisions and to understand the risk in decisions but getting too much information can have real costs. In an active shooter situation, if we wait to gather more data then people may die; if you are buying a house and wait to gather more data about the neighborhood then the house could be sold before you act. Additional data do not increase information at the same rate, the marginal utility of another month, week, day of data decreases even as costs and time to gather that data rise. Most decisions can be and are made without all the information. Your best defense against premature or delayed decision making is a good strong risk management process.

19.5 CLASSIFICATIONS OF UNCERTAINTY

The uncertainty that remains after the best possible analysis has been done is called residual uncertainty (Courtney et al., 1997). Each risk management activity begins with significant amounts of uncertainty. A good risk management process will establish a comprehensive strategy to reduce uncertainty in a cost effective and efficient manner. When the analysis ends and efforts to further reduce uncertainty have ceased, the uncertainty that remains is residual uncertainty. Three classifications of uncertainty relevant to decision makers are offered below.

According to Riesch et al. (2013) there are several options for representing uncertainty. They are:

- Deny uncertainty or risk
- Concede there is some more or less undefined uncertainty
- List possible outcomes, qualitatively or quantitatively
- Provide likelihoods of the possible outcomes
- Provide statistical summaries and description of the uncertainty
- Provide a probability distribution

The representation people choose may depend on the point people want to make. In some instances, it may reflect philosophical stances or implicit assumptions made.

Decision makers must be aware of the level of residual risk in their decision problems in order to avoid adopting a dangerous binary view of uncertainty, that is, the world is predictable or it is not. A number of scholars have proposed categories or levels of uncertainty. Courtney et al. (1997) define four levels of residual uncertainty.

Level 1 is a clear enough future. While confident of the general shape of the future, we do not have precise values for some key variables. Decision makers have a single forecast of the future that is sufficiently narrow to point in a single strategic decision. The forecast is precise enough for decision making and the residual uncertainty is, for the most part, irrelevant.

Level 2 consists of a few discrete alternative futures. There are a variety of future outcomes, but we can list them and they are mutually exclusive and collectively

exhaustive. Analysis cannot identify which outcome will occur, although it may help establish probabilities for the outcomes. The possible outcomes are discrete and clear but it is difficult or impossible to predict which one will occur. The decision strategy would change if the outcome became predictable.

Level 3 residual uncertainty comprises a range of futures that is defined by a limited number of key variables. The eventual outcome could lie anywhere along a continuum of possibilities. The range of potential outcomes is so numerous there are no natural discrete scenarios. Scenarios that can be constructed, like an optimistic or pessimistic case, are more representative of the many possible scenarios than they are unique scenarios of interest. The best decision strategy could change if the outcome became more predictable.

Level 4 is characterized by multiple interacting dimensions of uncertainty that make it virtually impossible to predict an outcome. The situation is so fluid and so unstable that it is impossible to even frame scenarios. Unlike level 3, the range of potential outcomes cannot be identified. In fact, it might not even be possible to identify, much less predict, all the relevant variables that will define the future. Level 4 is rare and these situations tend to migrate toward one of the other levels over time. Nevertheless, they do exist. The four levels are depicted visually in [Figure 19.6](#).

Courtney et al. (1997) have suggested that at least half of all decision problems fall into levels 2 or 3, while most of the rest are level 1 problems. They note that executives who think about uncertainty in a binary way tend to treat decision problems as if they fell into either levels 1 or 4. Perhaps most unsettling, those executives are most likely to apply the same set of analytic tools regardless of the level of residual uncertainty they face. Consequently, an important starting point for all decision makers is to understand the magnitude of the residual uncertainty in the outcomes of their decision problem.

Three types of decisions are identified by Courtney et al. (1997) as relevant for decision making under the four conditions of uncertainty above. They are big bets, options, and no-regrets moves. Big bets are large commitments that will result in either large payoffs or large losses. Big bets are employed as shaping strategies (see box). Options involve modest commitments that can be ramped up or scaled back as uncertainties are resolved. No-regrets moves pay off no matter what happens. Decision makers who are more sophisticated about decision making under uncertainty will be aware of the residual uncertainty and the types of decisions they face in their decision problem.

SHAPING STRATEGIES

Courtney et al. (1997) identify three distinct strategic intents for decision makers under uncertainty. Shapers aim to drive the futures of their industries toward a new structure of their own devising. Adapters take the current industry structure and its future evolution as givens, and they react to the opportunities they are given. Those who reserve the right to play make incremental investments to preserve the option to decide and then wait until the environment becomes less uncertain to make a decision.

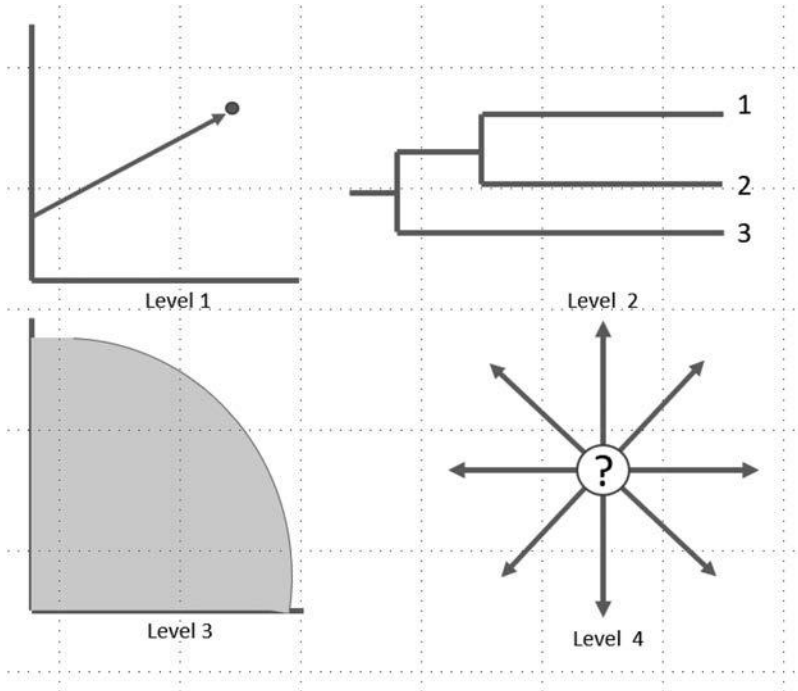


FIGURE 19.6 Four levels of uncertainty defined by Courtney et al. (1997).

Walker et al. (2013) build on these ideas and define five levels of uncertainty bounded by complete certainty and total ignorance, as seen in [Figure 19.7](#). The authors state there are many quantitative approaches for dealing with levels 1 to 3 uncertainty. Levels 4 and 5 comprise deep uncertainty (see text box), with level 4 being the “do not know” portion of the definition and level 5 uncertainties being the “cannot agree upon” portion of the deep uncertainty definition. There are fewer effective means for dealing with deep uncertainty.

Lempert et al. (2003) define deep uncertainty as “the condition in which analysts do not know or the parties to a decision cannot agree upon (1) the appropriate models to describe interactions among a system’s variables, (2) the probability distributions to represent uncertainty about key parameters in the models, and/or (3) how to value the desirability of alternative outcomes.” The authors use the language “do not know” for individual decision making and “do not agree upon” for group decision making.

Riesch et al. (2013) offers his own five level classification of uncertainty. Level 1 is uncertainty about the outcome. This occurs when the model is known, the

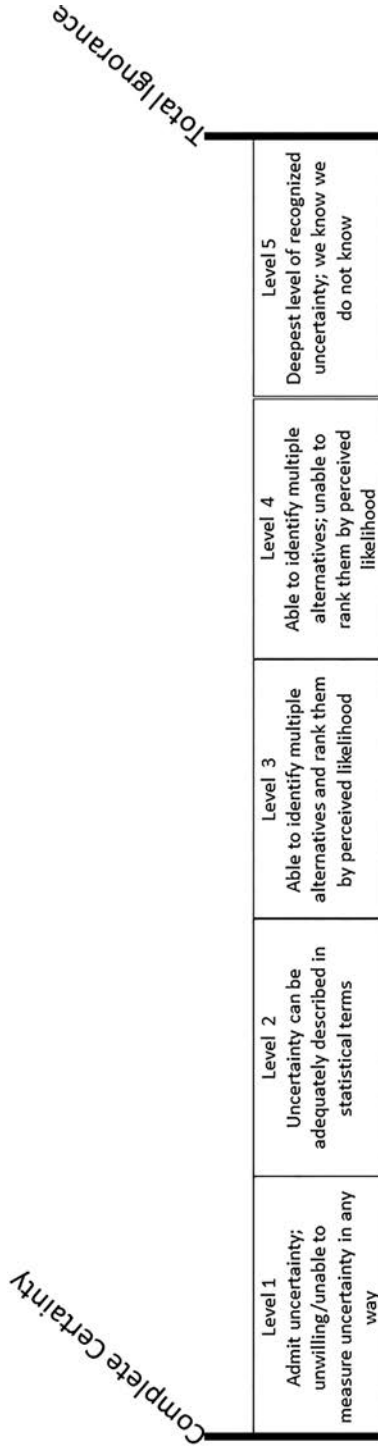


FIGURE 19.7 Walker et al.'s (2013) five levels of uncertainty.

parameters are known, and the model predicts a specific outcome with a probability p . Level 2 is uncertainty about the parameters. We know the model but its parameters are not known. A quantity may be normally distributed but its mean and standard deviation may be unknown. Level 3 is uncertainty about the model. Models are usually simplifications about how the world works, and there are often several ways of modeling any given situation. Level 4 is uncertainty about known inadequacies and implicitly made assumptions. There are inevitable limitations to even the best models. Level 5 is uncertainty about unknown inadequacies. This is where we do know what we do not know.

19.6 STRATEGIES FOR DECIDING IN DEEP UNCERTAINTY

It is not likely that risk managers will master any of these classification systems but they may be of interest to those who want to think more carefully about uncertainty, especially for the purposes of helping decision makers laboring under uncertainty to choose a strategy for addressing it. Decision makers facing significant uncertainty often ask the wrong question, “what will happen?”, instead of which actions available today are likely to serve best in the future? Several overlapping strategies for dealing with deep uncertainty (levels 4 and 5 from the previous classification systems, which have no useful probabilities) are identified here (Reeves, 2016; Walker et al., 2013). These are:

- Classical—traditional approach of analysis, planning, and execution that basically ignores uncertainty and assumes one can rely on this information
- Resistance—plan for the worst-case scenario
- Resilience—choose a solution that results in quick system recovery no matter what happens in the future
 - Redundancy—buffers against unexpected events
 - Diversity—multiple ways of thinking and doing things as a hedge against change and to form the substrate for experimentation and learning
 - Modularity—firebreaks stop problems in one part of the entity from affecting the whole
 - Adaptation—learn and evolve by leveraging diversity in the face of change
 - Prudence—embrace unexpected upsides, while designing decisions to be robust to plausible unfavorable scenarios
- Adaptive robustness—prepare to change the policy in case conditions change
- Static robustness—choose a solution that performs reasonably well in practically all conceivable situations
- Adaptive management—use research, experiments, test plots, trial and error, and so on to reduce uncertainty to better inform managers before risk management options are irreversibly implemented
- Visionary—in a malleable environment, envision and realize new possibilities
 - Shaping—in both malleable and unpredictable environments, entities orchestrate the decision ecosystems using new business models

- Renewal—when viability is threatened, business models must be decisively transformed
- Precautionary principle—use discretionary decision making when the possibility of harm is not firmly established by the science

The classical response to uncertainty is nonviable. Resistance is usually costly and it may not perform well against black swans. Resilience accepts negative system performance in exchange for the ability to recover quickly. Static and adaptive robustness do not identify an optimal solution. Instead they provide a satisfactory level of performance across myriad potential futures. This stands in contrast to an optimal solution that achieves the best possible results but only across a narrow set of circumstances. Static robustness seeks to satisfy over a range of identifiable futures, while adaptive robustness adapts to changing conditions over time.

Adaptive management is a series of steps that promotes intentional learning about a problem and its potential solutions for the explicit purpose of reducing uncertainty to avoid irreversible errors or costly revisions to projects. In newly created, disrupted markets or other malleable environments organizations must be ready to seize opportunities. Shaping strategies are discussed in a preceding text box. When supply shocks, demand conditions, regulatory change, or competitive developments threaten the viability of organizations, new business models may be needed. The precautionary principle implies a social responsibility to protect the public from exposure to harm when scientific investigation has identified a plausible but largely uncertain risk.

The best risk managers will want to understand their residual uncertainty and the strategies available for responding to it. Such risk managers are likely to be rare for the foreseeable future so the responsibility for so informing them may fall to the astute risk assessor.

19.7 COMMUNICATING UNCERTAINTY TO DECISION MAKERS

Preventing a false sense of certainty may be the single best reason for making decision makers aware of the uncertainty that attends their decision making. We need to banish that traditional approach of ignoring uncertainty to the dustbin of history. It is simply not sustainable. If we are to inform decision makers about uncertainty, it is wise to ask what decision makers want to know about uncertainty?

Relatively little research has been done on this topic, but Wardekker et al. (2008) provide a starting point. They report that policymakers participating in a survey have expressed the sentiment that assessment reports should not contain every nuance of uncertainty but should present only the most relevant uncertainty messages. Focus on instrumental uncertainties.

Survey takers said that uncertainty information may be used to:

- Assess the effectiveness and efficiency of policy measures more realistically
- Argue for one's own conclusions and against those in opposition
- Weigh information and the risks of using information that may turn out to be incorrect
- Determine the desirability of actions

- Estimate the plausibility of scenarios and trends
- Develop a vision on future government policies

Wardekker et al. (2008) point out that knowing about uncertainty has its drawbacks. It can make negotiations more difficult and it can weaken policy proposals. Decision makers can use it to argue in support of their own conclusions and against proposals that do not suit their interests or agenda. Too much uncertainty information could paralyze decision making through unnecessary discussion and delay of action. The general public may be confused by the complexity added by uncertainty information.

Decision makers identify three main areas where they would like more uncertainty information. These are:

- Topical issues that have received media attention
- Issues where uncertainty plays an important role but where there is little to no uncertainty communication
- Matters that are important for finding, selecting, and prioritizing policy responses

The policy relevance of uncertainty information was found to increase when:

- Being wrong in one direction carries more serious consequences than being wrong in the other.
- Uncertain outcomes can have a large influence on policy advice.
- Indicators are close to a policy goal or threshold.
- Large effects or catastrophic events are possible.
- There is societal controversy.
- Value laden choices may conflict with the interests or views of stakeholders.
- Public distrust in outcomes that show low risk can be expected.

Uncertainties can be present throughout the risk management process beginning with the initial identification of a problem. It should come as no surprise that risk assessors and risk managers approach and regard uncertainty quite differently. Decision makers appear to be less interested in the extensive lists of uncertain values and the taxonomies of their source and type than in the direct implications of the uncertainty for decision making.

Textbooks and journal articles are filled with frameworks that tend to overengineer the decision-making process. Many existing frameworks for decision making under uncertainty are both comprehensive and complex. Their comprehensiveness tends to make them too complex and time-consuming to fit routine decision making. Experience teaches us that decision makers do not need more advanced techniques for making decisions under uncertainty, especially if we expect risk management to become increasingly more mainstream. Decision theory provides a useful and important set of tools that are quite appropriate for certain kinds of decisions. However, the vast majority of decisions being made in

enterprise risk management organizations and in regulatory settings do not often fall into those categories of decisions. Most decision makers simply need some help wading through the flood of uncertainty that increasingly accompanies decisions. Consequently, what is needed is a good, common sense, practical approach to making decisions under uncertainty.

19.8 A PRACTICAL APPROACH

Uncertainty is an inevitable fact of life that can significantly limit the extent to which evidence can provide knowledge. Wardekker et al. (2008), adapting the work of Van der Sluijs et al. (2005) suggest a four-point scale of archetypes of attitudes towards uncertainty that are encountered in the decision-making world. These are:

- **Avoid**—Uncertainty is unwelcome and is to be avoided. Science is challenged to eliminate uncertainty by means of more and better independent research.
- **Quantify**—Uncertainty is unwelcome but unavoidable. Science is challenged to quantify uncertainty and to separate facts and values as effectively as possible.
- **Deliberative**—Uncertainty presents chances and opportunities. Science is challenged, by the existence of uncertainty, to contribute to a less technocratic, more democratic public debate.
- **Science as player**—The distinction between science and politics is artificial and untenable. Science is challenged to be an influential player in the public arena.

A survey by Wardekker et al. (2008) showed that a majority of policymakers held the “quantify” view with a sizable minority taking the “deliberative” view. The majority of scientists in the survey identified as “deliberative” with a sizable minority as “quantify.” Some policy makers and scientists identified with “science as a player,” and a few scientists identified with “avoid.” The remainder of this chapter adopts the “quantify” archetype.

The best leaders know how to make decisions in extremely uncertain circumstances and to keep moving forward (Johnson, 2015). Johnson offers a practical suggestion for decision making under uncertainty: get comfortable with the unknown. Humans want to reduce uncertainty, and seeking more information sometimes feels like progress, when in fact, it can be a delaying tactic when the information we really need does not exist or is so difficult or costly to find that we cannot get it in time. He argues that decision making under uncertainty is sometimes best served by a balance of information and instinct.

Decision makers are not always motivated to reduce uncertainty. A common reaction to uncertainty is still to ignore it and act as if it does not exist. We may do that because we do not recognize it, we do not consider it relevant to our situation, or because we have learned to live with it. If our minds are made up, new information might conflict with our decision.

COPING WITH UNCERTAINTY

Lipshitz and Strauss (1997) identify three broad strategies for coping with uncertainty: reducing it, acknowledging it, and suppressing it. Tactics for reducing uncertainty include: collecting additional information, deferring decisions, extrapolating from available information, assumption-based reasoning, mental simulation and scenario building, improving predictability through shorter time horizons, selling risks to other parties, selecting one of the possible interpretations of equivocal information, control the source of variation through standard operating procedures (SOPs), and constraining the external environment by incorporating critical elements into the organization. Tactics for acknowledging uncertainty include taking it into account when choosing a course of action, preparing to manage potential risks, including uncertainty as a decision factor such as with the minimax or regret criteria, choosing options with clear outcome probabilities. Tactics for suppressing uncertainty include ignoring or distorting undesirable information and coping with uncertainty symbolically by going through the motions of reducing or acknowledging it.

A less common approach to uncertainty is to embrace it and use it creatively and innovatively. Look for ways that uncertainty might be used to create a new future and to unlock untapped potential. The discomfort created by uncertainty might make us explore options we would not have considered in its absence.

The most obvious action to take when confronted with uncertainty is to reduce it by seeking new information and increasing our knowledge. But, will the additional information enable you to make a better decision? The answer is not always yes. Johnson notes that making a decision is one way to reduce uncertainty even if the decision is subsequently proven wrong. An incremental approach to decision making is, therefore, one way to reduce uncertainty while avoiding the risks of one big decision.

At the outset of this chapter, two fundamental decision-making issues were identified with uncertainty. They included not knowing the true values of the decision criteria and not knowing what decision to make in the face of uncertainty. To meet these challenges decision makers must be clear about the decision that is before them; they need to understand the risks associated with the decision options and the uncertainties that give rise to those risks. Then they need to make a decision. A practical approach to meet these challenges is proposed here. The steps in this practical approach are:

- Understand the decision to be made.
- Understand the residual risks and residual uncertainty.
- Ask clarifying questions.
- Make a decision or not.

Each of these steps is described below.

19.8.1 UNDERSTAND THE DECISION TO BE MADE

Decisions are hard because of four broad sources of difficulty (Clemen and Reilly 2014): complexity, multiple objectives, competing viewpoints, and uncertainty. Complexity is related to the number of issues that arise in a decision setting. Decision makers can be overwhelmed by complexity, making it difficult to give appropriate consideration to each component of the decision. When facing multiple objectives, progress toward one objective could impede progress toward other objectives. Such decision problems will always involve trade-offs. Decisions get difficult when different values and perspectives lead to different conclusions. This source of difficulty becomes especially pertinent when the number of decision makers grows beyond one. Of particular interest in this chapter is the inherent uncertainty in a decision situation. Decision making under uncertainty begins with the decision(s) to be made. If that decision is not understood there is little hope of a desirable outcome. This simple process begins by clarifying the decision that needs to be made.

Understand the risk complexity of the decision. Are the instrumental risks explicit or implicit? Is there a single risk or are there many? Some decisions involve a single risk decision. These can be as simple as should we cross the street now or as complex as what is an acceptable daily intake for a new food additive. The decision maker focuses on a single primary risk decision in these instances.

By contrast, some decisions are more risk complex. These may require risk managers to make many incremental risk management decisions before arriving at the primary risk management decision. Imagine, for example, developing an anti-terrorism strategy for a city, or developing a comprehensive water resource management plan for a region. Such decisions require complex risk management options that entail many risk decisions and risk management features before a final go or no-go implementation decision.

Finally, there is a class of decisions that may not even be characterized as risk management decisions. Business decisions are an obvious example of this class. Opening a new store, introducing a new product line, reorganizing a division may seem far from risk characterizations by decision makers. Even so, there are going to be risks associated with many of these decisions. Decision makers need to have a good understanding of the risk complexity of the decisions they are tasked with making.

Pay attention to complexity and carefully examine what the decision entails. As just noted, even when presented with a seemingly simple go/no-go decision there can be many implicit decisions embedded in the decision before you. Good risk management chooses the best risk management option from amongst an array of different options, most of which will consist of multiple measures. Each of these measures may bring its own issues, its own objectives, and its own stakeholders with varying perspectives. When you make a seemingly simple go/no-go decision you are also making a decision about each of those issues, objectives, and perspectives. Some of them may be significant. Some of them may entail risks of their own. Consequently, it is imperative that a decision maker understands the full implications of the decision before them. You may be very comfortable with the presenting decision but have grave misgivings about deploying a specific feature of that decision. Explore the embedded decisions before deciding.

No consideration of a decision problem can be complete until the decision maker(s) understand(s) the potential outcomes of their decision. Any half decent decision process will identify the expected outcomes of a decision, but that is just the starting point. Decision makers must understand the full range of potential outcomes from each decision alternative. If we pass this regulation, build this public works project, institute this new product line, what will happen? What else could happen? What do we want/expect the outcome to be and what else could it be as a result of making this decision? These questions need to be asked of each and every decision alternative the decision maker faces. Once the potential outcomes are understood it is time to understand the residual risk and uncertainty.

A good risk management process will go a long way toward providing this information for you. A thoroughly established decision context will provide a list of problems to solve and opportunities to attain; it will identify the risks relevant to the decision. There will be a set of objectives and constraints that define what a successful resolution of the problems and attainment of the opportunities will look like. These objectives and constraints define successful outcomes for decision making. An ever present generic decision question is which of the risk management or decision options will best achieve the objectives and avoid the constraints. If a good risk management process has been followed, this information will be more readily available. Otherwise, it will have to be generated before a decision is made.

19.8.2 UNDERSTAND THE RESIDUAL RISKS AND RESIDUAL UNCERTAINTY

Residual risk is the risk that remains after risk management options are implemented and functioning. Inherent risk minus risk reduced equals residual risk. Residual risk probably ought to be a decision criterion in every risk-informed decision, whenever it is available. Residual uncertainty is the uncertainty that remains when all the data collection and analysis are completed for a decision problem. Part of the consideration of residual uncertainty ought to be to understand how it might affect the residual risk that accompanies each decision option. There may or may not be additional options for reducing the residual uncertainty. With respect to the decision to be made, residual uncertainty may be irrelevant, relevant and noninstrumental, or relevant and instrumental. Instrumental uncertainties are those that could have an effect on the decision choice or on decision outcomes. In addition to residual risk, new risks may arise as a direct or indirect result of a decision for convenience we will consider them residual to the decision. Broadly construed, new risks also include transferred and transformed risks.

Uncertainty can exist in any part of the knowledge pyramid. There can be gaps in our data, our information, our knowledge, or our wisdom. Uncertainty about the value of a decision criterion tends to reside in the gaps in our data and information, uncertainty about what to do resides in our knowledge and wisdom. There is an evidence gathering process in every risk management activity. Its purpose is to identify the relevant knowns and unknowns about a decision problem. Risk assessors and risk managers then develop a strategy for reducing or at least characterizing the unknowns that are instrumental to the decision(s) to be made.

It is the risk assessor's responsibility to communicate the significance and source(s) of the residual instrumental uncertainty. It is the risk manager's responsibility to

decide how to weigh that in the decision process. Risk assessors begin by identifying the relevant uncertainty in their input variables and they proceed by efforts to reduce that uncertainty and/or by characterizing the effects of the instrumental uncertainty on assessment outputs.

Let us illustrate with a very simple example that considers two different scenarios. Acme Cleaners is considering producing and selling a new line of vacuum cleaners and they would like to know how profitable this product would be. The presenting choice is whether to produce 500,000 vacuum cleaners or not. On the left of [Figure 19.8](#) is a scenario where the quantity sold and the average cost per vacuum cleaner are uncertain. The uncertain average cost is depicted by the uniform distribution at the top of the center column. The uncertainty about the quantity is represented by the pert distribution in the middle of the center column. These are the instrumental uncertainties. On the right is an alternative scenario where all inputs are known except the quantity sold.

The decision criterion is profit, which is shown in the bottom figure with two distributions, the instrumental risk is of a negative profit. Knowing the variation in outputs is important. Knowing why the outputs vary is also important. Communicating the uncertain inputs provides the decision maker with potential options. Imagine that a decision has to be made in the scenario on the left, with two uncertain inputs. The decision maker might have the option of negotiating a contract to solidify the costs of production, reducing cost uncertainty. This would reduce the profit uncertainty from the larger background distribution to the narrower foreground distribution. To reduce the uncertainty further, the decision maker could commission more detailed market research that might produce a more precise description of the uncertain quantity sold, than the pert distribution does. Knowing which inputs are uncertain can make a difference to decision makers. In other decision problems, knowledge of the uncertain inputs may be irrelevant to the decision.

Addressing the uncertainty in the decision criterion, profit, is solely the responsibility of the risk manager. [Chapter 18](#) has provided some discussion on how to consider an output distribution. The decision maker must know the range in potential outputs. In the scenario with two uncertain variables, a minimum profit of $-\$40$ million and a maximum of $\$54$ million with a mean return of $\$9.8$ million are all possibilities. A sensitivity analysis (not shown) indicates that the uncertain quantity sold contributes more to the variation in output than the uncertain cost.

It is useful to understand the likelihood of the various outputs and outcomes, especially those that could affect the decision choice. Clearly, decision makers will not produce the vacuum cleaners if the probability of a negative return is unacceptable. In the example, the probability of a negative outcome for the scenario with two uncertain inputs is 27.5% and it is 24.5% for the scenario with one uncertain input. Risk managers must now decide if this is an acceptable, tolerable, or unacceptable risk. Such thresholds may not always be so obvious for other decision criteria.

What new risks might be introduced by the decision choice? Language can be subtle, so let us point out the range in model outputs is not necessarily the same as the range in outcomes. Outcomes can go beyond model outputs and decision criteria. What happens to Acme Cleaners if losses of $\$40$ million are suffered? Will the company remain viable? What happens to Acme Cleaners if they make $\$54$ million

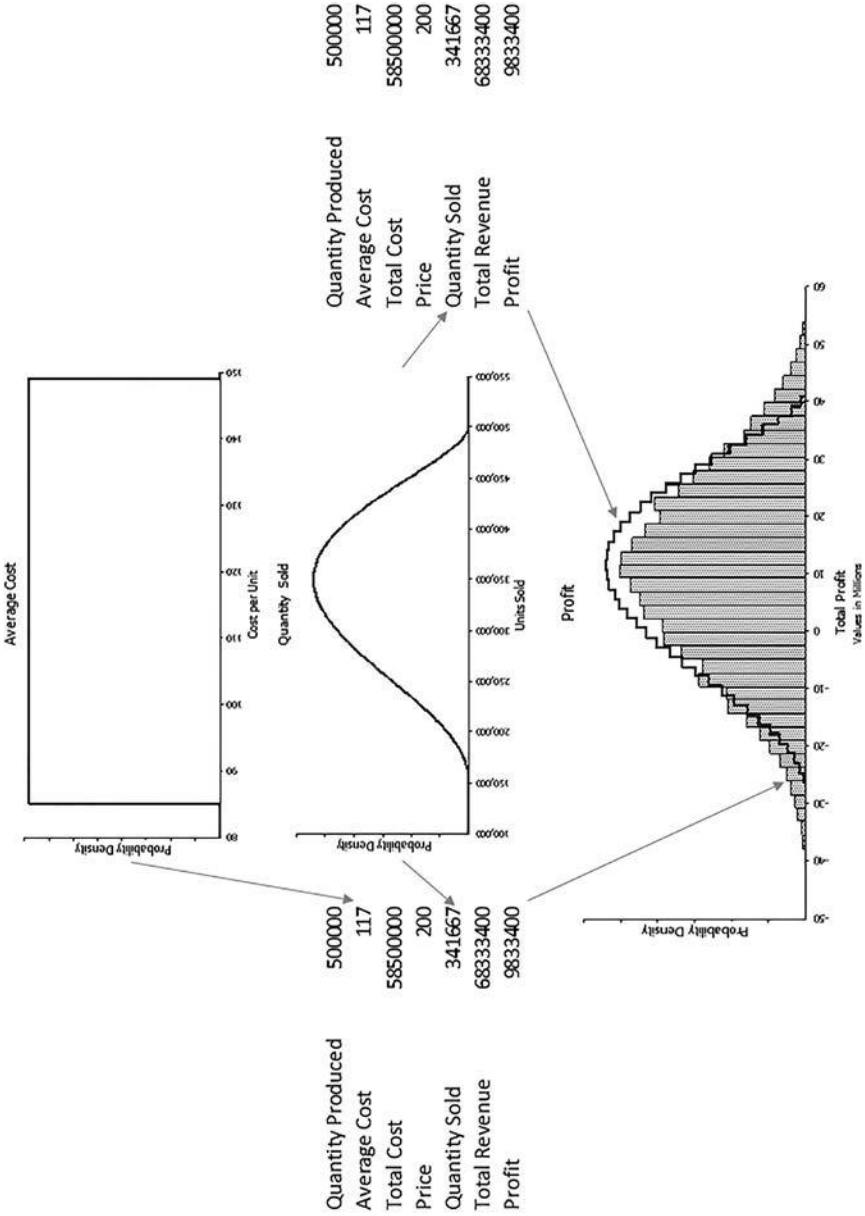


FIGURE 19.8 A simple example with two uncertain input scenarios and two different output scenarios.

on the new product? Will it expand? What is the expected outcome? What will the company look like? What impact will this have on the company's strategic objectives? So, it helps if decision makers understand how decision criteria estimates and risk assessment outputs relate to outcomes of interest.

It is one thing to ask what the profit might be, it is an entirely different thing to ask what the outcome of different realizations of profit will be. Profit was the decision criterion in the example, but it is important to go beyond the outputs to think about the outcomes of interest. Considering the outcomes of a decision made under uncertainty amounts to conducting a simple risk assessment of the final decision choices. Consider new risks that might arise as a result of the decision choice. If we say yes to the production of 500,000 vacuum cleaners, what can go wrong? How can it happen? What are the consequences? How likely is it that they will occur? Are there potential outcomes we cannot live with? How likely are they to occur? These are all relevant considerations.

Residual uncertainty may be described narratively, qualitatively, or quantitatively. When the decision maker is presented with a range of outputs or decision criteria to consider, the decision implications of the entire range of values should be considered. For example, if the minimum value of $-\$40$ million obtains what might the outcomes be? What decision would be made if the decision maker knew the minimum would obtain? If a five-number summary is used to display the uncertain results, the decision maker would repeat this process for the first quartile ($-\$1$ million), median ($\$10$ million), third quartile ($\$21$ million), and maximum ($\$54$ million) values as well.

Can the decision maker live with all the outcomes? Must some of them be avoided? Are there any feasible options for reducing the risk of their occurrence? Have they been included as part of the risk management options being considered? With Courtney et al.'s (1997) level 2 uncertainty you have discrete outputs or alternative futures. Some of these will be more attractive than others. With level 3 uncertainty there is more of a continuum of outputs as seen in the example above. At what point does the continuum become unacceptable? These are the sorts of understandings to seek about the residual uncertainty and the outcomes they can produce. It will often be the risk assessor's responsibility to facilitate this kind of analysis.

It is important for a decision maker to understand what further options there may be for reducing the residual uncertainty? How might the decision data be improved? How much can the accuracy of the decision data be improved? Will ranges be narrower? Will confidence be higher? What will it cost to reduce uncertainty further? How long will it take?

19.8.3 ASK CLARIFYING QUESTIONS

Unlike risk assessors, many risk managers are likely to be uncomfortable with uncertainty. As a result, it is important for decision makers to "wrap their heads" around the uncertainty and become comfortable with its implications for decision making. Uncertainty about decision criteria is more than a five-number summary; it includes the reasons for that spread in the data.

Once the decision maker has a sound understanding of the decision to be made and its residual risk and uncertainty, it is time to focus on reducing or at least

understanding decision outcome uncertainty, a phenomenon quite different from the output uncertainty considered until now in this process. At its most fundamental level, decision outcome uncertainty appears when we do not know what the best decision is.

In situations where people may be reluctant to be transparent, Brooks and John (2018) suggest that you ask yes or no questions to avoid evasive answers, then ask detailed follow-up questions to elicit more information. Ask the most sensitive question first so following questions feel less intrusive making people more forthcoming. Frame tough questions with pessimistic assumptions to reduce the likelihood that information is withheld. “This risk is likely to get worse before it gets better,” will elicit more honesty than “you’ve got this risk under control, don’t you?”

This is the time to clarify the range of outcomes that could result from the decision choices. If the decision outcomes differ from the decision criteria this needs to be carefully noted. Recall the example above where outcomes of interest to the Acme Co. could be distinguished from profit on the vacuum cleaner sales. The immediate goal is to make the potential results of the decision less confusing and more clearly comprehensible. Clarify the decision choices and their expected outcomes, then clarify the range of those expected outcomes and their probabilities. Clarify the causes of different outcomes, clarify the tipping factors and what causes an outcome to go from good to bad or from desirable to undesirable. Clarify thresholds and values that matter to you. What causes profits to be negative? What causes them to exceed \$50 million? What makes costs jump over \$70 million? What causes the revenue to exceed \$70 million? What conditions have to be present? What is the likelihood that will happen? This is the time for decision makers to probe.

Following is a sequence of questions that could be used to start the process of clarifying uncertainty for decision making:

1. What is the decision that needs to be made?
2. What do we know with certainty?
3. What do we still need to know?
4. Do we have enough information to make this decision now?
5. What is the range of possible outcomes for this decision?
6. What combination of uncertain factors will result in a desirable outcome for this decision?
7. What combination of factors will result in an undesirable outcome for this decision?
8. How likely is a desirable outcome?
9. How likely is an undesirable outcome?
10. What are the risks associated with making this decision?
 - a. What can go wrong?
 - b. How can it happen?

- c. What are the consequences?
- d. How likely are those consequences?
- 11. What am I afraid of in making this decision?
- 12. What is the worst case, how likely is it?
- 13. Can I cope with the results of my decision?
- 14. Why am I making this particular decision?
- 15. Can I logically and honestly defend my decision?
- 16. Can I live with the risks that may be created, transferred, or transformed as a result of my decision?
- 17. What am I not asking you that I should?
- 18. Am I ready to decide?

19.8.4 MAKE A DECISION OR NOT

This is a subjective step in the process. There is no foolproof way to make decisions; there is no recipe. When you are ready to make a decision, do so. If you are not, it may be time to escalate the decision to a higher authority. Document the decision rationale no matter how convinced you are that you will never forget it.

19.9 PRACTICAL CHANGES

Introducing effective risk management to an organization is likely to present a monumental challenge. This section offers four early steps to take to implement the practical approach to risk-informed decision making described above. The steps are:

- To change the decision meeting
- Question the numbers
- Power down decision making
- Socialize errors that result from a good risk management decision-making process

19.9.1 CHANGE THE DECISION MEETING

The best way for an organization to begin to change decision making is by changing the decision meeting. When a decision needs to be made, decision makers should come to the meeting prepared to make a decision. That means doing whatever preparatory work that needs to be done. To apply the simple process described previously decision makers should make sure they understand the risks that can affect the decision or the outcomes of the decision. Decision makers should ask their staff, if I make this decision:

- What can go wrong?
- How can it happen?
- What are the consequences?
- How likely are they?

Once the risks associated with a decision choice are understood the decision maker must understand the uncertainty that can affect the decision or the outcomes of the decision. Decision makers can do that by asking:

- What is uncertain?
- Why is it uncertain?
- How uncertain is it?
- Why is the uncertainty important?

Forearmed with this information, the decision maker is better prepared to make a risk-informed decision.

19.9.2 QUESTION THE NUMBERS

Risk analysis addresses the uncertainty inherent in decision making. That uncertainty needs to be adequately expressed to decision makers. It can range from a very simple and straightforward admission that we do not know the precise values of decision criteria to the presentation of probability distributions for decision criteria and everything imaginable between these two extremes. When a value is uncertain, it is important to characterize that uncertainty.

If risk managers are not presented with realistic summaries of uncertain decision criteria, it is incumbent upon them to question the numbers. Faced with making decisions under conditions of uncertainty, risk managers can do much worse than to make “there is no such thing as the number” their mantra. Point estimates of risky outcomes provide an illusion of precision that is not present. Point estimates of decision criteria derived from uncertain estimates of quantities can be misleading.

Many decision-making processes run on a single number. Analysts are trained to calculate it, decision makers adamantly insist upon it, the web master asks for it, financial systems require it to balance the books, and reporters want to know it. In a great many of these circumstances “the number” is understood to be a “best estimate” or even a “best guess.” To make decisions under uncertainty, decision makers must be well-informed about the uncertainty, the estimate, or the guess. Decision makers must take responsibility for becoming well-informed about the instrumental uncertainty.

One of the best ways to do this is to question the numbers with which they are provided for decision making. If given the number of individuals affected by a risk to health and safety, ask to see the distribution or a five-number summary. If one is not available, ask for realistic minimum and maximum values. If they have not been estimated, ask what circumstances could cause the minimum and maximum numbers to occur and how likely those circumstances are. If staff cannot answer those questions, then pose a scenario that could cause a lower and a higher value. Do what you must to find out what the true range of the risk estimates and other decision criteria could be.

Budgets are notorious for running on precise numbers. Estimating revenues or operating costs for the coming year is anything but a certain process. Give your staff permission to say they do not know for sure when uncertainty is present. Get comfortable with ranges and be very slow to accept a point estimate for any decision criterion without exploring its potential range of values.

19.9.3 “POWER DOWN” DECISION MAKING

Highly effective organizations have leaders at every level, not just at the top. A third step to take to enhance an organization’s ability to make decisions under uncertainty is to push down decision-making authority or to “power down.” With risk-based and risk-informed decision making, outcomes may well matter more than chain of command or compliance with every bit of organizational guidance. Every risk an organization faces has or should have an owner who is responsible for actively managing that risk. A concerted effort to let the people closest to the outcome make the decision will be rewarded by better outcomes. These are the people who will be best informed about the risks, they will be closest to new information that can reduce uncertainty and they are most readily available to manage these risks.

Organizations in a competitive environment may only have to reduce uncertainty a little faster than their opponent to gain a competitive advantage. The edge often goes to those who can learn quickly. Power down decision making and give less guidance. Pushing decision making down the organization, closer to the data enables you to integrate more data into decision-making processes more quickly. The people closest to the job know it best. Do not slow the process down with excessive guidance and policy.

19.9.4 SOCIALIZE ERRORS FROM GOOD RISK MANAGEMENT

Managing risks means some things are not going to turn out as hoped. Bad outcomes should not be punished when they result from good risk management process. Berman (2015) suggests that organizations socialize the inevitable errors that will occur in risk management decision making. A culture of risk-informed decision making must be socialized. This includes both learning and teaching behaviors, beliefs, and actions. If an organization follows good risk management practice, some undesirable outcomes will inevitably occur. Owners of these risks can learn from those experiences and the organization benefits from those lessons.

19.10 RISK METRICS

Decision making under conditions of uncertainty may include yes or no decisions on a single action, rating a series of alternatives, ranking the alternatives, or choosing the best option from among a set of alternatives. It is the risk assessor’s job to address the uncertain assessment inputs, to characterize uncertain outputs, and to convey the significance of the uncertainty in their assessments to risk managers. It is the risk manager’s job to address the uncertainty in the assessment outputs and decision criteria and to take these explicitly into account in decision making. To do this, risk managers need to request and use risk information to aid in their decisions made under uncertainty. This means developing risk-related decision metrics. To the extent that risk managers become explicit about the risk metrics of interest to them, the decision-making process will be improved.

Typical risk metrics vary with the nature of the risks being considered in the decision context. They may include such things as mortality, morbidity, and life-safety risk, including such things as the number of lives at risk and social vulnerability. Relative risk, increases or decreases in risk, and odds ratios may also be used.

Examples of other values at risk include profits, net economic benefits, financial risks, engineering risk and reliability, and the like. The risks considered and their measurements should include the full range of existing risk, risk reductions, residual risk, risk transformations, risk transfers, and new risks as appropriate to the decision.

Risk-informed decision making is a new enough concept that the most useful risk metrics may have not even been identified as yet. Certainly, we have a good handle on the most obvious risk measures, and many of them have been in use for a long time. The emphasis on risk analysis, however, is young, and clever assessors will hopefully continue to develop new metrics to aid in decision making. One such metric is obtained from the partitioned multiobjective risk method (PMRM) developed by Haimes (1998). The PMRM was developed to respond to the common inadequacy of an expected value as a measure of risk. It develops conditional expected-value functions that represent the risk, given that an event of a certain magnitude, frequency, or circumstance has occurred. The method can, for example, be used to isolate one or more damage ranges by specifying a partitioning probability. It then generates a conditional expectation of the consequences, given that the consequences fall within the identified range. An example follows.

Flooding is a serious risk to life and property in many parts of the world. Floods cause property damage and reductions in these property damages are a common measurement of the benefits to flood risk management measures. These damages are often estimated using the hydroeconomic model shown in [Figure 19.9](#), which is used to estimate the expected annual damages (EAD) associated with flood regimes and flood risk management options.

Beginning in the upper right quadrant, property damage is shown to increase as flood depths increase. Moving to the left, we see that increasingly large flows of water (measured in cubic feet per second) are needed to increase flood depths. Moving down a quadrant, the annual exceedance frequencies of these quantities of water are shown. The lower right quadrant links the three relationships. Choosing any damage amount \$a from the horizontal axis of the upper right quadrant shows that damage is caused by b feet of water (upper left), which occurs with a flow of c cubic feet per second of water flow (lower left). That flow occurs with an annual exceedance frequency of d%, and so we have \$a occurring with an exceedance frequency of d%. Such derived damage-frequency pairs (\$a, d%) trace out the existing-condition damage-frequency curve. When the area under this curve is integrated, it yields an estimate of the expected annual damages (EADs).

The EADs for the example in [Figure 19.9](#) are \$12,411,000. The most common interpretation of this value is if the development in the flood plain and its hydraulics and hydrology remained unchanged for a long time (say 10,000 years) and we added the flood damages in constant dollars for each of these 10,000 years (most of these years would be zeros) and then divide the sum by 10,000, we would have an average annual damage of \$12,411,000. This is a common flood-risk metric.

If this risk is judged to be unacceptable and it is to be reduced through a risk management option, the model in [Figure 19.9](#) can be used to estimate the effectiveness of the risk management option (RMO). Most RMOs will alter one or more of the first three relationships in the model. A levee is shown in the upper right quadrant of [Figure 19.9](#), and its effect on the estimate of expected annual damages is shown in

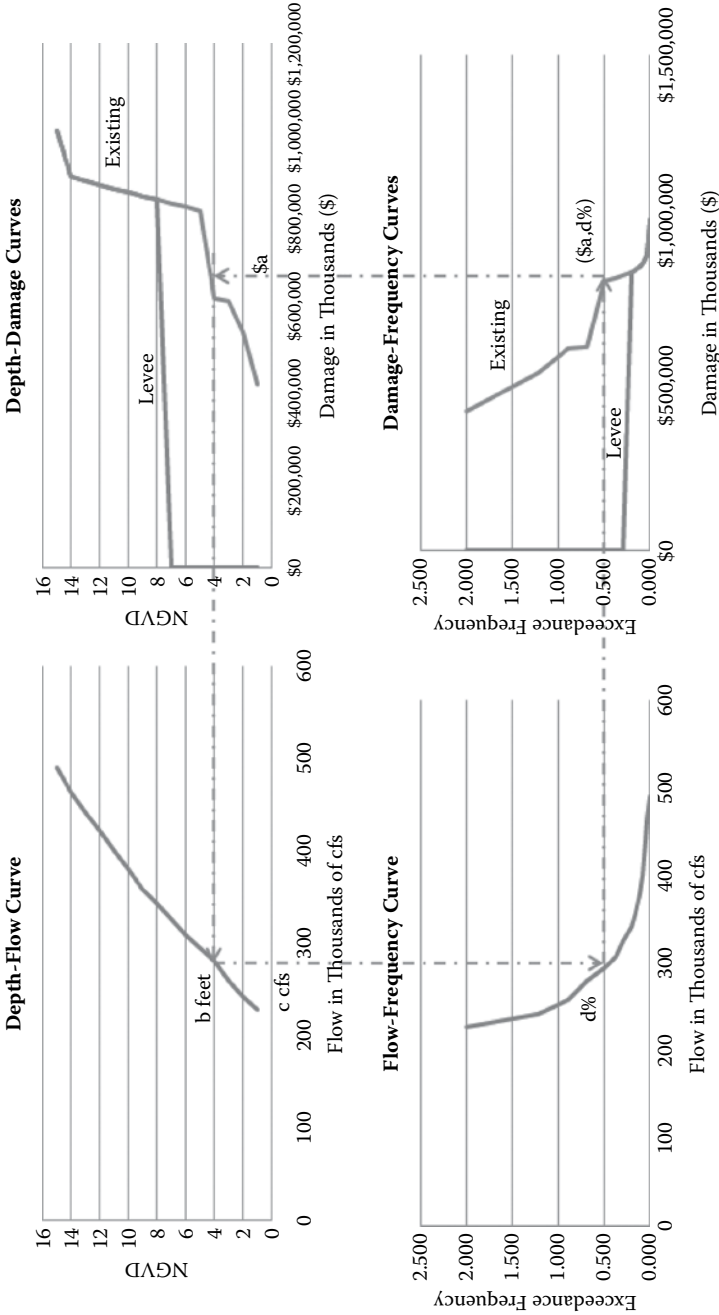


FIGURE 19.9 Hydroeconomic model for estimating expected annual flood damages.

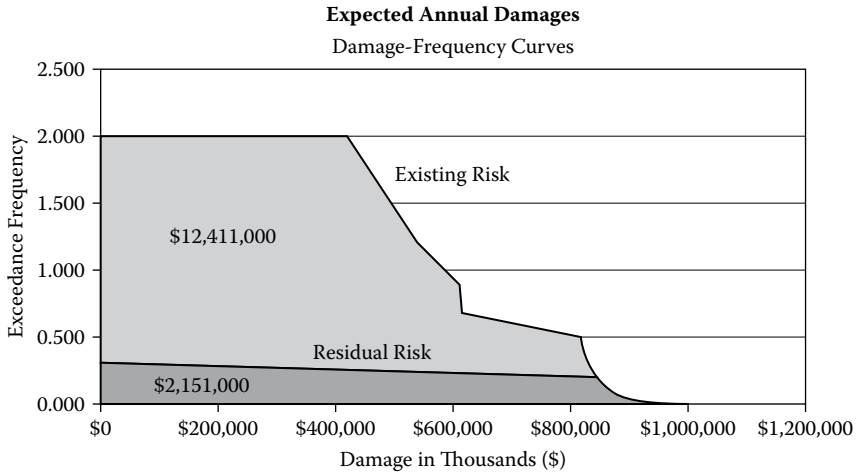


FIGURE 19.10 Damage-frequency curves for existing and improved condition scenarios.

the lower right quadrant, which is reproduced in [Figure 19.10](#). Damages from floods up to seven feet in depth are reduced to zero by the levee. For the simplicity of the example we ignore the risk of levee failure.

A levee is one option for managing the flood risk. Using the improved-scenario curve (levee) in place of the existing scenario, a residual risk damage-frequency curve is traced out for the levee, as shown in [Figure 19.10](#). The area beneath this curve yields EAD of \$2,151,000. This is a measure of residual damages. A measure of risk reduction is the difference between the EAD estimate for existing risk (\$12,411,000) and residual risk (\$2,151,000), in this case \$10,260,000. This is the standard way of estimating the risk of property damage from flooding and of informing risk managers and the public about this risk.

EAD is now much lower, but what happens to the community when a flood large enough to overtop the levee occurs? Hurricanes Katrina and Rita as well as flooding in the Midwest early in this century have demonstrated the devastation that can result when levees fail or are overtopped. Risk partitioning is a useful tool for better informing risk managers and the public about extreme risks, and it is an example of a more creative risk metric to better inform decision makers.

[Figure 19.11](#) illustrates the notion. Let us consider that a flood with an annual exceedance frequency of 0.002 or less occurs and overtops the levee. Now what is the expected value of damages? This is quite a different metric from the usual EAD. Haines (2004) provides a rigorous treatment of this partitioned risk concept. In essence, it entails rescaling the probability (vertical axis) partitioned segment of the curve (circled) over the 0–1 scale and calculating the expected value of that new distribution. Recall that residual damages are \$2,151,000. However, given that an event of equal or greater severity than the 0.002 exceedance frequency flood occurs, then the expected damages are \$872,659,000. This provides an entirely different perspective on the residual risk. The likelihood of a flood overtopping the levee is low, but the consequences are devastating. This is not obvious from the more traditional measure of residual damages.

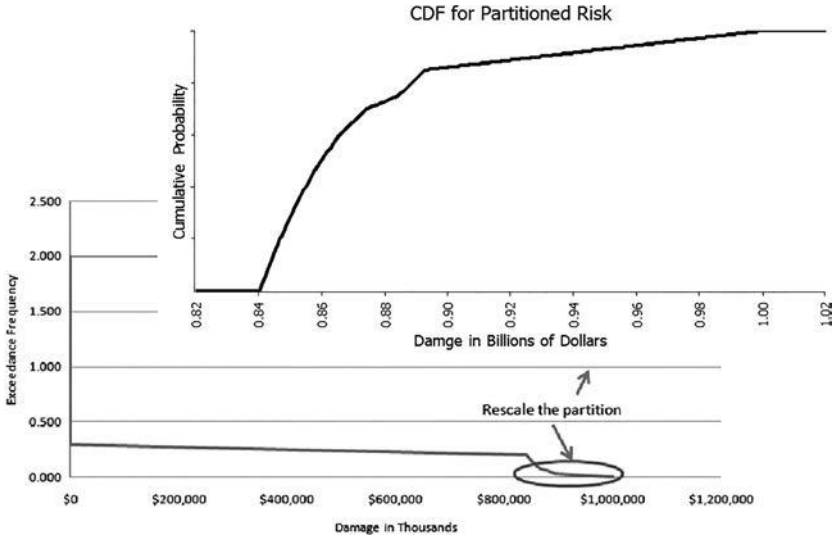


FIGURE 19.11 A risk partition for the hydroeconomic estimation of flood risks.

Different RMOs can yield different partitioned risks. For example, a channel or nonstructural flood risk management option might yield a lower traditional estimate of EAD reduced but also a much-reduced partitioned risk. Such risk metrics can provide valuable new insights for evaluating a flood RMO. The risk assessment community of practice needs to continue to develop and use clever and revealing risk metrics like this in all aspects of risk-informed decision making.

19.11 DECISION ANALYSIS

There is no magic bullet coming. You will not learn a foolproof way of making a decision under uncertainty here because none exists. For all the helpful mathematics and science, decision making is still fundamentally an exercise in judgment. People weigh and choose. The methods they use for doing so may be formal or informal. Decision analysis, however, provides us with systematic approaches to decision making that reduces the likelihood of an uninformed decision.

Borrowing a definition from the *Business Dictionary* (www.businessdictionary.com) decision analysis is a: “Management technique in which statistical tools such as decision tree analysis, multivariate analysis, and probabilistic forecasting are applied to the mathematical models of real-world problems. The objective of a decision analysis is to discover the most advantageous alternative under the circumstances.” Decision analysis can be used to develop an optimal strategy when decision makers have multiple decision alternatives and an uncertain future. Decision analysis is used to make better decisions, where better decisions are those that use a logical and coherent process that matches the decision maker’s needs (Clemen and Reilly 2014). Better decisions cannot guarantee good outcomes. Good decisions sometimes result in bad outcomes.

This section introduces the use of influence diagrams and decision trees in decision making. The treatment here is abbreviated because these topics are well-covered in the literature. The section begins with an example followed by considering some methods for making decisions under uncertainty without probability information. It then considers methods that can be used when probability information is available. The section concludes with a discussion of the value of information.

19.11.1 THE EXAMPLE

Let us use a hypothetical example to develop the concepts and terminology of decision analysis. Silver Train Corporation (STC) purchased land that will be the site of a new luxury condominium complex in Sweet Virginia. STC commissioned preliminary architectural drawings for three different projects: one with 30, one with 60, and one with 90 condominiums. The financial success of the project depends upon the size of the condominium complex and the uncertain market demand for the condominiums. The STC decision problem is to select the size of the new complex that will lead to the largest profit given the uncertainty concerning the demand for the condominiums.

This decision problem is characterized by decision alternatives, states of nature, and resulting payoffs. The decision alternatives are the different possible strategies the decision maker can employ; in this case the alternatives are building 30, 60, or 90 condos. The states of nature refer to future events which may occur that are not under the control of the decision maker. In this case the states of nature are weak, moderate, or strong success, which depend on the demand for condos at the Sweet Virginia site.

Figure 19.12 begins to explore this problem with an influence diagram. An influence diagram is a graphical device showing the relationships among the

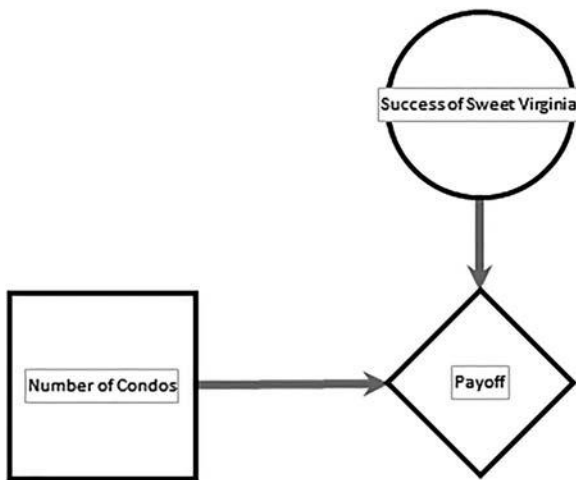


FIGURE 19.12 Simple influence diagram for STC development of the Sweet Virginia project.

decisions, the chance events, and the consequences. Influence diagrams use several conventions:

- Squares or rectangles depict decision nodes
- Circles or ovals depict chance nodes
- Diamonds depict consequence nodes
- Lines or arcs connecting the nodes show the direction of influence

The “Success of Sweet Virginia” node identifies the three states of nature and their respective probabilities. The “Number of Condos” node identifies three decision alternatives, and the “Payoff” node contains the payoff values.

The next tool is a payoff table derived from the influence diagram inputs. The consequence resulting from a specific combination of a decision alternative and a state of nature is a payoff. So, a 30-condo project with strong success returns \$1,000, moderate success returns \$500, and weak success breaks even at \$0, as seen in Table 19.2. Other combinations of decision alternatives and states of nature have different payoffs. A table that shows the payoffs for all combinations of decision alternatives and states of nature is a payoff table. Payoffs can be expressed in terms of any appropriate measure; in this example payoffs are the accumulated present value of all profits in thousands of dollars.

19.11.2 DECISION MAKING WITHOUT PROBABILITY

We begin by considering decision making without probabilities. Five commonly used criteria for decision making when probability information regarding the likelihood of the states of nature is unavailable are:

- Maximax or optimistic approach
- Maximin or conservative approach
- Laplace criterion or equally likely approach
- Minimax or regret approach
- Hurwicz criterion

Maximax would be used by an optimistic decision maker. The decision with the largest possible payoff is chosen. In this instance 90 condominiums provides the maximum payoff at \$3,000. If the objective had been to minimize costs instead

TABLE 19.2
Sweet Virginia Condo Project Decision Analysis Matrix

Decision Alternatives	States of the World (\$ Thousands)		
	Strong Success	Moderate Success	Weak Success
Condominiums			
90	\$3,000	\$200	(\$2,000)
60	\$2,000	\$400	(\$200)
30	\$1,000	\$500	\$0
	P (Strong) = 0.5	P (Moderate) = 0.3	P (Weak) = 0.2

of maximizing profit and the payoff table showed the costs of the project instead of profits, the decision with the lowest cost would be chosen under this optimistic criterion.

The maximin approach would be used by a conservative decision maker. For each decision the minimum payoff is listed and then the decision that yields the maximum of these minimum payoffs is selected. Hence, the minimum possible payoff is maximized. The 30-condominium project meets this criterion with a payoff of \$0. If the objective and payoff were expressed in terms of costs, the maximum cost would be determined for each decision and then the decision that yields the minimum of these maximum costs is selected. Hence, the maximum possible cost is minimized.

The Laplace criterion considers all the payoffs for each alternative equally likely. In other words, each state of nature is assumed to have a $1/n$ chance of occurring, where n is the number of states of nature considered. In this event, each state of nature has a $1/3$ chance of occurring. The criterion proceeds by finding the average payoff for each alternative and the alternative with the highest average is selected. Thus, the 90-condo alternative has a Laplace value of \$400, the 60-condo value is \$733, and the 30-condo value is \$500. The 60-condo decision is best under this criterion.

The regret criterion requires us to construct a regret table or an opportunity loss table as shown in Table 19.3. This is done by calculating the difference between each payoff and the largest payoff for that state of nature for each state of nature. Strong success has a maximum payoff of \$3,000. If the 90-condos option is chosen and strong success is realized the regret for having chosen 90 condos is $\$3,000 - \$3,000 = \$0$. However, if 60 condos had been chosen, the regret would be $\$3,000 - \$2,000 = \$1,000$, and so it goes for all the table entries. Then, using this regret table, the maximum regret for each possible decision is listed. The option chosen is the one that minimizes the maximum regret, in this case that is the 60-condo project with a maximum regret of \$1,000.

An alternative approach is to use the Hurwicz criterion, sometimes called the criterion of realism or the weighted average. This criterion was developed as a compromise between the optimistic and pessimistic criteria. It requires the decision maker to select a coefficient of realism a , with $0 \leq a \leq 1$, such that a perfectly optimistic decision maker would set $a = 1$ and a perfectly pessimistic decision maker would set $a = 0$. The value for a represents the decision maker's coefficient of optimism and $1 - a$ represents their coefficient of pessimism. These two coefficients become the weights in the following equation:

$$\text{Hurwicz value} = a(\text{Optimistic value}) + (1 - a)(\text{Pessimistic value}).$$

TABLE 19.3
Sweet Virginia Condo Project Regret Matrix

Decision Alternatives	States of the World (\$ Millions)			
	Strong Success	Moderate Success	Weak Success	Maximum Regret
90	\$0	\$300	\$2,000	\$2,000
60	\$1,000	\$100	\$200	\$1,000
30	\$2,000	\$0	\$0	\$2,000

Now, compute the weighted averages for each alternative and select the alternative with the highest value. Assume, for the sake of the example, the decision maker is rather optimistic and chooses $\alpha = 0.8$, these values are:

$$90 \text{ condos: } 0.8(\$3,000) + 0.2(-\$2,000) = \$2,000$$

$$60 \text{ condos: } 0.8(\$2,000) + 0.2(-\$200) = \$1,560$$

$$30 \text{ condos: } 0.8(\$1,000) + 0.2(0) = \$800.$$

The best choice is 90 condos. A more pessimistic decision maker might well end up with a different ranking of the decision choices. The coefficient of optimism should not be confused with a probability value. Notice these criteria can and do provide different answers. There are no magic bullets.

19.11.3 DECISION MAKING WITH PROBABILITY

Now we turn to decision making with probabilities and begin with the expected value approach. If probabilistic information regarding the states of nature is available, we may use the expected value (EV) approach, see [Table 19.4](#). The expected return for each decision is calculated by summing the products of the payoff under each state of nature and the probability of that state of nature occurring. The decision with the best expected return is chosen.

The expected value of a decision alternative is the sum of weighted payoffs for the decision alternative. The expected value (EV) of decision alternative d_i is defined as:

$$EV(d_i) = \sum_{j=1}^N P(s_j)(v_{ij})$$

where

N = the number of states of nature

$P(s_j)$ = the probability of state of nature s_j

v_{ij} = the payoff corresponding to decision alternative d_i and state of nature s_j .

For this example, the expected values are shown in [Table 19.4](#). [Figure 19.13](#) presents the problem as a decision tree.

TABLE 19.4
Expected Values of STC’s Sweet Virginia Development Scales

Decision Alternatives	States of the World (\$ Thousands)			Expected Values
	Strong Success	Moderate Success	Weak Success	
90	\$3,000	\$200	(\$2,000)	\$1,160.0
60	\$2,000	\$400	(\$200)	\$1,080.0
30	\$1,000	\$500	\$0	\$650.0
	P (Strong) = 0.5	P (Moderate) = 0.3	P (Weak) = 0.2	

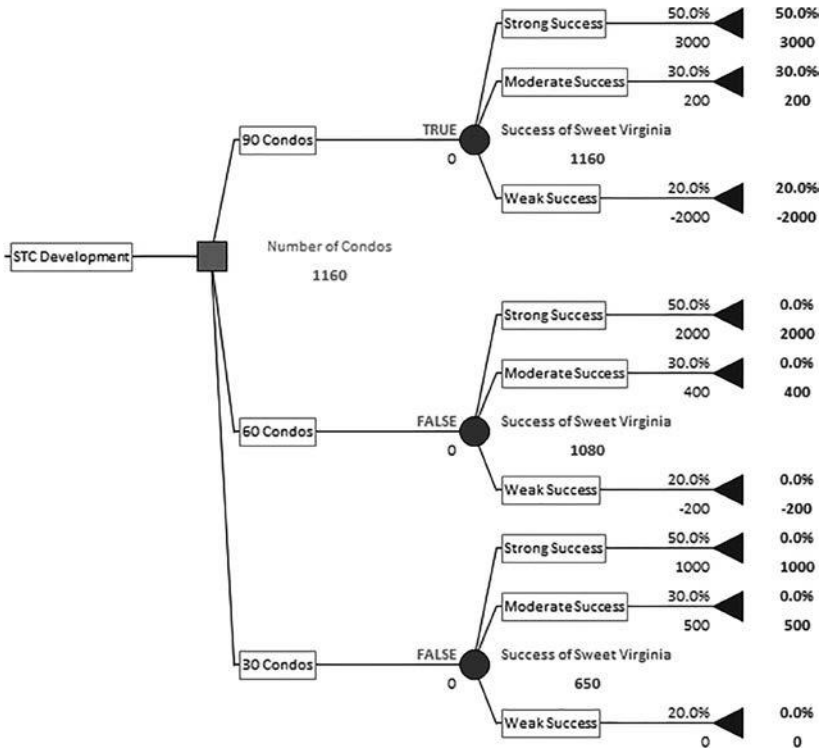


FIGURE 19.13 Decision tree model of STC decision problem using expected values.

The tree shows the expected value of each chance event and the maximization objective identifies the 90-condominium project as the best option based on expected value, with a payoff of \$1,160.

19.11.4 RISK PROFILE AND SENSITIVITY

Risk analysis helps the decision maker recognize the difference between the expected value of a decision alternative and the payoff that might actually occur. A risk profile* for the example is shown in Figure 19.14. It presents deviations from the expected value and shows the possible payoffs for the decision alternatives along with their associated probabilities. Notice the expected value of \$1,160 is not one of the potential outcomes.

A sensitivity analysis can be used to determine how changes to the tree inputs, that is, probabilities for the states of nature and values of the payoffs, affect the recommended decision alternative. Table 19.5 provides a sensitivity analysis for consequences. To read the table, look at step 3 of 90 Strong. If the input, that is,

* As used here, “risk profile” is a Palisade PrecisionTree software feature that visually summarizes the potential consequences of an event tree. It should not be confused with previous definitions of that term. Risk language is messy.

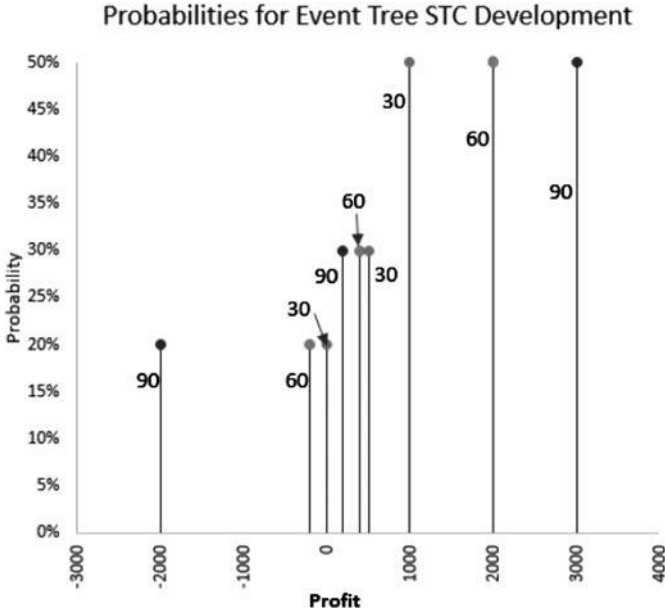


FIGURE 19.14 Risk profile for STC development of Sweet Virginia.

profit, rises from \$3,000 to \$3,750 this is a 25% increase. This results in a new output, that is, best expected value. It increases from \$1,160 to \$1,535, a 32.33% increase. If profit fell to \$2,250 the best expected value would fall to \$1,080, a 6.9% decrease. The 90-condo decision is reasonably robust across changes in profit. Notice that changes in the last five clusters of profit inputs do not affect the expected value because none of these changes is large enough to swing the best choice from the 90-condo option.

19.11.5 VALUE OF ADDITIONAL INFORMATION

Imagine that STC had the ability to consult a seer who could eliminate the uncertainty about which state of nature would be realized. What would that perfect information be worth to STC, that is, what is the expected value of perfect information? Frequently, additional information is available that can improve the probability estimates for the states of nature (or the size of the consequences if they are uncertain). The expected value of perfect information (EVPI) is the increase in the expected outcome, in this case, profit, that would result if one knew with certainty which state of nature would occur. The EVPI provides an upper bound on the expected value of any additional sample or survey information undertaken to reduce the uncertainty about which state of nature is more likely.

Here is how it works. For each state of nature, select the highest payout and weight it by its probability, call this the value with perfect information (EVwPI). It is \$1,650 and is seen below. The expected value without perfect information (EVwoPI) is the

TABLE 19.5
Sensitivity of Expected Value to Changes in Consequences

Spider Graph Data
 Decision Tree “STC Development” (Expected Value of Entire Model)

Input Name	Step	Input Variation			Output Variation		
		Value	Change	Change (%)	Value	Change	Change (%)
90 Strong	1	2250	-750	-25.00	1080	-80	-6.90
	2	3000	0	0.00	1160	0	0.00
	3	3750	750	25.00	1535	375	32.33
90 Weak	1	-2500	-500	-25.00	1080	-80	-6.90
	2	-2000	0	0.00	1160	0	0.00
	3	-1500	500	25.00	1260	100	8.62
60 Strong	1	1500	-500	-25.00	1160	0	0.00
	2	2000	0	0.00	1160	0	0.00
	3	2500	500	25.00	1330	170	14.66
90 Moderate	1	150	-50	-25.00	1145	-15	-1.29
	2	200	0	0.00	1160	0	0.00
	3	250	50	25.00	1175	15	1.29
60 Moderate	1	300	-100	-25.00	1160	0	0.00
	2	400	0	0.00	1160	0	0.00
	3	500	100	25.00	1160	0	0.00
60 Weak	1	-250	-50	-25.00	1160	0	0.00
	2	-200	0	0.00	1160	0	0.00
	3	-150	50	25.00	1160	0	0.00
30 Strong	1	750	-250	-25.00	1160	0	0.00
	2	1000	0	0.00	1160	0	0.00
	3	1250	250	25.00	1160	0	0.00
30 Moderate	1	375	-125	-25.00	1160	0	0.00
	2	500	0	0.00	1160	0	0.00
	3	625	125	25.00	1160	0	0.00
30 Weak	1	-50	-50	-	1160	0	0.00
	2	0	0	-	1160	0	0.00
	3	50	50	-	1160	0	0.00

decision alternative with the highest expected value, the 90-condo choice at \$1,160. These calculations look like this for our example:

Expected value with perfect information (EVwPI):

$$0.5(\$3,000) + 0.3(\$500) + 0.2(\$0) = \$1,650$$

Expected value of optimal decision without perfect information (EVwoPI):

$$0.5(\$3,000) + 0.3(\$400) + 0.2(-\$2,000) = \$1,160$$

Expected value of perfect information (EVPI):

$$\$1,650 - \$1,160 = \$490.$$

It would be foolish to spend more than \$490 (a year) for perfect information.

These are simple examples of some common applications of decision theory. Note, as mentioned earlier, the theory is far more sophisticated than has been demonstrated in this brief overview. Those interested in learning more should consider Clemen and Reilly (2014) *Making Hard Decisions with Decision Tools* for an introduction, and Kochenderfer et al. (2015) *Decision Making Under Uncertainty Theory and Application* for a more complete treatment of the topic.

19.12 SUMMARY AND LOOK FORWARD

If risk assessment and its intentional focus on uncertainty do not improve decision making then the risk analysis sciences will have failed in a fundamental way. Risk analysis is decision making under uncertainty.

There are a great many sophisticated methods for decision making under uncertainty but many of them are simply not practical for most organizations that struggle with fundamental issues like how much analysis is needed to make a decision and how to get decision makers to consider uncertainty. To address these fundamental needs this chapter has argued there is a best time to make a decision and a practical approach to making decision under uncertainty is needed. Four tasks are identified as a foundation for a practical approach. These are understanding the decision to be made, understanding the residual risks and residual uncertainty, asking clarifying questions, then making a decision or not. Four tactics to help initiate this process are: change the decision meeting, question the numbers, power down decision making, and socialize errors that result from a good risk management process.

Communicating uncertainty to risk managers is only one of the communication challenges risk analysts face. After a decision is made it must be communicated to stakeholders and the public. The next two chapters pick up where decision making leaves off to consider the remaining communication challenges. The first of these is developing specific messages for risk communication found in the next chapter. The following chapter turns its attention to documenting a risk management activity and telling the risk management story.

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20 Message Development

20.1 INTRODUCTION

To be a successful risk communicator, you need to be able to prepare an effective message. Risk communication is not an incidental task, and successful risk communication is never accidental. Everyone involved in a risk management activity needs to know something about risk communication if for no other reason than to keep colleagues from shooting themselves in the foot. There may not be risk communication experts on every organization's staff. Some organizations are unaware of the importance of the task. That means there may be times when you may have to bring some of this knowledge to the table.

Risk communication presents unique challenges to communicators for two very specific reasons. One of these is that the content of the messages is often difficult material. Risk, uncertainty, probability, and science are not the easiest things for even eager and interested parties to understand. These are often the subjects of risk communication messages. The other reason risk communication is especially challenging is that the audience is often upset and frightened, experiencing strong emotional noise during the communication process.

If risk communication is to succeed under these circumstances, someone needs to know how to develop an effective message. Developing that message is the focus of this chapter. It begins with a brief review of a basic communication model, so we can consider how the risk communication model differs from it, especially during high-stress situations. From there we consider the need for risk communication strategies and then turn our attention to crisis communication strategies during the four stages of a crisis. This is followed by a practical review of message mapping and consideration of some risk communication message templates. The chapter concludes by considering impediments to risk communication before the final summary and look forward.

20.2 COMMUNICATION MODELS

After all of humanity's time on the planet, communication remains as our greatest challenge. In the arena of risk analysis, information is often mistaken for communication. Information is almost a by-product of risk analysis; risk communication is a thoughtful and intentional primary product. George Bernard Shaw said, "The single biggest problem in communication is the illusion that it has taken place." Understanding a bit about the basic communication model is a good starting point for understanding how risk communication differs from basic communication.

There is a very rich literature describing a great variety of communication models. David Berlo (1960) offers a simple and influential model that suits the current purpose well. Described as the source-message-channel-receiver (SMCR)

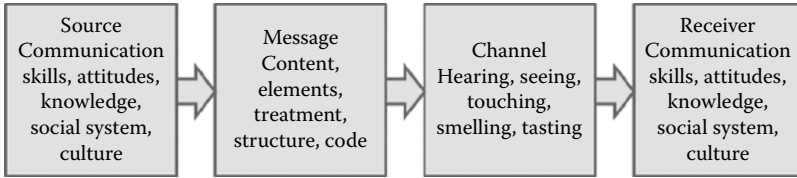


FIGURE 20.1 Berlo's SMCR communication model.

model, it has the four major components shown in [Figure 20.1](#). The source is a person, organization, or any generator of messages. Berlo offers the message as the central element of his model, which stresses the transmission of ideas. Meaning is encoded into messages. Messages are transmitted through a channel and are then decoded by a receiver. That the message received is not always identical to the message sent is a common basis for many situation comedies and undoubtedly a good portion of the divorce rate.

In risk communication, this model is tested at several points. If the source has not used a good risk management process, the purpose for communication may not even be clear. The perceived trust and credibility of the sender will be critical. Multiple channels must be used to reach the multiplicity of audiences for risk information. Perhaps most significantly, the receiver may be highly stressed. People in these situations can lose up to 80% of their ability to effectively process information. The message, which may have already been challenging because of its content, needs to be simplified. It is harder for people to hear, understand, and remember in stressful situations. In other words, risk communication, is not well-served by the basic communication model.

The developing field of risk communication offers a model that addresses these and other concerns. Two of the most important differences in the risk communication model are that it is a multidirectional model and it actively involves the audience as an information source. Risk communication is often more than two-way communication because of the complexity of the issues and the number of interested parties. It is an audience-centered form of communication because it often addresses situations of high stress, great concern, or low trust. These situations call for as much attention to the methods of communicating as to the messages. Those who are not risk communication experts are likely to have more input in the development of key risk messages than in any of the other subtler nuances of risk communication strategy and methods. Hence, this chapter focuses on message development.

20.3 RISK COMMUNICATION MESSAGE STRATEGIES

The need for message strategies abounds in the risk communication community of practice and not just for crisis communication. Internal risk communications between risk managers and assessors would be enhanced by some simple message strategies for clearly communicating problems and opportunities, objectives and constraints, as well as the questions to be answered by risk assessment. Another significant risk communication stumbling block has been the lack of strategic attention given to how to communicate the findings of risk assessments most effectively to its varying

audiences. The general practice seems to be to do the work and document it all in a risk assessment; add an interpretative or executive summary for those whom we know will not read it all, which is virtually everyone; and then make it available to anyone who wants it, that is, information = communication.

That last thought needs to be amended to information \neq communication. There is a pressing need for message development strategies for reporting the results and relevance of risk assessment for several key and recurring audiences that include risk managers, industry, those responsible for implementing the risk management option, consumers, the media, special-interest groups, and the general public, especially those most affected by the risk. How do we explain complex scientific subjects that are highly uncertain or results that are based on probabilistic methods to these audiences in ways that are meaningful to them? Message strategies are needed for risk management decisions. How do we best convey how trade-offs were made, how decisions were arrived at, as well as what those decisions are and who has what specific responsibilities for managing the risks?

Flood risk management provides an excellent example of the need for risk communication strategies in noncrisis/low-stress situations. Although many flood risk management investigations are initiated in response to flood events, they often take a long time to complete, and the public's attention may have been long since diverted elsewhere. These extended planning periods can produce audiences that are often closer to the low-stress, low-interest circumstances than to the high-stress, high-interest conditions that follow a damaging flood. In addition, the topics are complex and rest on probabilistic concepts we now know are not intuitive.

In the past, the U.S. Army Corps of Engineers, which has primary authority for addressing flood problems in the United States, has done their planning investigations and then "sold" them based on the "protection" they were expected to provide. A typical situation would have had a damaging flood of record followed by identification of a flood risk management option that would protect the community against a recurrence of such a flood.

A simple schematic, shown in [Figure 20.2](#), illustrates the situation. A person living in the so-called 10-year floodplain for a 75-year lifetime (no mitigation) is virtually certain to experience one or more floods in that time.* The darker shading indicates the probability of one or more floods in a lifetime. A flood with a 1% annual exceedance frequency has, in the past, been called a 100-year event, because in the very long run there would be such a flood on average once in 100 years. (Perhaps you begin to see why message strategies for noncrisis/low-stress situations like this one are needed!) If protective works, say a levee, are constructed to prevent flood damages from the recurrence of such a flood, that reduces our lifetime resident's risk by the amount of the lighter shading in the second column (100-year). That reduction in risk is what the people living in the floodplain were "sold" in the past. The positive effects of the protective works were the focus of the conversation. What was not adequately communicated was the residual risk, the risk that remains even with that levee in place. There is still a 53% chance a person will be flooded one or more times in a lifetime behind this levee.

* To get that value, calculate one minus the binomial probability of zero successes with $n = 75$ and $p = 0.1$.

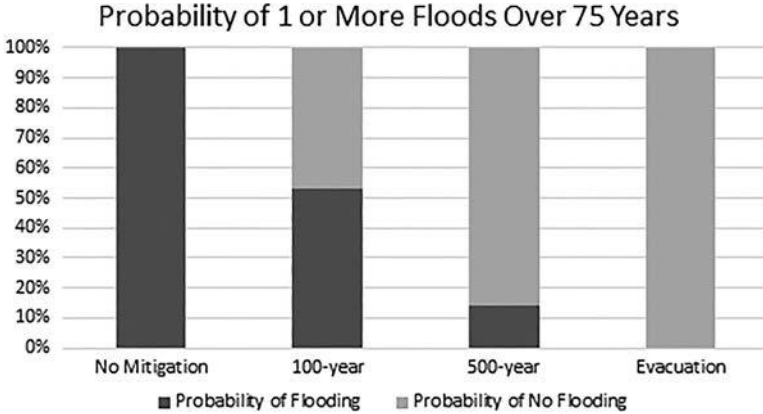


FIGURE 20.2 Residual flood risk for selected risk management options.

If the flood of record had an annual exceedance frequency of 0.2%, it has a recurrence interval of 500 years ($1/0.002$) and has been called the 500-year flood. Protection from a flow of this magnitude could require a much higher levee. The risk reduction provided by that levee is shown as the light shading of column three (500-year). Even though living behind a very high levee, there is still a 14% chance of one or more damaging floods in a lifetime. Permanent evacuation of the floodplain is the only effective way to eliminate the risk of flooding to its residents. This simple discussion does not even consider how a flood risk is transformed when catastrophic failure of protective works, as occurred in New Orleans, is now a possibility. So, it is not difficult to appreciate the complexity of the message flood plain residents need to absorb.

Let us return to the residual risk (the darker shading) of columns two and three for a moment. What can be done to manage the residual risk, and whose responsibility is that? These are important additional risk messages to craft and communicate. One of the principle reasons the so-called 100-year flood has been targeted as a minimum level of flood protection is that if the 100-year floodplain is confined, say to between the levees along a river, then residents no longer live in the 100-year floodplain and are no longer required to buy flood insurance. The figure shows the foolhardy nature of this strategy. The chance of a house fire over 75 years is far less than 53% and everyone with a mortgage is required to have fire insurance, yet flood insurance remains an option.

Residual risks can be addressed in a variety of ways. Homeowners could be required to purchase flood insurance, agree to evacuate when an order is given, and provide a trapdoor escape hatch on the roof of their homes. A great many people who drowned in New Orleans had moved to the highest floor or attic of their homes only to become trapped and drown in rising water. This is all part of the message those at risk of flooding should hear and understand.

Not only do we need to formulate management strategies, but we need to formulate message strategies for a great many noncrisis risk communications. Too often there is no effective strategy for communicating complex information to laypeople in a risk management activity. Strategies for communicating about residual, new, transformed, and transferred risks could be used in a great many situations.

20.4 CRISIS COMMUNICATION

Crisis communication strategies, by contrast, have received a great deal more attention. The National Center for Food Protection & Defense's (NCFPD) excellent free teaching resources form the foundation for this section, and the work of the NCFPD is gratefully acknowledged (Food Insight 2010). Their communication model consists of a sender, receiver, channel, message, feedback, noise, and an environment, that is, a time and place for the communication. For normal situations, where there is little to no stress, audiences tend to base their trust in the communicator on his or her level of competence and expertise. During a crisis or in other high-stress circumstances, trust factors change, as discussed in [Chapter 5](#). Listening, caring, and empathy become far more important than competence and expertise.

Stress interferes with the function of the basic communication model. The choice of the best sender of a message may change from a low-stress to a high-stress situation where the communicator's effectiveness depends more on credibility and trust. The audiences (receiver) have a reduced capacity to process complex information, so the messages must be simplified to be effective. Feedback to gauge the public's response becomes more important than ever. Noise, that is, barriers that interfere with the receiver's ability to process information, can increase during a crisis. Communications systems may be compromised, and even when they are not, stress levels and emotional responses to the situation can present significant barriers to the normal communication model.

DIFFERENCES BETWEEN COMMUNICATING DURING LOW- AND HIGH-STRESS SITUATIONS

Low: Receiver processes an average of 7 bits of information

High: Reduced to 3 information bits

Low: Information processed in a linear order (1,2,3)

High: Information processed in order of primacy (1,3,2) or recency (3,2,1)

Low: Information is processed at an average grade level (local newspapers written at 8th grade reading level)

High: Information is processed at 4 grade levels lower (e.g., from 8th grade to 4th grade)

Low: Focus is on competence, expertise, knowledge (title, credentials)

High: Focus is on caring, empathy, compassion concept (metamessages)

Source: NCFPD Training Module 3 Message, Delivery and Development

This mental noise disrupts the listener's ability to process information to such an extent (see box) that overcoming the noise must become an explicit counterstrategy for risk communication. This means we need to simplify the message: offer no more

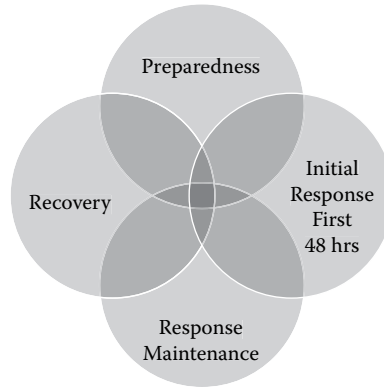


FIGURE 20.3 Reynolds and Seeger’s four stages of a crisis.

than three message points and use short sentences. Numbers should be used sparingly and carefully. Ideas are often more effectively presented through pictures or graphics during high-stress situations.

Reynolds and Seeger (2005) have identified four stages of crisis communication, shown in [Figure 20.3](#). The preevent planning for a crisis response takes place in the preparedness stage. Credibility and trust cannot be readily established in the midst of a crisis. They are slow to build and so must be strategically cultivated as part of an organization’s crisis preparedness. Educating and informing the public about more complicated information is also better initiated during low-stress times. The preparedness stage is the time to develop message maps, a subject touched on later in this chapter, and risk communication strategies. Messages that may be needed in a crisis can be tested with stakeholders and the public during this stage as well. A crisis is not the time, for example, to begin looking for a translator to reach your multicultural audiences, nor is it the time to start wondering what to say or to whom to say it.

The initial response to a crisis spans the first two days of the event. During this time there may be a lot of unknowns. Uncertainty or “mystery” intensifies the fear during this period. Effective risk communication must begin immediately. You cannot wait until you have all the answers to communicate.

The first 48 hours is a time for responding, not for planning. This need to respond quickly makes the preparedness strategies very important. It is that preparedness that enables you to respond.

Reynolds and Seeger (2005) offer several principles for the initial response:

- Be first, be right, be credible
- Acknowledge the event with empathy
- Explain the risk and inform the public; tell them what you know, what you don’t know, and what you’re doing about it
- Commit to continued communication
- Keep communication channels open

The response maintenance phase of the crisis is a time to continue to build on the response to the crisis. It is important to help the public understand the risks they may face and to provide useful information in a way that empowers people to make their own risk/benefit trade-off decisions. These can be simple messages like: “Stay indoors until the spill has been cleaned up”; “If you are worried, don’t eat spinach”; “To be safe, evacuate the area”; and so on.

Subject matter experts may help at this point by providing background information. The risk communication team needs to listen to their various audiences and stakeholders for feedback and to correct misinformation. This is a time to improve understanding of the problem and to build support for the response and recovery plans.

After the event has passed, the recovery stage begins. It is often accompanied by feelings of relief, celebration, and gratitude for getting through the event. Not everyone will share in these feelings, however, and it is important to continue to express empathy and caring for those who have suffered through the event. It is time to listen to the public and the stakeholders to hear how they perceived your effectiveness during the event. It is important to acknowledge any shortcomings and to explain how they will be rectified in the future. Actions must match the messages, or trust and confidence may be irreparably harmed.

COMMON MISTAKES MADE IN A CRISIS

Overreassure

Sound too certain, too confident

Wait too long

Fail to communicate the complexity of decision-making or to acknowledge opinion diversity

Try to appear objective by excluding emotions from our messages and metamessages

Treat the public as though they are children

Downplay the mistakes we have made

Source: NCFPD Steve Venette.

20.5 MESSAGE MAPPING

Many crisis situations can be anticipated by an organization. Floods and other natural disasters, traffic accidents, food-borne disease outbreaks, terrorist attacks, train wrecks, airline crashes, product recalls, bank failures, toxic spills, and the like are expected events for a variety of organizations. Planning the communications response to these events is often as important as planning the first responders’ activities.

Based on how people process information during times of stress, Dr. Vincent Covello (2002) of the Center for Risk Communication has developed the idea of message mapping. Message maps are a good first step for developing risk communication messages during the preparedness stage of crisis communication.

They enable staff to develop effective messages that organize and simplify complex content in a systematic way during periods of low stress. Message maps can also be useful for many of the noncrisis/low-stress events discussed earlier.

Covello describes this tool as “a roadmap for displaying detailed, hierarchically organized responses to anticipated questions or concerns. It is a visual aid that provides at a glance the organization’s messages for high concern or controversial issues.” A message map provides a framework for organizing information and developing clear and concise messages that anticipate stakeholder questions and concerns. Done in advance of a crisis in a thoughtful way, they offer an organization the opportunity to promote a consistent message and voice in the midst of a crisis. Message maps offer a systematic approach for preparing effective risk communication messages. The message map is not the message, however. It is a device that aids in the development of risk communication messages.

Remember, in high-stress situations, people can process three bits of information effectively. So, message maps are based on the “rule of threes.” In high-stress situations it is best to:

- Present three key messages
- Repeat key messages three times
- Prepare three supporting messages for each key message

This rule is supplemented by Covello’s 27/9/3 Rule, which says to use a total of 27 words, delivered in no more than 9 seconds, to deliver three key messages.

These message maps can be used to prepare risk communication messages for emerging or anticipated crises. They are also useful for preparing for media interviews, press conferences, and other public forums. They are a good first step in creating a risk communication message or statement.

The steps for developing message maps are simple. Begin by making a list of all the questions you may be asked to address. Then prepare a message map for each question. In answer to each question you should identify the following:

- The three most important things you would like your audience to know
- The three most important things your audience would like to know
- The three most important things your audience is likely to get wrong unless they are emphasized

A message map template can be used to organize this information. The key messages in a template should be able to stand on their own. The support points for each key message provide factual information, visual aids, citations to credible third-party information, and sources of more information.

The NCFPD provides a sample message map, shown in [Figure 20.4](#), that addresses the question: “What should I know about anthrax?” Note that the three key messages, the top item in each column, are expressed in a total of 22 words. There are also three supporting ideas for each key message; these also total to 27 words or less. The message map content is constructed based on the answers to the bulleted items outlined previously. One such map should be constructed for each significant question; thus, the bulleted items could lead to nine maps. These maps are then used to craft the message.

1. Anthrax is a disease that can affect people and animals.	2. Anthrax occurs naturally in the soil.	3. Anthrax is both preventable and treatable.
1a Anthrax is caused by bacteria that form spores.	2a Anthrax occurs worldwide.	3a Effective vaccines are available for livestock.
1b The spores can be inhaled, swallowed or enter the skin (contact).	2b Spores are resistant to manmade disinfectants.	3b Vaccines for humans are developed and can be used prior to or after exposure.
1c Animals most commonly affected are cattle, sheep, and goats.	2c Anthrax spores can survive for many years in soil without an animal host.	3c Early treatment antibiotics can be effective.

FIGURE 20.4 Sample message map for anthrax scare. (From Food Insight. 2010. Risk communicator training for food defense preparedness, response and recovery: Trainer’s overview. http://www.foodinsight.org/Resources/Detail.aspx?topic=Risk_Communicator_Training_for_Food_Defense_Preparedness_Response_Recovery [accessed October 30, 2018].)

20.6 DEVELOPING RISK COMMUNICATION MESSAGES

Developing a risk communication message requires the communicator to integrate all he knows about risk communication. It begins with the goals and desired outcomes of the risk communication. A good message recognizes risk perception as a combination of facts and feelings as well as common human reactions to risk, such as fear, denial, and panic. This necessitates careful attention to techniques for communicating in high-stress situations.

The NCFPD team has developed a risk communication message template, shown in Figure 20.5. The scenario for using this template can be found in any of the four phases of a crisis. The strategy for the communication might include such things as relationship building, partnership responsibilities, trust building, changing behavior, coming to agreement, and so on.

The communicator’s role and communication goal identify the who and the why of message development. The who may include such roles as subject matter expert, industry representative, government official, emergency responder, agency spokesperson, university scientist, consultant, and so on. The purposes of the communication are varied and might include increasing awareness of a potential risk, providing background or technical information, executing a response plan, or supporting recovery.

Key audiences need to be identified. Communicators must be aware of the education level, general awareness of the risk or event, as well as relevant demographic and cultural characteristics of the population.

The medium and delivery mode depend in part on the desired impact and influence of your communication. Channels have varying extents of persuasive influence and they reach audiences of varying size (impact) and type. Channel choice often goes back to knowing your audience. Where are they? How do they get their information? How do you reach them? What do they listen to? What do they read? What radio/television stations do they tune into? What other communications do they use? The most commonly used channels include interpersonal communications, television,

MESSAGE DEVELOPMENT TEMPLATE

SCENARIO:
 COMMUNICATOR ROLE:
 COMMUNICATION GOAL:
 PREPAREDNESS STRATEGIES:

Key Audience(s)	Medium/ Delivery Mode	Key Questions and/or Messages	Metamessage Strategies
Message Text			

FIGURE 20.5 National Center for Food Protection and Defense message development template. (From Food Insight. 2010. Risk communicator training for food defense preparedness, response and recovery: Trainer’s overview. http://www.foodinsight.org/Resources/Detail.aspx?topic=Risk_Communicator_Training_for_Food_Defense_Preparedness_Response_Recovery [accessed October 30, 2018].)

radio, print, Internet sites, blogs, e-mail, mobile phone, text messaging, tweeting, chat rooms, and other social media. Each has its pros and cons. Multiple channel strategies are often most effective.

The key message grows from the message mapping activity. Metamessages are the nonverbal messages you want to send. The substantive information of your message is only part of the message content. All the other things and ways your message communicates comprise the metamessage. Metamessaging should be an intentional strategy that, among other things, reveals your empathy and caring. Whether you decide to come across as confident or tentative, open or not, how human and how official, your degree of candor, openness, and such: these are all strategies you should consider beforehand. Metamessage strategies do not preclude sincerity. Deciding to be sincere does not make one insincere. Deciding to sound sincere while not being sincere does, however.

Best risk communication practice uses as many opportunities as possible to reinforce the metamessage strategy. If you have decided to be more official, then staging may include flags and podiums with official symbols. Dress will be formal and the attendees will include officials at all relevant levels. A more informal and human metamessage strategy will lead you to choose other nonverbal metamessages.

In a risk communication message’s text, you provide information, give people meaningful things to do, and reinforce your metamessage. The information content includes what you know and what you don’t know. It should also include what you are trying to do about the situation. The information should also include when you’ll provide the next update. The text may come from messages you have mapped.

Your risk message should empower people to make decisions and take actions to help themselves. This is the self-efficacy component of the message. The intent is to help restore a sense of control over an uncertain and threatening situation. You empower audiences by giving people the information they need to make informed decisions and by giving them meaningful things to do.

A good risk message includes three kinds of self-efficacy statements. It tells people the things they must do now. It tells them what they should do to reduce the risk or their exposure to it. Finally, it tells them what they could do to help themselves further. An alternative emergency message development worksheet developed by the Centers for Disease Control is shown in Figure 20.6.

Message Development Worksheet for Emergency Communication

First, consider the following:

Audience:	Purpose of Message:	Method of delivery:
<input type="checkbox"/> Relationship to event <input type="checkbox"/> Demographics (age, language, education, culture) <input type="checkbox"/> Level of outrage (based on risk principles)	<input type="checkbox"/> Give facts/update <input type="checkbox"/> Rally to action <input type="checkbox"/> Clarify event status <input type="checkbox"/> Address rumors <input type="checkbox"/> Satisfy media requests	<input type="checkbox"/> Print media release <input type="checkbox"/> Web release <input type="checkbox"/> Through spokesperson (TV or in-person appearance) <input type="checkbox"/> Radio <input type="checkbox"/> Other (e.g., recorded phone message)

Six Basic Emergency Message Components:

- Expression of empathy:

- Clarifying facts/Call for Action:
 Who _____
 What _____
 Where _____
 When _____
 Why _____
 How _____
 Add information on what residents should do or not do at this time _____
- What we don't know:

- Process to get answers:

- Statement of commitment:

- Referrals:
 For more information _____
 Next scheduled update _____

Finally, check your message for the following:

Positive action steps Honest/open tone Applied risk communication principles Test for clarity Use simple words, short sentences	Avoid jargon Avoid judgmental phrases Avoid humor Avoid extreme speculation
---	--

FIGURE 20.6 CDC emergency message development worksheet. (From www.health.gov/living/lpha/toolkit/chap7/01.doc [accessed February 7, 2011].)

20.7 IMPEDIMENTS TO RISK COMMUNICATION

There are many issues that affect our ability to communicate about risk. Covello et al. (1989) offer a dozen factors that complicate risk communication. They are well worth understanding for constructing effective messages. First among these, is that risk is an intangible concept that the general public does not understand. As a result, their risk-taking or risk-managing decisions can be based on bad information. Second, the public likes simple solutions. They are more likely to take effective action when the action is simple, for example, “Don’t eat spinach.” They are less likely to take effective action if the solution is more complex, for example, “Move out of the floodplain.” Third, the public does not like uncertainty or probability. They much prefer concrete facts upon which to base their decisions. People are prone to draw inappropriate conclusions from uncertain and probabilistic information. When the media draw the wrong conclusions, the consequences of that faulty information can be magnified. Fourth, the public can react unfavorably to fear.

A fifth confounding factor is people’s aversion to a loss of control over their personal well-being. Risks perceived as beyond the control of the individual present a special challenge for message development. When the U.S. Army Corps of Engineers described two dams upstream of Houston in need of repair as “extremely high risk” in February 2010, citizens were concerned despite the fact the Corps said not to be alarmed.* Sixth, the public sometimes doubts scientific predictions. Y2K disasters and flu epidemics that did not materialize have taught people that the scientists and experts can be wrong. A seventh factor is that the risk at issue may simply not be one of the public’s priorities. Feelings of invincibility among the young, for example, may render some risk messages ineffective because they cannot imagine their susceptibility to the risk. Related to this is an eighth confounding factor: The public tends to underestimate their personal risk. Bad things happening to other people is not just a defense mechanism of youth.

Ninth, the public hold contradictory beliefs, for example, “I am not going to get cancer”/“Everything causes cancer!” Tenth, a majority of Americans lack a strong future orientation. Some version of “live for today and let tomorrow take care of itself” is a common perspective on the future. It is not easy to get people to change their diet today in exchange for better health in the future. The future is less relevant to those in the lower socioeconomic strata of society.

READABILITY SCORE

For readable messages experts recommend writing for a 7th to 8th grade reading level. Several indices are available for evaluating your written messages.

The Flesch–Kincaid Grade Level

$$\text{FKRS} = (0.39 \times \text{ASL}) + (11.8 \times \text{ASW}) - 15.59$$

* “Engineers to Update on Addicks, Barker Dams.” <http://www.ultimatekaty.com/stories/4406-engineers-to-update-on-addicks-barker-dams>. These dams subsequently proved to be critical factors in the damages from Hurricane Harvey in 2017.

where FKRS is the Flesch–Kincaid Readability Score, ASL is the average number of words in a sentence, and

ASW is the average number of syllables per word.

Gunning's Fog Index Grade Level = $0.4 (ASL + PHW)$, where PHW = Percentage of Hard Words. Hard words are words of three or more syllables that are not (1) proper nouns, (2) combinations of easy words or hyphenated words, or (3) two-syllable verbs made into three with -es and -ed endings.

The last two factors include the public's tendency to personalize new information. When risks are described at societal or aggregated levels above the individual, people have to translate it into terms that are personal. This invites opportunities for misinterpretation. Finally, the public does not understand science. The models, methodologies, and descriptions of risk can be too technical for many people. The facts that science evolves and changes and that risk assessment is iterated just further confuse people. Many people are poorly equipped to understand scientific messages. Armed with an awareness of these factors that complicate risk communication, careful message development becomes an indispensable skill for a risk analysis organization. It is important to write messages that readers can understand (see box).

20.8 SUMMARY AND LOOK FORWARD

Risk analysis is an effective paradigm for decision making under uncertainty. Communicating about risks and communicating uncertainty are especially challenging tasks. This is in part because the subject matter is difficult and in part because the audience for this communication is often in an emotional state. Risk communication entails a great deal more than providing people with information. Best-practice risk communication necessitates that key messages be developed carefully and, as often as possible, well before they are needed.

Message development strategies are a critical part of effective risk communication. Message mapping is a useful component of these strategies. How do you explain the complex distributions, sensitivity analyses, and other details we have discussed throughout this book? The answer may well be that you do not have to; just remember the "rule of threes." Know the impediments to successful risk communication and develop messages to avoid them.

Continuing down the faulty path of information = communication, people often dump all of their risk data into a more or less coherent document that hopefully meets the needs of that risk management activity's stakeholders. We need to stop dumping data and to start telling effective stories. Story telling is another invaluable skill for those who engage in the risk analysis sciences and it is the subject of the next chapter.

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21 Telling Your Story

21.1 INTRODUCTION

Many people, including experts and decision makers, are simply not capable of sifting through the evidence of a risk assessment and figuring out what happened. They need the aid of a good story. Stories are at the heart of how people think, learn, exchange ideas, and struggle to understand the world around them. Stories are what we need to use to manage facts and process ideas. Learning to speak in the language of our respective fields makes us special. It also challenges us to learn how to talk about difficult risk topics and problems using ordinary, everyday English.

How does a risk analyst (inclusive of assessors, managers, and communicators) tell a good story—one that is effective, purposeful, persuasive, and compelling while remaining meticulously factual and truthful? Risk analysis needs ethical and truthful storytellers. Storytelling often determines the outcomes in decision-making situations. So, we must ask, what are the desired outcomes of risk assessments and risk management activities? Are they merely compendiums of data? Research documents? Decision documents? Or are they calls to action? If the desired outcome is nothing but the risk assessment output, the compilation of data, the results of the analysis then, perhaps, no story is required if the report is the desired outcome. So, let us be clear from the outset, storytelling may not apply to every risk documentation task.

Risk analysis is an action-oriented application of science. Its purpose is to support decision making and that distinguishes risk documents from research, descriptive studies, journal articles, dissertations, and the like. The desired outcomes of risk documents are effective risk management decisions. Decision making is often aided by storytelling.

Your first job is to know what kind of documentation you are being called on to provide. A well-formed logical argument looks very different from a well-told story. Know your intention before you begin. If you work for an organization that has and requires an established report template, use the template. If you are expected to present the science in an unbiased manner, by no means should you adopt an advocacy position. Even so, you can tell the story of the hazard you are assessing, you can tell the story of the risks that threaten us, or of why or how you decided as you did. It may be easier and more effective to do so in the narrative style of storytelling rather than simply data dumping.

If you have done the science and arrived at a recommended plan of action as the result of a rigorous and effective decision-making process, it may be appropriate for you to advocate for your recommendation in some organizations and settings. If your task is to document a risk management activity in a way that motivates employees, stakeholders, or the general public to action, then maybe you can use a good story. Reports can convince but they rarely motivate. It takes a story to motivate people to take action.

When people work hard on something they want to show their work and show you the data they used. Such writers may dump everything they gathered during an assessment into one of several formulaic chapters. Data dumping can have its value but neither “good reading” nor effective communication are ever part of that value.

A lot of great work is being done in risk assessment but it is all for naught if it does not influence judgment and decision making. Some risk documents deluge the reader with so much data that they must be summarized, boiling complex results down to simplistic synopses to satisfy decision makers. This can undo the entire point of risk-informed decision making. Uncertainty could be ignored or overlooked when this happens. So, we must ask, what good are all these data and all this analysis if it is not used effectively? Risk documents rarely make good reading. Few decision makers are likely to read them in their entirety. They may read your story, however. This chapter argues that we need more stories and fewer reports that go unread.

We humans have used stories to teach, inform, and share from the beginning of time. Stories help us find the relevance of the content. We can connect a story with our own experiences. People read and understand stories. Stories work. They concisely communicate facts in memorable ways. Stories can inspire action. People need to be motivated and inspired to take action to change conditions and that action may be the essence of risk management.

The facts and figures and all the rational evidence we place such a premium on in risk assessment rarely stick in our minds. Data inform, they do not motivate or inspire. Nor do data connect with emotions in ways that result in effective actions. Only a good story can do that. Stories attach emotions to things that happen in the stories. A good story can make people see how the science of risk can and does affect them.

This chapter focuses on documenting the facts for effective decision making in stories. It does not advocate manipulating emotions, marketing ideas, down-playing the science or the uncertainty, advocating positions, or any other abuse of the risk management process. It strongly advocates telling the truth in more effective, interesting, and engaging ways. We recognize that many organizations with a stewardship responsibility are to construct risk assessments and other risk documents in a specific format to meet statutory, regulatory, policy, or other requirements. Private organizations, on the other hand, may document risk management decisions in more ad hoc ways. Some organizations may not document their work at all. Storytelling can enhance the value added by a risk management process. When it comes time to explain the significance of the results of a risk assessment or a risk management activity, stories with a narrative quality may be more effective than dry reports filled with data and details that may not be necessary for understanding the issue and its resolution.

In regulatory and stewardship settings, especially those likely to be controversial, the science and other evidence can be preserved, presented, and explained in technical appendices or other adjunct documents. The science should never be misrepresented or manipulated for the sake of storytelling. Risk assessment must document the science and the uncertainty. Stories, rather than reports, may be one way to do this (see box).

I have been espousing the value of telling stories instead of dumping data for a few decades. Once a client took me up on this challenge and asked me to help them tell the story of a food safety risk. So, I told the story of how an egg can become contaminated with *Salmonella enteritidis* and then make someone (deathly) ill. The story included ideas for how to prevent this from happening, and it was going to include a “here is what we are doing to change this” situation. That story never saw the light of day because scientists who worked on the risk assessment objected. They wanted to make sure their “reports,” that used half the Greek alphabet, did not get ignored. I still think “How an Egg Can Make You Sick” is more interesting than a 213-page risk assessment.

The chapter proceeds with a clarification of its intent before considering some of the problems encountered with standard format reports and formal documents. It then defines what we mean by a “story,” because there are a variety of entities making risk management decisions and not all of them document those decisions in written formats. You will find storytelling to be a very flexible concept and a potential means for alleviating some of the problems formal reports pose. The chapter builds on this potential, discussing the value of stories and when they are needed with emphasis on why they seem to work better than reports. At that point, the chapter offers suggestions on how to write an effective story. This begins with the invented concept of a riskography, the biography of a risk, and proceeds through a number of other options. Recognizing that a great many practitioners of risk management are not bound by regulations, we also consider news stories as an alternative means for communicating about risks and risk decisions. Suggestions for structuring stories follow before the chapter turns its attention to the unique challenges of telling stories with data, including the use of graphics and visualizations. A bit of advice on writing simply is offered before the last topic, alternative means of documenting your risk story.

21.2 LET US CLARIFY

Risk assessment results, risk management decisions, risk profiles, risk appetites and tolerances, and risk metrics are some of the kinds of things that might be documented by an organization that is practicing risk analysis or risk management. Organizations operating in the public sector can be expected to have different reporting requirements from those operating in the private sector. Some of these reporting requirements may be mandated by law or policy. Clearly, any organization has an obligation to comply with all relevant laws and policy guidance. Likewise, common practice may exert a great deal of influence on decisions about how to document activities. It is the expressed purpose of many risk documents, especially formal risk assessments, to make an objective presentation of the state of the science on a matter of interest. Nothing in this chapter should be construed to suggest that purpose or any reporting requirements should be compromised in any way. However, using a story and honestly portraying the science are not mutually exclusive choices. This chapter is intended for the use of any and all risk analysis teams that have the leeway to tell their story in a more flexible format.

21.3 THE PROBLEMS WITH REPORTS

Reports are dull. It is dangerous to generalize from personal observation, but I suspect few of the larger risk reports are read in their entirety by decision makers. You may be lucky if they read the executive summary. While in this speculating mode, I further speculate that there are two main ways that reports come into being. One method is to find a recent report that is believed to have been well received and to emulate its contents and format. Then, of course, it is natural to want to personalize it by adding features or content of one's own devising. This is how reports grow larger and larger with each emulation. In the second method, most of us spend so much time and budget on the actual research that we find ourselves with little time and budget for reporting. As a result, we dump our data into a report to meet our reporting requirement rather than taking time to look for the story that makes the report truly useful.

I would have written a shorter letter, but I did not have the time.

Blaise Pascal

Johnson (2017) says reports are dull and when we hear “report,” we do not expect a story. We expect numbers, charts, and straightforward facts, none of which move us the way we expect to be moved by a story. Reports inform. If informing is your only intent, there is no need for a story. Doyle and Tharme (2011) have called current research report formats a “dying breed.” A number of recurring problems plague report formats in addition to their dullness. Reports present complex information that is often overly complicated with lots of facts, technical details, and sophisticated research methods and little or no insights (Zikmund and Babin 2010). They are frequently too data intensive and statistical. Clients and other users of the reports often do not comprehend the statistical terms, calculations, or conclusions. Clients tend to be reluctant to admit these things (Mahmoud 2004). This impedes understanding and the ability to take effective action based on the risk results.

HOW MANY WRITERS?

Risk reports are often written by the various team members, and they read like it too. Everyone writes his or her part, it all gets stapled together, and it is called a report.

Not all writers are equally gifted. Not all use the same writing style. Few things are more annoying to a reader trying to understand a complex issue than to try to wade through a poorly organized report written by a dozen people in a dozen different voices who apparently never spoke to one another or bothered to read what the others had written. That does not mean a report must be written by one person, but it probably should at least be edited by one.

The length of reports and the detail in them limit the client's understanding of the results and this lowers the effective impact the risk work has on their business (Bain, 2012b). Some reports describe the current situation in detail but fail to provide any direction for future action (Davison 2011). Research reports frequently do not report the research results in an effective manner (Bain 2012b).

As a result, clients are demanding a change in report formats. They want actionable research with strategic impact as opposed to large data sets (Appleton 2011; Bain 2012a). One result of the Information Age is a wealth of data that overloads people with too much information and not enough actionable insights. Marketing research consultants, in particular, are finding ways to deliver insights along with the data (GreenBook 2011; Van Slooten and Verheggen 2011).

These and other limitations of standard reporting formats give rise to a need for more effective formats for documenting the results of risk work. Maritz et al. (2014) found the use of storytelling is no longer just a "theoretical" demand; it is seen by marketing research firms as essential to the delivery of research reports. Storytelling is used in a growing number of business disciplines, some of which are leadership, management, coaching, selling, education, and branding (Silverman 2006; Carr and Ann, 2011; Bosworth and Zoldan 2012). Risk management is not marketing, selling, branding, or any business discipline. Nonetheless, we can do better than a dry report that will never be read.

21.4 WHAT IS A STORY?

Perhaps it makes sense to ask, what do we mean by a story? Segel and Heer (2010) describe Jonathan Harris, the creator of *We Feel Fine* and *Whale Hunt*, saying, "I define 'story' quite loosely. To me, a story can be as small as a gesture or as large as a life. But the basic elements of a story can probably be summed up with the well-worn Who/What/Where/When/Why/How." That is a serviceable definition, as risk analysts convey the stories of their risk assessments and risk management activities to a number of audiences in a wide array of venues and in a wide variety of ways, from the 30-second elevator description to the full-blown formal report with technical appendices as well as everything in between. To avoid continued unwieldy references to a variety of communications we will simply use "risk documents" to encompass the materials that may be improved by storytelling.

There is a great variety in what we mean by a story. It can be a short oral narrative, a brief news story, or told in a detailed report. The elements of storytelling vary a bit from one context to the next. Many risk stories may never be written down. As enterprise risk management continues to be adopted by more and more organizations, it is likely that increasing numbers of initiatives will go without formal documentation. Telling the risk story is, perhaps, even more necessary in these situations. There is a great deal of variation in the extent and manner of risk documentations and risk stories. A great many risk activities do, however, get documented in writing. This chapter applies to both the documented and undocumented risk stories that must be told.

Some organizations may have little more than a risk matrix or a risk profile to document assessments with very little supporting narrative. Risk actions may be documented simply by a spreadsheet risk register. Some risk management activities

will be documented as a series of bullet points in an annual report. The stories related to some documentation efforts may only be oral narratives. At the other extreme, a formal document may be prepared with documentation of the extensive data collected in a series of technical appendices. None of these circumstances, however, preclude the use of and reliance on a good compelling story to convey the most meaningful elements of a risk action.

That same Jonathan Harris said, “I think people have begun to forget how powerful human stories are, exchanging their sense of empathy for a fetishistic fascination with data, networks, patterns, and total information... Really, the data is just part of the story. The human stuff is the main stuff, and the data should enrich it.” Any risk information documentation process can be enhanced by an effective story.

21.5 WHY WE NEED STORIES

Data can persuade people, but it doesn't inspire them to act. A story can go where quantitative analysis cannot, a story can reach our hearts. Stories can move people to take action. A vision wrapped in a story that ignites the imagination, touches the heart, and stirs the soul can be a powerful force for action (Monarth 2014). Uniting a powerful idea with an emotion is a much more persuasive method than the more commonly applied intellectual process of data dumping. Inundating an audience with data, facts, and statistics can be effective in convincing others of the logical appeal of an argument, but it may also stop well short of motivating action. People are not often inspired to act by reason alone (Fryer 2003).

The best way to unite an idea with an emotion is by telling a compelling story. A good story can arouse the audience's emotions and energy while conveying important and useful information. Persuasive stories are not easy to construct. Reports are easier to write, all they require is rationality and endurance. Storytelling requires creativity, vivid insight, and storytelling skill sufficient to pack enough emotional power to inspire action (Fryer 2003).

Anthony Tjan (2014) speaks of people who have a way of making the complex clear. They are able to sharply crystallize ideas and vision and speak in simple, relatable terms. Such people can make the subject much more accessible, understandable, and enjoyable by bringing structure and common language to something that so many people find complex.

Alyssa Keefe (2014) says the human brain engages in up to 2,000 daydreams a day as it spends half its time wandering. Our brains have a strong tendency to wander. Storytelling is a powerful way to communicate information, build relationships, sell ideas, and inspire others, while limiting the brain's tendency to wander.

Risk analysis is science applied to decision making. Active risk management requires people, often many people, to take effective action. People can be required to take action, but people who are inspired to take action will do so more effectively. Risk analysis is science-based, and science is anything but emotional. Risk management, however, combines science with values and beliefs, that are often founded in emotions, to make decisions. Risk assessment isn't only about assessing risks, but also about expressing those risks so that other people can understand them and their significance. A risk assessment that others cannot understand or appreciate is as good as no assessment in the first place. There is always a story about risk, the choice is whether and how to tell it.

21.6 WHEN ARE STORIES NEEDED?

Stories are needed throughout the life of any risk management activity. In some instances, despite the preceding disavowal, some risk managers may be marketing ideas, advocating positions, and trying very directly to influence decisions through facts and manipulation of emotional responses to information. This may be entirely appropriate for private interests, less so for the public interest, but even there, not unimaginable.

The risk team crafts a story by telling it, then repeating it to one another in meetings and when working together. They will use stories when coordinating their progress with clients, higher authority, and reviewers. Stories are needed for decision meetings as decision makers may not be as intimately familiar with the details as the risk team is. Stories will be needed for conversations, encounters, and meetings with stakeholders, other interested parties, and possibly the general public. Finally, stories will be needed to document the decisions and results of the risk management activity, in whatever manner that is finally done. The stories may need to be told in face-to-face encounters, in social media, in a wide variety of other communication media, as well as in formal written communications.

There is a tendency to equate story telling with report writing, that is, telling a story in a formal report document. That can be an important part of storytelling but it is likely to be only one way in which a story gets told. Stories are needed almost from the beginning. There are stories within the story. There may be the story of how the risk management activity was scoped. How did you identify the risks? Why did you choose to do what you did? There may be a story of how the risks affect certain people in society or how a risk is affecting activities within a firm. When you think about storytelling, do not think too narrowly and equate it with report writing. It is quite possible that even a risk management activity that requires a very specific risk report will need to tell a hundred stories before it is done.

21.7 WHAT MAKES A GOOD STORY?

In a good story results do not meet expectations. So, “What makes a good story?”, one might reasonably ask. A display of the struggle between expectation and reality, in all its nastiness, is a good place to begin (Fryer 2003). Monarth (2014) reports that stories that use Freytag’s pyramid (Figure 21.1) are the most popular. The exposition introduces important background information. A series of events build toward the point of greatest interest in the rising action. These events are often the

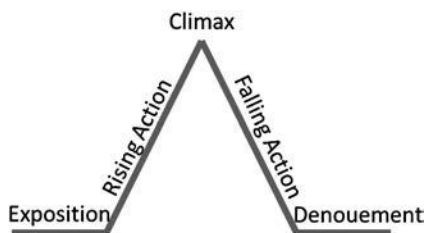


FIGURE 21.1 Freytag’s pyramid.

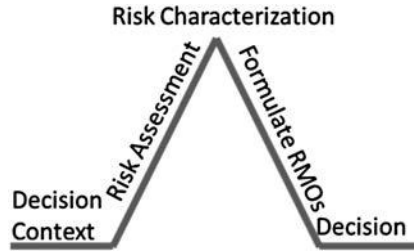


FIGURE 21.2 Adaptation of Freytag's pyramid.

most important part of the story as the climax or turning point depends on them. The falling action sees the conflict between the protagonist and antagonist lessening. The story is resolved in the denouement.

Translating this pyramid to a risk analysis context yields [Figure 21.2](#), which outlines the five-act play for most risk management activities. The action begins when a trigger is “pulled” to begin a risk management activity and it continues through the establishment of the decision context. The risk assessment describes the series of events that leads to the fullest understanding of the risk in risk characterization. The conflict begins to resolve as risk management options are formulated. Resolution of the story comes in the risk management decision.

21.8 HOW TO WRITE AN EFFECTIVE STORY

Maritz et al. (2014) have identified four barriers to storytelling in lieu of report writing. These are skills, client relations, confidence, and time. Storytelling is perceived as a difficult skill to acquire. Gershon and Page (2001) note that effective storytelling requires skills that may be beyond a technical expert's knowledge. Junior-level staff do not often possess these skills. It is difficult to tell effective stories if the risk analysts do not know the client's business or if the client does not trust the analysts. It is hard to deliver the story convincingly without confidence. Risk analysts must be confident in the nature of their story. Finally, storytelling is time intensive. Large amounts of data and information need to be distilled to find the appropriate story that answers the client's business question or that addresses the public's needs.

Peter Guber (2007) identifies four truths of storytelling. First is “truth to the teller.” The storyteller must enter the hearts of his listeners, where their emotions live, while the information he seeks to convey appeals to their brains. Next, there is “truth to the audience.” The best storytellers take the time to understand what the audience knows about, cares about, and wants to hear. Third is “truth to the moment.” An effective story is always tailored to the audience and the immediacy of the situation. Finally, there is “truth to the mission.” A good storyteller is devoted to a cause beyond self and in his story offers a value proposition that is worthy of its audience.

You can always write a riskography, that is, the history of your risk. So that is where we will begin.

21.8.1 WRITE A RISKOGRAPHY

The simplest story to tell is to say what you did and why you did it. There was a risk. Why do we care about this risk? How did we become aware of it? How and why does it arise? Who is affected by it? Why did we get involved with this risk? What did you do to learn more about it? What surprising things did you learn along the way? Why should others care about this risk? How does or will it affect people or things people care about? Are we going to try to do anything about this risk? Why or why not? What are the options we have for managing the risk? What option will we try? Why did we choose that option? Why didn't we choose another one? How will the recommended option affect people or the things people care about? Why should the reader care about the plan for addressing this risk? How is the reader affected by this risk or the RMO used to address it? What aspects of the story are uncertain? What could turn out differently? What would make that happen? How likely is it to happen?

The simplest way to tell a story is to begin at the beginning and go on until you reach the end. Chronology is your friend. It offers clarity, credibility, and causality. A linear timeline presents how events transpired; this adds clarity. Anachrony can raise suspicion, especially among skeptical listeners. Chronology presupposes that earlier events in a story cause what happens next. When story time is reshaped, through anachrony, the narrative often ends up emphasizing the procedures that were followed while downplaying the story itself.

There are a thousand variations on a story like this and you can tell virtually all of them without Greek letters, equations, dose-response curves, lengthy citations of the literature, and other technical details. The science stands behind the story. Chronology can be a friend to your story. First, we did this, then we did that and someone told us something surprising so we went to see for ourselves and we realized we were going about this all wrong. Tell it the way it happened, you know, tell a story!

Contrast that with the table of contents from any traditional risk assessment. Assessments that used a conceptual model to guide the assessment often use the steps of their model as chapter headings. For example, the food safety community of practice frequently uses the four steps: hazard identification, hazard characterization, exposure assessment, and risk characterization as chapter headings. The general practice, then, is to show the data and summarize the science and analysis done in each of these steps. The reader is sometimes left to make the connections among the various pieces. There is little or no explanatory or connecting narrative. Presenting data and information is often the apparent goal. Alternatively, these risk assessments could be constructed as stories like those shown in the box.

EXAMPLES OF FOOD SAFETY RISK STORY LINES

Salmonella e. in shell eggs—how an egg becomes contaminated and can make you or a family member seriously ill and what we can do to prevent that

Vibrio p. in raw oysters—people love their raw oysters despite the number of people they make sick and there is only so much we can do to prevent that

Antibiotic resistance in domestic chickens—the use of antibiotics in food producing animals is creating disease that is resistant to treatment by antibiotics

Every risk management activity has a story. In fact, there are many stories you could tell for any given risk management activity. It is important to think about what the story should be and to make this decision early on in the risk management activity. This is the story the team tells to each other as they figure it out. It is the story that must be addressed in decision meetings. It is the story that stakeholders, including higher authorities, clients, and the people who ultimately own parts of the risk management responsibility must come to know.

A riskography is the biography of a risk. It tells its “life story.” Here are 10 questions to help you write the biography of your risk:

1. When did it begin?
2. What caused it?
3. How was it discovered?
4. What is known about the risk?
5. Are there anecdotes that illustrate the risk?
6. Who or what is or could be affected and in what ways?
7. Does the risk need to be addressed?
8. What are the options for addressing the risk?
9. Which did you choose and why?
10. How did it work or how is it expected to work? (With special attention to uncertainty.)

21.8.2 WRITING NEWS STORIES

You are not likely to write a news story if you are documenting a formal risk assessment that is used for public sector decision making. Bear in mind, however, there is often a wide variety of circumstances where news stories, oral or written, may be ideal. A news story proceeds differently from a riskography or a story that follows the Freytag pyramid previously mentioned. If you want to write a news story, follow the journalists. Journalists’ rule number one for writing a good story might be, “Get out of the building.” Get the facts. The risk equivalent of that is to gather the evidence and identify the uncertainty. You have to get the story elements right to tell an effective story. Journalists frequently use the inverted pyramid to structure their content. The “base” of the pyramid, which includes the most fundamental facts appear at the top of the story. A successful lead paragraph (lede) communicates, on

a basic level, the essential facts of who did what, when, where, and why. If you don't capture the user's attention in the first sentence, you've already lost them. Make sure you quickly answer the questions, "why?" and "so what?"

WHO IS YOUR READER?

The purpose of a story is to communicate ideas to another person. The first and most important question the writer must ask is who is my primary reader? Is it a risk manager, the media, the general public? Once you identify the reader, empathize with them throughout the writing process. Put yourself in the reader's position. Do not write for your professional peers or for personal glory. Write for the person who is going to read your story, then tell it in a way that can be easily understood. A story written for a technical reviewer or an expert with intimate knowledge of the problem is going to be very different from a report written for Jane Q. Public.

The "nut grafs" that follow your lede contain additional details, quotes from sources, statistics, background, or other information. These are added to the story in order of importance, so that the least important items are at the bottom. The paragraphs answer the question, "so what?" They explain the significance of the risk, your process, the viewpoints, the decision, and so on. They also motivate the reader to read on. Risk stories rise or fall on their evidence, so tell the reader how you know what you know and when you obtained the information. Source every piece of critical information.

In a news story, each sentence connects, like links in a chain. A news story does not use data or lists. Move the story along by making a statement and expanding on it in the next paragraph. Illustrate it or provide additional evidence in the paragraphs immediately following. Then move on to the next idea. Use signpost sentences to signal readers you are moving to the next idea or theme. It can be as simple as a short sentence that summarizes what follows. Keep the story moving.

Reuters' (N.D.) offers the following suggestions for expanding the story:

- Expand on the items, events, data, themes in your introduction sequentially.
- Use subheadings to build your story. A subhead about every 300 words helps the reader.
- Each block of text should follow logically and add detail or data.
- Consider the following themes:
 - What is changing and what is not?
 - Who are the parties in conflict and why?
 - What is at risk politically, economically, financially?
- For Reuters, national and international is usually more important than local.
- Forward-looking is more important than backward-looking.
- Be fair to all parties and points of view.

Connect the dots for the reader, do not leave holes in the logic or mention a story element unless you explain it. An effective news story is efficient, intense, and practical. When it comes to content, less is more. The story teller must give readers clear value before they lose interest.

De Jong (N.D.) suggests the following four steps to cut the fat in your story:

1. Write the first draft with no constraints of time or space.
2. Review the first draft, and try to cut the word count in half.
3. Have a critical and honest reader edit the work and make suggested changes in “track changes.”
4. Review the final draft to make sure it retains your voice and main message.

Know your audience and your topic. Keep the story as simple as possible. It is much easier to write a lengthy report than a concise story. Write about interesting ideas and people. Do your homework. Tell the truth. Do not stray far from the five W’s, who, what, where, when, and why, in a news story. Make sure you have good evidence and a clear understanding of the uncertainty and its significance for outcomes and decision making. Be honest and accurate about uncertainty. If you have content about everything you have content about nothing (de Jong, undated).

Here is a quick test before you publish your story. Explain your “in a nutshell” paragraph (nut graf) in 10 words or less. If you cannot do it, you may not understand your story.

Source: De Jong (undated).

Alternatively, make a list of 10 key words without which you simply could not write the story. Use these words or concepts in your story. Focus on the facts or concepts which must be there to guide your story structure.

Source: Reuters.

21.8.3 GENERAL GUIDANCE FOR STORYTELLING

21.8.3.1 Structure Your Story

Feamster (2013) warns against the temptation to just jump in and start writing full paragraphs. This often ends poorly. You would not build a house without a plan; do not write a story without an outline. Feamster suggests you figure out the storyline and how you want the story to read when it is done before you begin writing. Start by identifying sections and writing topic sentences first, build the scaffolding before filling in the details. Budget pages when you figure out how much you plan to write about each topic. Follow convention, find a storytelling style that suits you, then stick to it.

Your reader needs help to understand how your story is constructed, and they will form a quick first impression of your story based on the title and a quick skim through your story. Make a good first impression. Headings and subheadings show readers how your story will proceed. Signposts call the reader's attention to specific points you want to make.

Examples of signposts include:

- First, second, third, ..., finally
- Additionally, in addition, furthermore
- To conclude, to summarize, to review, to repeat
- This means, therefore, consequently

Spend a lot of time on the introduction to your story; it's the most important part. Some people are not going to read past the introduction, no matter how compelling your story is. Start to write it early because you will not get it right on the first try. Give yourself time to rewrite.

Landscape your story; make it look good. It should be pleasing to the eye. Avoid walls of text. They are psychologically tiring. Create white space. Use headings and subheadings to break up large chunks of text. Space figures, tables, and graphs throughout the text so most pages have a mix.

Assume the reader is busy and simply wants to learn what you've done as quickly as possible and then move on. You want a story that efficiently transfers information and motivates the reader to care about your issue. Economize on words. Keep words simple and sentences short. The easier it is to read your story, the more likely a reader will keep reading.

21.8.3.2 The Structure of a Strong Story

The elements of a good story are the same, no matter how that story is being told. Begin with a character with a story to tell. The risk team is always a primary candidate for this role. If a story is to be told in a science-based risk assessment, the risk team is most logically going to tell it. Characters are the lifeblood of the story. They make the audience care. You were asked to do some work; tell your audience why you were asked and who asked you. Then tell them what you did and why you did it, but let the storyline drive the whys rather than the analysis.

There may be occasions when it is effective to tell a story from the perspective of the people, animals, plants, natural systems or assets that are at risk. Your company or a division of it may be the storyteller. It is important that the character ring true for the audience, however, so do not go for cute or quirky. Select a character that is believable and effective.

Second, a problem occurs. This is the story of the risk. It should be based on real-life situations that are at the heart of the issue. Dose-response curves and complex exposure pathways may be essential to the risk assessment; they may also be carefully

documented in excruciating detail in a technical appendix. However, effective stories can be told without mentioning them.

Third, a series of relatable events follows our awareness of the problem. This is where you tell the story of what you did and why you did it. The actions you took had or are expected to have consequences. Do not neglect explaining the consequences, the uncertainty that attends them, and the actions you will take to manage them. There should be a decision at the end of these events. Tell us whether you decided to take an action or not and tell us why you decided as you did.

In good stories, a lesson is learned. The lesson(s) we learn are about what will happen if we fail to take action and what will happen if we do take action.

21.8.4 EIGHT GOOD IDEAS FOR A RISK STORY

Here are eight good ideas for writing a story about risk.

1. Use an engaging beginning, interesting middle, and satisfying ending
2. Give it a narrative quality, that is, no data dump, no default formats, no taking the last report and adding a little to it
3. Chronology is your friend; tell it the way it happened
4. No acronyms or geek speak
5. Cut to the chase; write it the way you'd say it and remember that nouns and verbs beat adjectives and adverbs
6. Include user-friendly and informative figures and features; write on a map or a picture, let people access data and information in the ways they like
7. Tie decisions and judgments to the evidence, that is, say why you did what you did and what you still don't know
8. Tell the truth no matter where it takes you

A beginning requires nothing to precede it, an end requires nothing to follow it, and a middle needs something both before and after it.

21.9 TELLING STORIES WITH DATA

The information stored in the literature, your databases, and gleaned from your models cannot speak for itself. There are important stories to tell in that information and only you can give it a voice. Storytelling requires skills that most of us have never learned. Data storytelling is just a more specialized and slightly more complex form of storytelling. Take a step back from the data and look at the bigger picture. The story is more likely to be in the big picture than in the data; use the data to paint the big picture.

Few (2009) says, a good statistical narrative is simple, sequential, seamless, informative, true, contextual, familiar, concrete, personal, emotional, and actionable. Find the core of the message and then present it as simply as possible, without distractions. Tell the audience all they must know to get the message, but no more than that. Simplification involves stripping away everything that is nonessential to the story you are trying to tell. This allows the audience to easily focus on the

key information. Simplicity is not easy. Leonardo da Vinci said, “Simplicity is the ultimate sophistication.”

A sequential story has a beginning, middle, and end. It is told by revealing facts only in their proper time. Thus, visuals are only revealed when their content has been revealed in the story. If you are explaining complex concepts, build them piece by piece. Add complexity in stages once each previous stage has been absorbed by the audience.

Good statistical narratives seamlessly interweave figures with the text that describes them. These stories always require words and images, and these are just different ways of presenting information. When you speak to a live audience you can speak the words and show the pictures simultaneously. Statistical narratives should strive for that simultaneity in all story forms. Do not separate the graphics from the text. Let a graphic function as a paragraph about data. Use words to carefully unpack what the graphic contributes to the story. Avoid the figure numbering style employed in this text, make all images an organic part of your story.

Stories must be informative. They should reveal facts or interpretations of facts your audience does not already know. To arouse your audience’s curiosity and interest, give them something new to chew on. Surprise the audience in some way by revealing things they did not expect.

If risk management is going to improve conditions, the stories must be true. To help assure your story is perceived as true, back it up with relevant evidence. If your audience perceives the story as true, they will care about it more and are more likely to respond in a positive way.

Quantitative stories require context, and good comparisons provide context. A good story tells us where the numbers came from and how they are used. The meanings in numbers are revealed primarily by comparing them to other numbers and by comparing the patterns, trends, and exceptions that live within them. Appropriate comparisons provide the context that makes numbers meaningful in a way that enables people to form judgments, make decisions, and take action. Good stories compare what is going on today to what has happened in the past, or to target values, forecasts, other things in the same category (e.g., comparing products or hazards), and norms or standards.

Good data stories are both familiar and concrete. There is an art to using simple words and images that can be understood by everyone. When a story is told to a different audience it may help to tell it with different words and images, so it can be expressed in terms familiar to that audience. Quantitative risk stories are often complex and the people who assess these risks are able to think in abstract ways, but we do not live in an abstract world. The world we experience is concrete. The delicate balance you seek in presenting data is to boil your stories down to simple terms without watering them down.

Stories rarely work unless people can connect with them in personal ways. Few of us care passionately about people we do not know or issues that do not affect us. It is best to make data stories personal when they affect your audience directly. Other times you will have to work a little harder to make the data story personal for your audience.

People will only respond to a story if they care about the message. They have to feel something. A good storyteller will use the information in the data to engage emotions and give people a reason to care. If you care about your story, there is a

better chance your reader will too. The most effective stories use data in ways that make it easy for people to respond and take action. The data can be used to suggest ways to respond.

Discuss your story with other people, both inside and outside of your organization. If you do that throughout your process, you might be surprised by what you learn about the story. Put yourself in the audience's shoes. What will they be more receptive to, the data presented as a story or the data presented as a standard report? There are times when your audience expects and wants a standard report. When they do, give it to them. However, there will be many times when the data will be more compelling if presented as a story, not just as numbers and charts.

Risk assessment is generally going to be heavy on the science and evidence and there is a devil's compromise between telling a story and showing the data. One easy solution is to include the science in technical appendices that can be accessed by anyone with an interest in the evidence used to support the story that is told about the risk work you have done.

How does one "tell a story with data?" Davenport (2014) says narrative stories, along with visual analytics, are an important way to communicate analytical results to nonanalytical people. Just knowing these stories work, however, is not much help to anyone trying to master the art of analytical storytelling. Davenport argues that we need a framework for understanding the different kinds of stories that data and analytics can tell. One thing seems eminently clear, if you don't know what kind of story you want to tell, you probably won't tell a good one. Davenport offers four key dimensions to help you understand your story.

First, there is the time frame. Analytical stories can be about the past, present, or future. Data vary by time frame. Descriptive analytics are not going to be used to describe the future. Surveys may describe the present. Simulations may be done and predictions used to describe alternative futures. Second, there is the focus of your story. Are you telling a what story, a why story, or a how story to address the risk? A third consideration is the depth dimension of your analytical story. Stories can range in depth from little "what is going wrong here" investigations to long, analytically-driven searches for a solution to a complex problem. Fourth, consider the analytical methods used. What you know and how you know it can influence a story.

1. *What's the point of your story?* Figure this out first. Build your story around your main point.
2. *How does the data help tell the story?* The story isn't about data. Use data to help tell the story.
3. *Why should those listening care?* What is really important about the story? What does it mean to people?
4. *What's the magic in the data?* What things does the story actually talk about that are of interest to humans?
5. *How does it affect humans?* Do you want your story to elicit emotion, action, or interest?

6. *How will they remember the data?* What useful or interesting information can you include in your story to make it memorable?

Source: Molly Soat, <https://www.ama.org/publications/MarketingNews/Pages/3-ways-to-tell-story-with-your-data.aspx> (accessed June 28, 2018).

Quantitative information is uniquely able to capture attention, convey a story visually, and bolster your credibility. Samuel (2015b) has argued that the best data storytellers are not always the numbers people. She says to reach audiences with data-driven content, what really matters is your ability to craft a good story, and there's very little math required in a good story. The ability to recognize an engaging and actionable insight or finding is far more important than the method of moments or the statistical significance of a boring or irrelevant test, when telling a story with data. We are not talking about abandoning statistical rigor, we are, however, talking about its place in a good story. That place may be in a technical appendix.

Know your audience. Did math class make you or some of your friends break out in a cold sweat in high school? Chances are when you tell a story with data, you are telling it to an audience that includes many of those people. So, tell your story with more words than numbers. Make your key points in text. Use data to support or reinforce your point. The data parts of a story probably should not be provided by an analyst. Samuel suggests it is generally better for the story author to dig into the data of a story, and then to use their knowledge of the audience, messaging, and story to identify the interesting findings.

When you use a chart, make it as reader friendly as possible. Include plenty of clues about how to read the chart. Offer a descriptive title, axis labels, and identify highlights that point out the significance of one or two key data points. Vet your charts through someone unfamiliar with your subject. If they are confused, you know you have more work to do in crafting your story. Please note, storytelling with data is different from decision making with data. Showing the data, multivariate figures, doing the things described in [Chapter 18](#) are not going to be as useful for storytelling as they are for decision making.

Residual risks should be part of any story. How much risk we are left with can reach many emotional touchpoints.

Food safety—if we do all these wonderful things will people still get sick?
How many?

Flooding—if we build this levee will we be forever dry?

Finance—if we do not invest in that sector will we be a viable business in five years?

Many interesting stories can be found among residual risks.

Some of your audience will be very good with numbers, perhaps better than you. They may be very interested in details like sample size or data analysis methods. If it is reasonable to expect such interest, provide those details in a technical appendix that does not detract from the flow of your story.

Samuel (2015a) says data storytelling has become a powerful part of writers' communications toolkits, and it is a crucial skill for many professionals. One of the greatest challenges is to prevent your data from overtaking your story, so make sure you know the story you are trying to tell. Then use data and charts sparingly to support your story. Use data strategically, when it provides clear and concrete evidence for the story you are telling. No one is going to remember all the numbers you use, so focus on the words that capture the idea, insight, or conclusion you want people to remember. Tell the truth about uncertainty.

If you tell your story orally, remember that it takes people time to understand a chart or data table. Take time to unpack the story you see in the data for others. You have likely been pouring over it for weeks, your audience comes to it fresh. Don't rely entirely on words; visuals can provide vital support.

Uncertainty information that is instrumental should be prominently placed in the summary and conclusions. Other significant uncertainties can be added to the main text and appendices according to its relevance. In fact, background material that is available in appendices and from other sources should be clearly referred to with careful descriptions of its existence and location. Wardekker et al. (2008) have provided suggested guidelines for what kind of uncertainty information to include in the outer layers of communication in meetings, briefings, summaries, conclusions, and such and what to include in the inner layers of detailed reports, appendices, background materials, and the like.

Wardekker et al.'s guidance for outer layers follows:

- Integrate uncertainties in the message, using words such as “may” or “might.”
- Uncertainties are essential contextual information for the assessment results.
- The political and societal context of the uncertainties should be communicated.
- Emphasize the policy relevance of uncertainties.
- Emphasize the decision and outcome implications of uncertainties.
- Stress the implications of uncertainties for the assessment results and the policy advice based upon them.
- Translate scientific information into “common language.”
- Avoid the use of jargon.
- Include only policy relevant details.

Wardekker et al.'s guidance for inner layers follows:

- Mention uncertainties separately and explicitly.
- Identify uncertainties as part of the scientific accounting on the approach used in the study and the assessment results.
- Provide an account of the “untranslated” uncertainties from a scientific point of view.

- Provide a balanced account of uncertainties in all parts of the assessment.
- Emphasize the nature, extent, and sources of uncertainties.
- Discuss the implications of uncertainties for the value of the results, the representativeness of the study, and further research.
- Provide scientific information with a high technical sophistication.
- Use jargon as warranted by the technical audience.
- Provide a high level of detail.

Stikeleather (2013) says, don't be boring, find your story, make sure it has a hook, momentum, or a compelling purpose. Even a story that is trying to influence people should be based upon what the data says, not what you want it to say. He cautions that visualizations should not be selective about the data you include or exclude, unless you are confident you are giving your audience the best representation of what the data "says." He also encourages authors to really try to explain the data. Frick (2014) adds that data and narrative go best together, and visualizations are to be used to do a better job of telling stories. Data plots that help readers understand change over time are especially useful for representing a common narrative thread visually. He argues that visualizations should be well adapted to give readers themes, narratives, and plot, that help them understand really complicated concepts. In fact, some (Berinato 2016) have argued that a well-chosen visualization and a couple of paragraphs that lay out the conclusions from the data are often sufficient for decision making, but decision making is different from story telling.

21.9.1 USE GRAPHICS

Use graphics to help tell your story. Graphics include pictures, maps, charts, tables, drawings, numbers, illustrations, graphs, diagrams, blueprints, artist's conceptions, and virtually any kind of image you can imagine. You should expect to use very different graphics to support decision making than you would use to tell your story to the public. What kinds of things might you do to illustrate your story?

Photos of the team collecting data will be more interesting to people than the data. Is Asian longhorn beetle habitat important to your study? Show people what the bug and what its habitat look like. Tell them why people care about this insect. Tell a story, do not just dump facts.

- Show a map—this is where your story takes place.
- Show important places on a map and include ground level photographs as map inserts.
- Use pictures to illustrate problem conditions.
- Photoshop photographs to show improved conditions.
- Draw on a map—go easy on the blueprints; the public does not understand them.
- Show your team at work—let people see the fieldwork and the equipment you used.

21.10 PROBABILITY WORDS

Here is a topic that could fit in a discussion of qualitative risk assessment, decision making under uncertainty, expert elicitation, and perhaps a few other places in this book. It landed here because we use language to tell stories and risk stories will require probability language. There is an important story to know about probability language. It does not work well.

In our normal lives away from risk analysis, it is common practice for most of us to address uncertainty in our natural language. Things are “probable” or “unlikely,” and within the family circle these words function adequately. It makes sense, then, that so many people would approach probability using the qualitative judgments of our natural language. These words play an important role in several of the qualitative risk assessment techniques of [Chapter 10](#) where risk assessors try using natural language terms rather than the more precise statistical notions of probability that so many people find counterintuitive at best and inaccessible at worst.

Without some quantification, the use of qualitative words such as “likely” and “unlikely” to describe uncertainty can mask important, often critical, differences among the views of different experts, not to mention lay people. The same words can mean very different things to different people and they can mean different things to the same person in different contexts.

Sherman Kent’s classic paper on the need for precision in intelligence judgments, published in 1964, was one of the first that sought to standardize the language of “estimate probability” so that a chosen word or phrase would accurately describe the degree of certainty that would be understood similarly by writer and reader. [Table 21.1](#) presents the intelligence community’s first attempt at mapping words to numbers. In what Kent colorfully described as a debate between the poets of risk and the mathematicians of risk, variants for the chosen words grew. “Possible” was also called “conceivable,” “could,” “may,” “might,” and “perhaps.” “Almost certain” became “virtually certain,” “all but certain,” “highly probable,” “highly likely,” and “odds overwhelming.” “Probable” was “likely,” “we believe,” and “we estimate.” A 50–50 chance was “chances about even,” “chances a little better

TABLE 21.1
Five Gradations of Uncertainty Proposed
by the Intelligence Community

100% Certainty		
The general area of possibility		
93%	Give or take about 6%	Almost certain
75%	Give or take about 12%	Probable
50%	Give or take about 10%	Chances about even
30%	Give or take about 10%	Probably not
7%	Give or take about 5%	Almost certainly not
0% Impossibility		

than even,” “improbable,” and “unlikely.” “Probably not” was “we believe that... not,” “we estimate that...not,” “we doubt,” and “doubtful.” “Almost certainly not” was also “virtually impossible,” “almost impossible,” “some slight chance,” and “highly doubtful.”

Expanding the formalized language to include all these and other variants was impossible. Many of these phrases represented heresies to the mathematicians of risk. In essence, banning the use of some phrases and enforcing the common understanding of words that belong to the natural language proved impractical. A half century of continued effort has made little progress.

Many have tried to develop empirical mappings between numbers and natural language probability phrases (e.g., Lichtenstein and Newman 1967; Moore 1983; Boehm 1989; Hamm 1991; British Standards Institute 2000; Conrow 2003). Their work has found considerable consistency in the ordinal ranking of phrases among people, but considerable variability in the numbers assigned to those phrases by different people. It has also found that the context in which the words are used has a strong influence on the numerical meaning assigned.

Finding a lack of coherence among these studies that made comparison somewhat problematic, Hillson (2005) e-mailed a survey to members of the Risk Doctor network that asked them to quantify 15 terms, which were presented in alphabetical order. [Table 21.2](#) shows the average of all minimum and maximum scores for each phrase. There was good agreement for low-probability terms and less consistent agreement for large-probability terms. Interestingly, “definite,” which usually means 100%, and “impossible,” which means 0%, were interpreted differently by the respondents.

TABLE 21.2
Hillson’s Results for Values of Probability Phrases

Descriptive Phrase	Range
Definite	76.6%–83.5%
Almost certain	73.6%–84.1%
Highly probable	64.2%–78.3%
A good chance	54.3%–74.3%
Likely	49.9%–68.4%
Quite likely	51.8%–66.4%
Probable	47.5%–66.7%
Better than even	47.1%–65.6%
Possible	28.8%–57.5%
Improbable	10.6%–25.3%
Highly unlikely	9.8%–23.3%
Unlikely	6.6%–20.4%
Seldom	6.2%–17.1%
Impossible	5.5%–11.4%
Rare	3.9%–12.2%

Having worked in areas where probabilities of 1% or less are common, I am struck by how contextual a continuum of phrases must of necessity be. Most natural language mappings provide probabilities far too large to accommodate a 10^{-6} increase in lifetime cancer risk threshold or to address the risk of floods with an annual recurrence interval of 0.002. Natural language often fails these situations, and it would seem that new vocabulary is needed to meet the needs of those who work with risks in these magnitudes.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (2007) offered the following definitions to assist the communication of uncertainty when authors evaluated the likelihood of outcomes:

- Virtually certain—>99% probability of occurrence
- Very likely—90 to 99% probability
- Likely—66 to 90% probability
- About as likely as not—33 to 66% probability
- Unlikely—10 to 33% probability
- Very unlikely—1 to 10% probability
- Exceptionally unlikely—<1% probability

Many alternatives to these scales exist.

Over half a century of effort seems to have only succeeded in establishing that even well-defined, commonly used words are interpreted by individuals in unreliable and unpredictable ways. This clearly suggests that there is no consensus about the quantitative and true meaning of these words. Consequently, using natural language words to identify probabilities is not feasible unless they are carefully and precisely defined for a specific usage. Such categories of probabilities are of dubious value unless they are defined quantitatively. This begs the question, “If numerical definitions are required to define these categories, why give them names?”

This presents a conundrum for storytellers who must address probabilities of risks and such. If words are used and if it is important that the words be precisely understood, storytellers are going to have to remember or define and use their probability words in ways that will be clear to the reader.

21.11 ALTERNATIVE STORY MEDIA

Most risk assessments are documented in writing, but if you really want to tell a story it need not be. Consider the storytelling potential of alternative media if you have the freedom to deviate from the standard report format.

21.11.1 PERSONAL COMMUNICATION AS DOCUMENTATION

Here is a radical idea for the technology age: put the technology down and go talk to people. Tell them your story. Make it personal. Just think: face-to-face communication as documentation! There are lots of ways to do that.

Briefings, large and small group meetings, guest speaker engagements, news conferences, making presentations, manning exhibits and displays at fairs and such, participating in panel discussions, sponsoring field trips, relevant training sessions, brown bag lunch sessions, walking tours, classes, sponsoring symposia, and holding focus groups are a few ways to get a story out to interested people. Media interviews, hotlines, and talk shows are one step removed from face-to-face encounters.

21.11.2 DIGITAL STORIES

Digital technology has radically changed the way you can tell your story. Make a video and upload it to YouTube. Virtual tours enable people to visit interesting and hard to reach places. Digital stories can be an effective teaching aid for unfamiliar concepts. The USACE provides an interactive virtual tour of the Kissimmee River aquifer storage and recovery pilot facility at http://141.232.10.32/pm/projects/asr_tour/asr_interactive.aspx (accessed November 2, 2018). Virtual tours are an excellent tool for documenting conditions, solutions, and many other aspects of a risk management activity.

Interactive maps are a great way to present facts to people. They enable interested individuals to explore the data of interest to them. Charlotte-Mecklenburg presents a three-dimensional Interactive Floodzone Map <http://meckmap.mecklenburgcountync.gov/3dfz/> (accessed November 2, 2018) that offers the ability to explore the risk of individual floodplain structures. The point-and-click technology enables interested parties to discover and explore a wealth of data, to find the information that is most interesting and useful to them. That can be an important part of any story.

A scan of the Internet revealed the following kinds of videos you might consider for storytelling: brand films, animation videos, educational videos, demonstration videos, tutorials, documentaries, 360° experience, video e-mails, product videos, company culture videos, testimonials, PSAs, vlog, interviews, webinars, events, presentations, interviews, music videos.

Photo galleries enable people to see realistic images of conditions at a planning site. Animations have become comparatively easy to prepare with the advent of software like Macromedia Flash. Photography in the round, 360-degree photography, is a great way to take people to places that are an important part of your story. An outstanding example of the promise of this technology in storytelling is found at <http://www.360cities.net/> (accessed November 2, 2018). Just grab your cursor and start rotating the image. Search for the Strahov Library indoor tour. Use the zoom feature and notice how the details of an individual book can be displayed. Now think about how to use this technology to tell your story.

Interactive databases are another promising technology. They enable analysts to think less about what table to present and more about how to make the data available so users can access it in ways that are meaningful to them. One of the very best examples of an interactive database is provided by Gapminder (https://www.gapminder.org/tools/#_chart-type=bubbles [accessed November 2, 2018]). This

compelling site enables the user to explore the world over time from a desktop. Have a look and imagine how to adapt these technologies to your risk studies.

Many of the other tools are not nearly as dramatic by comparison, but do not overlook the obvious. Enabling people to download reports, documents, databases, maps, audio files, video files, photographs, and other forms of digital information from a web site can empower your most interested publics to get involved and informed.

Combine digital stories and personal communication. Use web conferencing to hold a virtual meeting or a question and answer (Q&A) session with the risk team. Bringing in an expert to answer the public's questions about an especially lively issue is a great use of the technology. Host a panel of experts with varying perspectives on an aspect of your risk work to help people understand the uncertainty that remains in your story. This leads naturally into the use of podcasts as a means of telling your story. A permanent and growing library of strategically created podcasts could be valuable storytelling resources.

THE SEVEN ELEMENTS OF DIGITAL STORYTELLING

The Center for Digital Storytelling in Berkeley, California is known for developing and disseminating the Seven Elements of Digital Storytelling, which are often cited as a useful starting point as you begin working with digital stories:

1. *Point of View*: What is the main point of the story and what is the perspective of the author?
2. *A Dramatic Question*: A key question that keeps the viewer's attention that will be answered by the end of the story.
3. *Emotional Content*: Serious issues that come alive in a personal and powerful way and connect the audience to the story.
4. *The Gift of Your Voice*: A way to personalize the story to help the audience understand the context.
5. *The Power of the Soundtrack*: Music or other sounds that support and embellish the story.
6. *Economy*: Using just enough content to tell the story without overloading the viewer.
7. *Pacing*: The rhythm of the story and how slowly or quickly it progresses.

Source: <http://digitalstorytelling.coe.uh.edu/page.cfm?id=27&cid=27&sublinkid=31> (accessed June 28, 2018).

An electronic mailing list or listserv can be created, managed, and used to communicate in an ongoing way about aspects of your story that prove to be of particular interest to people. Consider creating a listserv for your risk work early

enough in the process to enable you to tell your story in real time. Discussion boards and chat rooms can also be used to enhance communication.

Collaborative work spaces may be worth exploring. Wiki spaces enable interested parties to work collaboratively on problem solving and other creative efforts throughout a risk process. This enables stakeholders and the public to help write the story. A wiki space would be a great place to ask the public to share their ideas on how to solve the problems you face and to become part of the story.

Puzzles and games provide a great way to document a story for young people. World of Warcraft (https://us.battle.net/account/creation/wow/signup/?jsessionid=342BCB32C1C893C5874566EC79D14C7E.blade34_01_bnet-mgmt [accessed October 30, 2018]) provides a great example of how games can be used to engage many people in virtual exploring, problem solving, and other strategic activities. How long before some daring pioneer creates a game designed to help solve a wicked risk problem?

Pokémon Go offers a fascinating mix of technology and reality that opens doors for exciting adaptations of this new technology. Imagine the ability to walk an area's footprint with this new technology and see features of the problem or risk management option as they might look. It is all fantasy at this point, but all it will take is a courageous team to change the way risk stories are told.

As promising as these digital media are, do not overlook the digital divide. The digital divide refers to the inequalities among groups in terms of their access to, use of, or knowledge of information and communication technologies. Make an effort to become aware of the digital divide among your study's many publics when you consider using this technology.

21.11.3 SOCIAL MEDIA

Having a web presence for your risk work may be more important to stakeholder and public involvement than to storytelling, but it can be an effective tool for storytelling. How important is a web presence to your risk management activity?

Social media are often defined as a group of Internet-based applications that allow the creation and exchange of user-generated content. Social media are used for social interaction. This is considered to include but also go beyond social communication. Important features of these media are their ready accessibility and scalability. They may be important to interactive storytelling especially when reaction is an essential part of the story. Both individuals and organizations can make use of these media.

Wikipedia, one of the world's foremost examples of what collaborative people with access to technology can do, once broke social media into communication, collaborative, multimedia, reviews and opinions, and entertainment categories. Examples of each follow. Think about which forms may help you to tell your story.

Communication includes blogs, microblogging, Twitter, social networking (e.g., Facebook), events, information aggregators, online advocacy and fundraising, engagement advertising and monetization. Many public agencies and private companies can already be found on Facebook. Creating new accounts for specific risk work is the next logical step for all who want to friend or follow an issue. As the work unfolds, its story can be told in real time with these kinds of media. A couple of updates every week or two keeps interest alive. Stakeholders can and also do make

use of these media to present their own views on issues. A Twitter account for the risk team's use adds opportunities for immediacy and intimacy heretofore impossible to imagine.

The collaboration and authority building media include things like wikis, social bookmarking, social media gaming, social news, social navigation, and content management systems. Wikis may be one of the more popular and promising collaborative environments for risk analysts to exploit. Wikis can be used throughout the process. Publish the team's problems and opportunities statement and ask, "Did we get it right? What's missing that ought to be here? What's here that ought to be missing?" Let people wordsmith. Do the same with objectives, and then use wikis to ask for help with identifying solutions. A wiki space that includes that kind of collaboration with the public provides a powerful piece of the story itself.

Multimedia opportunities are exciting. They include photography and art sharing, video sharing, live casting, music and audio sharing, and presentation sharing. Three existing examples are especially exciting. Flickr is a service that enables people to upload and share their photographs. Sharing photographs of risk-related areas and events has promise. Asking people to share historical photos from an affected area could be a good source of information and data. Sharing those communal visions of the past, or of existing conditions, is a great way to tell a story. Instagram provides opportunities for video sharing. Affected area videos are no further away than your cellphone. Let people see the risk team when they are doing field work. Tumblr supports multimedia blogging in a convenient way. Photo sharing capability can be built into a web site, or media on the Internet can be used directly.

YouTube and Vimeo are two sites that are especially promising for gathering information. You could ask citizens to make their own videos showing problems or opportunities or explaining the history or importance of the area/issue. You could sponsor a contest for the best historical video or the best video depicting a problem. Make these videos part of the risk management activity's web site. The possibilities are unlimited.

Reviews and opinions frequently are used to review products or businesses. They have also been used as a sort of community Q&A at sites like Wikihow, Ehow, and the like. This is an idea readily adapted to a risk assessment. Ask people to review your product as you go. Have them review your evidence if you like. The dialogue becomes an important part of your work's ethnography.

The final major category of social media is entertainment. It includes things like media and entertainment platforms, movie reviews, virtual worlds, and game sharing. Some of these have already been touched on. Meanwhile, the world waits for a creative analyst to show us all how to use these tools to enhance the risk story.

21.12 SUMMARY AND LOOK FORWARD

When the time comes for you to document your risk assessment, your risk management decision, your risk appetite, and so on, consider doing that by telling a story instead of dumping your data into a report. All the scientific evidence and uncertainty analysis can be preserved and presented in technical appendices intended for technical audiences. Sometimes reality is too complex, stories can be used to reach, inform,

and motivate audiences in appropriate ways. Storytelling is a powerful way of putting ideas into the world.

The final chapter of this text presents eight risk assessment examples drawn from a variety of fields to illustrate the usage of some of the principles and methods introduced in this book. The variation in the examples demonstrates the robustness of the risk analysis paradigm.

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22 Example Applications

22.1 INTRODUCTION

This chapter offers summary descriptions of eight risk assessments to illustrate the general applicability of the risk analysis principles. The examples are:

- Nematodes from Mexico—qualitative assessment using enhanced criteria-based ranking
- Choosing a supply source—qualitative example using paired ranking
- Phytosanitary risk assessment—qualitative example using a generic process
- Asian carp—qualitative and quantitative examples using a generic process
- Cost risk—quantitative example using probabilistic scenario analysis
- Food safety risk assessment—quantitative example using probabilistic risk assessment
- Levee safety—semiquantitative example using a generic process
- Rainbow trout—quantitative risk assessment using ecological risk assessment

The variation in the examples demonstrates the robustness of the risk analysis paradigm. The examples have been simplified and stripped of unnecessary detail to focus on the question to be answered and the tools used to answer it.

22.2 QUALITATIVE RANKING ASSESSMENTS

22.2.1 ENHANCED CRITERIA-BASED RANKING

There are countless ordering techniques in use. You should feel free to invent your own techniques as long as they legitimately meet the science-based standards of risk assessment and the decision needs of risk managers. The example offered here uses a technique informally called enhanced criteria-based ranking. The ranking is based on criteria grounded in evidence. The technique is enhanced by its structure and by inclusion of a built-in “does it pass the red face (embarrassment) test” step.

This technique follows eight systematic steps:

1. Criteria
2. Evidence-based ratings
3. All possible combinations of ratings
4. Ranking
5. Evaluate reasonableness of ranking
6. Add criteria
7. New combined rating
8. New ranking

Like all good risk assessments, it begins with a clearly focused question. Like all good ordering techniques it requires a list of hazards, pathways, mitigation measures, or other items to be ranked.

In this example the question to be answered is which nematodes from Mexico are of quarantine risk concern to the United States? This example is based on an actual ranking done by PEARL (n.d).^{*} The nematodes of potential concern were:

- *Globodera rostochiensis*
- *Meloidogyne chitwoodi*
- *Punctodera chalcoensis*
- *Cactodera/Heterodera spp.*
- *Ditylenchus destructor*
- *Bursaphelenchus cocophilus*
- *Ditylenchus dipsaci*
- *Radopholus similis* and *R. citrophilus*

Step 1: Criteria. The first step is to identify a few science-based criteria that will enable you to answer the question. Design your criteria to reflect the most important aspects of the risk you are evaluating. Bearing in mind the “consequence x probability” definition of risk, it is often useful to develop a criterion or two for each of these risk factors.

In general, the number of criteria is limited. Five or less is a good rule of thumb for this methodology. If you really need more criteria, you may also need a more sophisticated tool. Once the criteria are identified, you must decide whether the criteria will receive different weights or not. PEARL used equally weighted criteria for this example.

The next task is to define mutually exclusive and collectively exhaustive scenarios for each criterion. The general practice for this particular technique is to carefully define what constitutes a high, medium, or low risk potential in such a way that the ranking can be based on evidence. Carefully documented criteria and their high, medium, and low scenarios provide a substantial and transparent science-based core for documenting the process and its resulting judgments. The criteria and scenarios for this example follow.

Criterion 1: Survival potential

- H = High cyst former, survives with or without host
- M = Medium, survives in soil without host
- L = Low, survives only with host

Criterion 2: Host range

- H = High, many commercial hosts
- M = Medium, 2–4 commercial hosts
- L = Low, 0–1 commercial host

^{*} Plant Epidemiology and Risk Analysis Laboratory. Undated. “A Demonstration Exercise Using Enhanced Hazard Identification for Criteria-Based Ranking of Pest Risk.” Prepared for Risk Analysis 101, Raleigh, USDA APHIS PPQ.

Criterion 3: Distribution

- H = High, wide distribution in Mexico
- M = Medium, limited distribution in Mexico
- L = Low, found in United States

Numerical values are avoided in the ratings, that is, H, M, and L are used rather than 1, 2, and 3, because numbers suggest scalar content to most people. Letters are preferred because they avoid that potential temptation and they better serve the relative comparisons being made. We have been trained to do arithmetic with numbers and tend to do so naturally. That is not appropriate with a qualitative approach like this, so letters are preferred when possible.

The criteria chosen must enable the assessor to discriminate among the hazards or items to be ranked. If there is an important criterion for which all items receive the same rating, then it is not a useful criterion and can be dropped. It will be sufficient to note that it was considered but was not used in the assessment because it did not help to separate or rank the items.

Step 2: Evidence-based ratings. With a list of hazards and the criteria for ranking them identified, it is time to gather the evidence needed to rate each hazard for each criterion. This is the most critical step in establishing the value and credibility of any qualitative assessment: gathering science-based evidence to support the qualitative judgments. Expert judgment may be used to critically evaluate the available information and develop estimates for each of the nematodes against the three criteria defined previously. However, that judgment must be documented as carefully as any other evidence.

Ratings for this example, based on the life history and experiential knowledge about the nematodes, are shown in [Table 22.1](#). The facts and evidence used to make these ratings would be referenced and included in the documentation of the process.

Step 3: All possible combinations of ratings. This step determines how the various ratings are combined and weighted to produce rankings. Prior to ranking the hazards, you must determine the hierarchy of risk potential. When different weights are used for the criteria, the importance of this step becomes more evident. For the equal weights assumed in this example, it is a straightforward process. All the possible combinations of ratings are shown in groups of similar risk potential as follows:

Greatest risk	HHH	
	HHM, HMH, MHH	
	HHL, HLH, LHH, HMM, MMH, MHM	
	HLM, MHL, HML, LMH, MLH, MMM, LHM	
	HLL, LHL, LLH, MML, LMM, MLM	
	MLL, LML, LLM	
	Least risk	LLL

Note that if, for the moment, we let H = 3, M = 2, and L = 1, the first row sums to nine, the second to eight, etc. If, in the first step, we had decided that criterion 1 was twice as important as criteria 2 and 3, an HMM would be a higher risk than MHM

TABLE 22.1
Nematode Ratings for Each Criterion

Nematode	Criteria 1	Criteria 2	Criteria 3
<i>P. chalconensis</i>	H	L	M
<i>G. rostochiensis</i>	H	M	M
<i>M. chitwoodi</i>	M	H	L
<i>D. destructor</i>	M	H	L
<i>R. similis</i>	L	L	L
<i>Heterodera & Cactodera</i>	H	M	L
<i>B. cocophilus</i>	L	M	H
<i>D. dipsaci</i>	L	H	L

or MMH, and the remaining groupings would look different. Finer distinctions can be obtained, if desired, by using weights or more criteria.

Step 4: Ranking. Using the results of steps 2 and 3, rank the nematodes according to descending relative risk. At this point it may help to group them into subjective clusters of relative risk or concern. The nematode rankings are shown in [Table 22.2](#). Note that the order of similarly rated items is arbitrary.

At this point in the process the greatest and least risk among the candidate hazards are objectively trivial to identify. The distinctions among the six nematodes ranked as risks of moderate potential were not sufficient to separate them further in the judgment of the analysts.

Step 5: Evaluate reasonableness of ranking. Take a look at the rankings. Do they make sense? If not, why not? What is missing? This step was intentionally inserted into the process to minimize the likelihood of an error based on overlooking some important criterion. Step 5 asks analysts to evaluate the thought process to this point in time before finalizing the rankings.

In this example, the team thought *P. chalconensis* would be ranked highest. This was the nematode that stakeholders and scientists were initially concerned about. Why did it show up as a moderate risk? The answer lies in the nature of the criteria.

TABLE 22.2
Subject Ranking Clusters of Nematodes

Nematode	Rating	Ranking
<i>G. rostochiensis</i>	HMM	Greatest risk
<i>Heterodera & Cactodera</i>	HML	Moderate risk
<i>M. chitwoodi</i>	MHL	
<i>P. chalconensis</i>	HLM	
<i>D. destructor</i>	MHL	
<i>B. cocophilus</i>	LMH	
<i>D. dipsaci</i>	LHL	
<i>R. similis</i>	LLL	Least risk

In other instances, an additional criterion may help to produce a finer distinction in the risk potentials.

Step 6: Add criteria. The initial criteria did a good job of presenting evidence in support of the probability of a nematode being introduced into the United States. They did not do as well addressing the consequences of that introduction. The original criteria overlooked the economic consequences of the risk of introduction. Although the number of hosts potentially affected does capture some aspect of consequence (as well as probability), the economic importance of the host is not addressed in the original criteria. A fourth criterion addressing the economic importance of the hosts was added to more accurately reflect the risk.

Criterion 4: Economic value of the hosts

- H = High, affecting major U.S. crop(s)
- M = Medium, affecting U.S. crop(s), but not major U.S. crop(s)
- L = Low, not affecting crops of strong economic significance

With this criterion, the process will better reflect the potential risk posed by the nematodes.

This step is sometimes misunderstood. Its purpose is not to manipulate the analysis to get the answer you want. That sort of manipulation could be easily hidden from the outset if that was the assessor's intent. This enhancement step is intended to reveal and document the evolutionary thinking about the question at hand for the sake of transparency.

A new criterion will not always be added. Sometimes criteria will be dropped as redundant or they will be replaced by better criteria. If the criteria change in any way, steps 2 and 3 are repeated. If no new criteria are added, the process is complete at this point.

Step 7: New combined rating. Each nematode is rated against the evidence for the new criterion to obtain a new combined rating for each nematode as shown in [Table 22.3](#). It will also be necessary to prepare a new set of all possible combinations

TABLE 22.3
Nematode Ratings with Four Criteria

Nematode	Criteria #4 Rating	New Combined Rating
<i>G. rostochiensis</i>	H	HMMH
<i>Heterodera & Cactodera</i>	L	HMLL
<i>M. chitwoodi</i>	H	MHLH
<i>P. chalcoensis</i>	H	HLMH
<i>D. destructor</i>	M	MHLM
<i>B. cocophilus</i>	M	LMHM
<i>D. dipsaci</i>	H	LHLH
<i>R. similis</i>	H	LLLH

TABLE 22.4
Final Ranking of Nematodes

Nematode	Rating	Ranking
<i>G. rostochiensis</i>	HMMH	Greatest risk
<i>M. chitwoodia</i>	MHLH	
<i>P. chalcoensis</i>	HLMH	
<i>Heterodera & Cactodera</i>	HMLL	Moderate risk
<i>D. destructor</i>	MHLM	
<i>B. cocophilus</i>	LMHM	Least risk
<i>D. dipsaci</i>	LHLH	
<i>R. similis</i>	LLLH	

that reflect the equal weights of the new and old criteria. That task is left to the reader. All that remains after that is to establish a new ranking.

Step 8: New ranking. Using the order established in the revised list of all possible combinations, a new ranking is established. Once that is done, the nematodes are again grouped into subjective clusters of designated risk potential as shown in Table 22.4. Note that where the lines are drawn for the subjective groupings is arbitrary. *Punctodera chalcoensis* has now been designated as one of the greatest risks.

The tables presented here provide an effective documentation of the decision process when accompanied by the supporting evidence. The criteria, ratings, and rankings are all transparently clear. Others may challenge any part of the evidence or judgment and present alternative evidence for doing so. Focusing on the evidence that underlies the rankings is a strength of the process. The process, as developed by PEARL, does not explicitly address uncertainty. Uncertainty ratings could be assigned to the hazard ranking or to the criteria ratings that comprise it.

Risk managers must now decide how to handle the nematodes with the greatest risk potential. That could include a more detailed risk assessment of the nematodes with the greatest risk potential or measures taken to reduce the risks associated with the introduction of these nematodes to the United States. The risk communication would vary with the risk management response. Because these nematodes are found in soil it was important to assure that trucks and other vehicles coming from infested states be cleaned of all soil before entering the United States. This would entail a significant communication campaign at the border between the United States and Mexico.

22.2.2 PAIRED RANKING

Consider another ranking problem through the lens of a different technique, paired ranking. This is an alternative form of weighted ranking. Following the method of Jones (1998) there are nine steps to this technique. They are:

1. List all criteria for ranking.
2. Rank the criteria pair-wise.

3. Assign percentiles to the criteria you will use.
4. Construct a ranking matrix.
5. Rank all items pair-wise for each criterion.
6. Calculate weighted criteria ratings.
7. Sum the criteria ratings.
8. Establish the rankings.
9. Conduct a sanity check.

Imagine a food producer is going to offer a new product line and is trying to decide which of four suppliers (W, X, Y, Z) to choose for a critical ingredient. Suppose the producer has decided the criteria for making this choice will be the cost of the ingredient (C), the suppliers' quality control measures (QC), and the future reliability (R) of the supply. Let us apply the paired-ranking technique to this problem assuming the decision maker wants to minimize the risk of any problems associated with the supply of the ingredient over the next three years.

The first step is to identify all the relevant criteria you can think of using to rank your items. The second step narrows that list to the most important criteria through pair-ranking. For simplicity, this example uses only three criteria but any number of criteria can be used. If you need a lot of criteria to provide the ranking, you may need a more sophisticated assessment method.

Pair-wise ranking works like this. Given three criteria C, QC, and R, we ask which is more important C or QC, C or R, QC or R. These choices are presented for all possible pairings of criteria. Given the risk of concern, assume the risk managers have a clear transitive ranking $QC > R > C$. Thus, given the three possible pairs, QC would receive two most important "votes," R would receive 1, and C would receive none.

When dealing with a larger number of criteria the preferences may not always be so obviously transitive. The process can also grow tedious quickly with a large number of criteria. Nonetheless, pair-wise ranking can be a useful way to identify the most important criteria from among the list of candidates. What lends an air of credibility and confidence to pair-wise ranking, however, is when the assessors carefully record the reasons and evidence used to support their rankings.

In the present case, QC is more important than reliability because it is essential that the company have complete confidence in the quality and safety of the supplier's product. Laboratory certificates, a total quality management plan, and a hazard analysis and critical control point (HACCP) plan may be important features of QC. Reliability is more important than cost because the success of the new product line rests on a dependable supply of the ingredient over a long term. Cost is not a trivial consideration, it is just the least important of the three.

The third step, assigning weights to the criteria you will use, is a subjective judgment step. There is no simple deterministic set of values to use. You should not use the votes a criterion received to calculate these weights. The weights should reflect the risk manager's preferences. If a tool like this is used for making public policy, additional care is going to need to be taken with this step. For this example, assume the weights are $QC = 0.5$, $R = 0.3$, and $C = 0.2$. The weights are usually easier to use and for others to understand if they sum to one (or 100). Note that equally weighted criteria are not an option with this methodology.

TABLE 22.5
Evidence for Criteria Used in Ranking Matrix

Supplier	Cost (C)	Quality Control (QC)	Reliability
W	Most costly	Second best controls	Most reliable
X	Third most costly	Third best controls	Second most reliable
Y	Least costly	Least controls	Third most reliable
Z	Second most costly	Best controls	Least reliable

The risk matrix is a simple table with the criteria in columns and the items to be ranked in rows. A completed matrix is shown at the end of this example. Step four in the process is another round of pair-wise comparisons that is based on evidence. Taking the first criterion, cost, we ask which supplier is better on cost W or X, W or Y, etc. [Table 22.5](#) summarizes the evidence available for this decision problem.

Using the data from [Table 22.5](#) for the pair-wise rankings of suppliers for each criterion, [Table 22.6](#) shows the votes received by each supplier for each criterion. For example, Y is cheaper than W, X, or Z and it gets three votes in pair-wise comparison. The relative weights appear in the column headings.

Weighted criteria rankings are calculated by weighting the number of votes by the criteria weights to obtain the ratings shown in [Table 22.7](#).

TABLE 22.6
Votes Received in Pairwise Comparison of Suppliers for Each Criterion

Supplier	Cost (C) 0.2	Quality Control (QC) 0.5	Reliability 0.3
W	0	2	3
X	2	1	2
Y	3	0	1
Z	1	3	0

TABLE 22.7
Calculation of Weighted Ratings for Each Criterion

Supplier	Cost (C) 0.2	Quality Control (QC) 0.5	Reliability 0.3
W	$0 \times 0.2 = 0$	$2 \times 0.5 = 1$	$3 \times 0.3 = 0.9$
X	$2 \times 0.2 = 0.4$	$1 \times 0.5 = 0.5$	$2 \times 0.3 = 0.6$
Y	$3 \times 0.2 = 0.6$	$0 \times 0.5 = 0$	$1 \times 0.3 = 0.3$
Z	$1 \times 0.2 = 0.2$	$3 \times 0.5 = 1.5$	$0 \times 0.3 = 0$

TABLE 22.8
Completed Risk Ranking Matrix

Supplier	Cost (C) 0.2	Quality Control (QC) 0.5	Reliability 0.3	Total Score	Rank
W	0	1	0.9	1.9	First
Z	0.2	1.5	0	1.7	Second
X	0.4	0.5	0.6	1.5	Third
Y	0.6	0	0.3	0.9	Fourth

The ratings are summed and the suppliers are ranked according to their rating in [Table 22.8](#), which shows a completed ranking matrix. Supplier W is the best choice.

This technique can be used to rank items in a simple and straightforward way. It represents the judgments of the people that established the weights and made the pair-wise comparisons and no one else's. These judgments are only as good as the evidence they are based on. When this technique is used to make private decisions about risks, it is a perfectly valid technique to aid decision making. Uncertainty is not explicitly accounted for.

22.3 PHYTOSANITARY GENERIC RISK ASSESSMENT

The international trade and international plant protection communities are concluding the first quarter century since the Agreement on the Application of Sanitary and Phytosanitary (SPS) Measures or SPS Agreement first sought to link phytosanitary decisions to risks. This linkage marked a bold initiative in the advancement of the risk sciences, which have made deep inroads into the international communities of practice for plant health, animal health, and food safety. The so-called “three sisters,” comprising the International Plant Protection Convention (IPPC), World Organization for Animal Health (OIE), and Codex Alimentarius are standard setting organizations, which have been responsible for the advancement of international standards based on risk assessment.

Much of the first 25 years was given over to interpretation of the SPS Agreement and development of the means by which it would be implemented by the various communities of practice. The primary emphasis in these early years was on risk assessment, and considerable progress has been made in structuring phytosanitary risk assessment approaches. The evolution of the risk assessment process and the state of the art in the United States are summarized in the paragraphs that follow.

Phytosanitary risks are risks to plants or plant products. The Animal and Plant Health Inspection Service of the U.S. Department of Agriculture pioneered the development of phytosanitary risk assessment with the 1993 publication of “Generic Non-Indigenous Pest Risk Assessment Process: The Generic Process” (Orr et al. 1993). The generic process developed by APHIS was more than just a risk assessment; it had three separate stages. They were:

- An initiating event
- Conduct risk assessment using the generic process
- Risk management

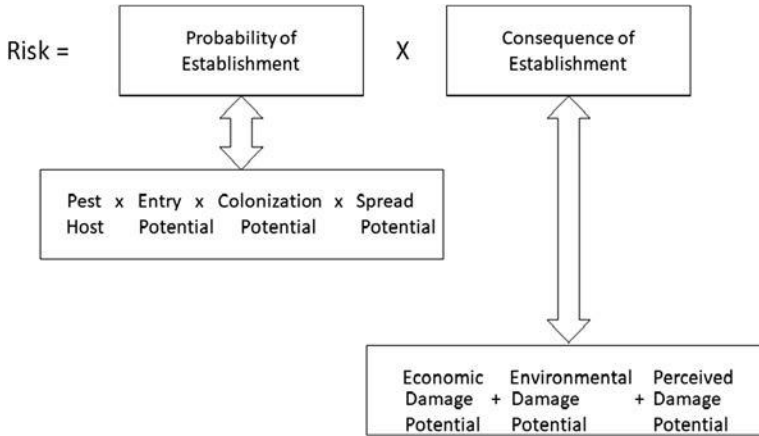


FIGURE 22.1 1993 APHIS generic phytosanitary risk assessment process.

The initiating event could be a new trade agreement or a new product from an existing trade partner or perhaps a new pathway for an existing plant commodity. Once an assessment was initiated, one or more risk assessors would complete a risk assessment on the proposed trade item using the generic process. Following completion of the generic risk assessment process there would then be a risk management decision. The risk management decision could include allowing the product into the country, preventing its entry, or allowing entry conditional on the exporters' compliance with mitigation requirements or other regulations affecting the product. [Figure 22.1](#) presents the generic risk assessment process proposed by the document.

This is a qualitative risk assessment process in which scientific evidence is gathered to support qualitative (high, medium, low) ratings for each of the seven individual assessment elements shown in the figure. The four probability elements are aggregated up into an overall probability rating and the three consequence elements are aggregated up into an overall consequence rating. These two ratings are, in turn, aggregated to produce an individual pest risk potential rating. One such assessment is done for each pest of concern associated with a trade commodity. The various pest risk potentials are used to produce an overall commodity risk potential.

The basic structure of this risk assessment technique has been preserved although it continues to evolve.

After the introduction of this generic process the International Plant Protection Convention issued International Standard for Phytosanitary Measures (ISPM) No. 2, Guidelines for Pest Risk Analysis, revised in 2007 and now called Framework for Pest Risk Analysis. The international standard process is summarized in [Figure 22.2](#).

The National Plant Protection Organization (NPPO) of each nation decides how to implement this standard. APHIS has described the evolving risk assessment process repeated for each pest as shown in [Figure 22.3](#).

[Table 22.9](#) provides a sample result from a 2017 draft risk assessment "Importation of Fresh Citrus Fruit, Citrus spp., from Swaziland into the Continental United States." The example is for *Paracoccus burnerae*. The question asked is, "What is

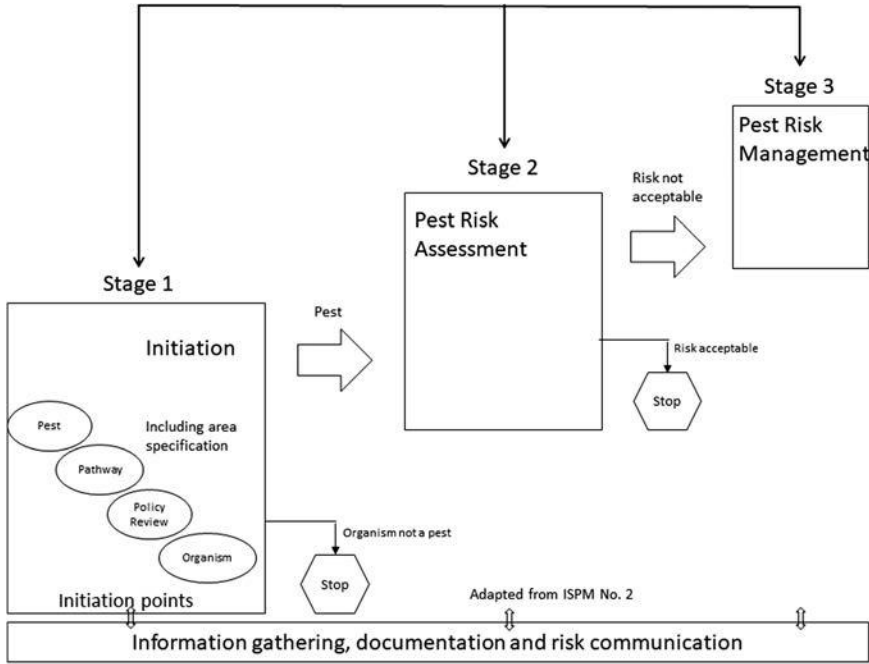


FIGURE 22.2 Summary of ISPM No. 2 pest risk analysis process.

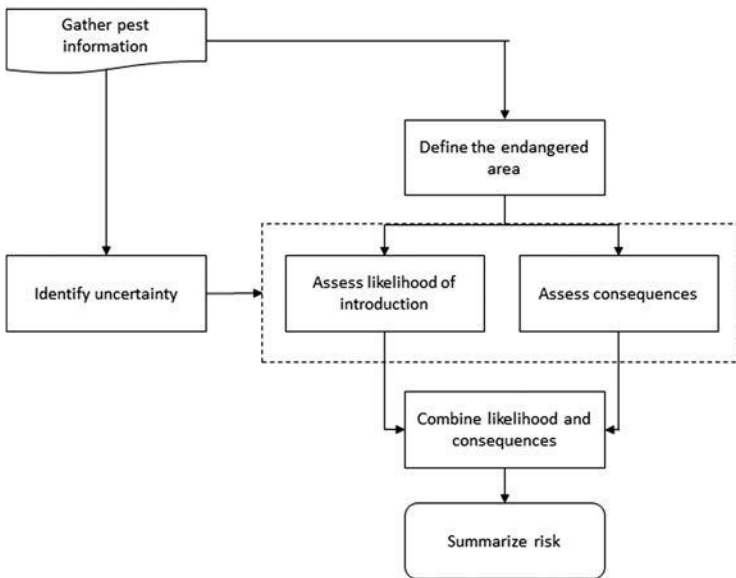


FIGURE 22.3 Overview of the plant protection and quarantine risk assessment process for individual pests.

TABLE 22.9**Assessment of the Likelihood of Introduction of *Paracoccus burnerae* into the Endangered Area via the Importation of Fresh Citrus spp. Fruit from Swaziland**

Risk Element	Rating
A1: Pest prevalence on the harvested commodity (= the baseline rating for entry)	Medium
A2: Likelihood of surviving postharvest processing before shipment	High
A3: Likelihood of surviving transport and storage conditions of the consignment	High
A: Overall risk rating for likelihood of entry	Medium
B1: Likelihood of coming into contact with host material in the endangered area	Low
B2: Likelihood of arriving in the endangered area	High
B: Combined likelihood of establishment	Medium
Combined likelihoods of entry and establishment	Medium
Risk element	Meets criteria?
C1: Damage potential in the endangered area	No
C2: Spread potential	N.A.
C: Pest introduction is likely to cause unacceptable direct impacts	No
D1: Export markets at risk	Yes
D2: Likelihood of trading partners imposing additional phytosanitary requirements	No
D: Pest is likely to cause significant trade impacts	No
Is the pest likely to cause unacceptable consequences in the pest risk assessment area?	No

the quarantine risk potential of *Paracoccus burnerae* on citrus fruit imported to the United States from Swaziland? The assessment shows unacceptable consequences in the pest risk assessment area are not likely.

Pest risk management is defined by the IPPC as the “evaluation and selection of options to reduce the risk of introduction and spread of a pest” (ISPM No. 5: IPPC 2017). When a commodity risk is unacceptable, usually when it has one or more pests rated medium or higher, risk management measures are required to facilitate the commodity’s acceptance in the importing country.

Measures may be applied at any point in the production chain to reduce the likelihood of entry or to reduce the likelihood of establishment or spread. International policy aspects of risk management are prescribed by the Sanitary and Phytosanitary Agreement of the World Trade Organization and the IPPC and they include the:

- Application of the appropriate level of protection (ALOP)
- Principle of least trade restrictive measures (minimal impact)
- Principle of nondiscrimination (including national treatment)
- Principle of managed risk
- Principle of equivalence

Risk communication receives little to no attention in the practice of phytosanitary risk analysis. Communication between nations can be extensive but it is generally considered part of risk management. The NPPO of each nation communicates with its respective stakeholders on the progress of a trade request.

22.4 AQUATIC NUISANCE SPECIES RISK

Aquatic nuisance (or invasive) species (ANS) are nonindigenous species that threaten the diversity or abundance of native species or the ecological stability of infested waters, or commercial, agricultural, aquacultural, or recreational activities dependent on such waters (Aquatic Nuisance Species Project, <http://www.aquaticnuisance.org/> [accessed July 19, 2018]). In 1996, the Risk Assessment and Management Committee of the Aquatic Nuisance Species Task Force published a report entitled, “Generic Nonindigenous Aquatic Organisms Risk Analysis Review Process.” This review process was a modification of the 1993 “Non-Indigenous Pest Risk Assessment Process” mentioned previously. The risk analysis process is summarized in [Figure 22.4](#).

The risk assessment process is similar to that shown in [Figure 22.1](#). The Great Lakes and Mississippi River Interbasin Study (GLMRIS 2012) conducted by the U.S. Army Corps of Engineers (USACE) at the direction of the U.S. Congress applied this process in the qualitative assessment of 33 ANS identified from a list of 254 organisms of potential concern. The risk question asked is, “What aquatic nuisance species present the greatest risk of establishment in the Great Lakes and Mississippi River basins, where $Risk_{est} = Consequence_{est} \times Probability_{est}$?”

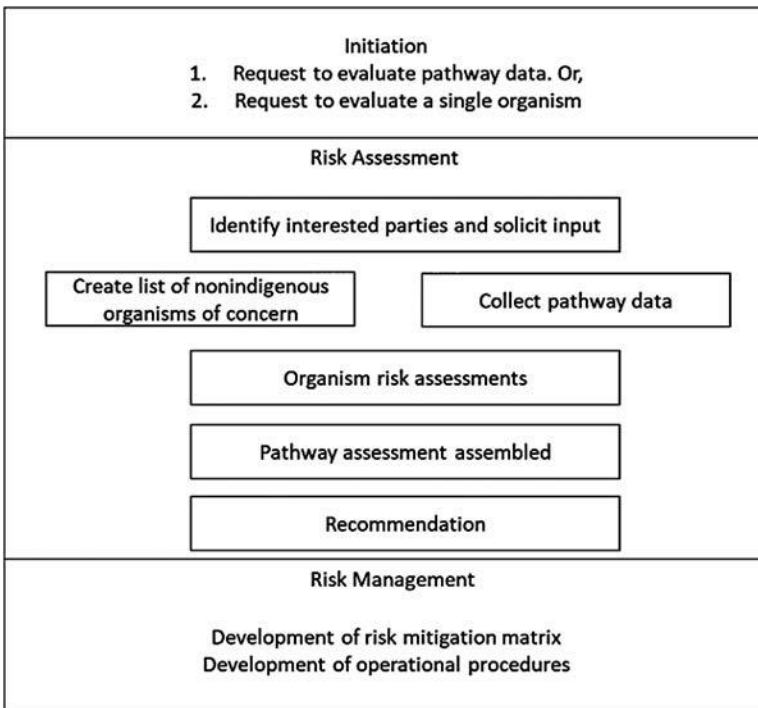


FIGURE 22.4 Flowchart showing the risk analysis process consisting of initiation, risk assessment, and risk management.

The probability of establishment was defined as:

$$P(\text{establishment}) = P(\text{pathway}) \times P(\text{arrival}) \times P(\text{passage}) \\ \times P(\text{colonization}) \times P(\text{spread})$$

Each probability element is assumed to be conditional on the occurrence of its preceding element. P(pathway) is the probability that a complete aquatic pathway is available for interbasin transfer. P(arrival) is the probability that the ANS will arrive at the pathway from its current distribution within a specified time given that a pathway exists. P(passage) is the probability that the ANS can successfully move through the aquatic pathway from one basin to the other given that the species arrives. P(colonize) is the probability that the ANS can establish a colony in the newly invaded basin given that the species survives passage along the pathway. P(spread) is the probability that the ANS can spread to elsewhere in the new basin given that a colony exists.

Each probability element was rated no, low, medium, or high based on scientific evidence. An NLMH uncertainty rating was also identified for each probability element. The elements were aggregated upward to an overall p(establishment) rating by taking the lowest probability element value. Thus, four elements rated HMLH would have an overall rating of L, mirroring the way numerical products would function. Uncertainty was not aggregated.

Consequences were defined as:

$$\text{Consequence} = \text{Environmental Consequence} + \text{Economic Consequence} \\ + \text{Social or Political Consequence}$$

Environmental consequences are defined as effects on ecosystem structure and function, including effects on resident species, populations, communities, habitats, and ecological services. Economic consequences are defined as effects on economic activities, such as changes in employment, earnings, tax bases, property values, and income. Social/political consequences are the effects on human services and activities such as recreation and subsistence, as well as changes in regulatory requirements. The overall consequence rating was the highest of the individual consequence element ratings. The overall risk rating was based on the scheme shown in the lookup matrix in [Table 22.10](#).

TABLE 22.10
Risk Lookup Table

		Consequence			
		None	Low	Medium	High
Probability	None	N	N	N	N
	Low	N	L	L	L
	Medium	N	L	M	M
	High	N	L	M	H

Thirteen species were judged to present an unacceptable risk. Species posing an unacceptable risk to the Great Lakes basin were:

- Scud
- Bighead carp
- Silver carp

Species posing an unacceptable risk to the Mississippi River basin were:

- Bloody red shrimp
- A diatom
- Fishhook waterflea
- Grass kelp
- Red algae
- Reed sweetgrass
- Ruffe
- Threespine stickleback
- Tubenose goby
- Viral hemorrhagic septicemia virus (VHSV)

Seven different risk management options were formulated to address these risks, ranging in costs from \$7.8 to \$18.3 billion dollars to construct. A nonstructural RMO with annual costs of \$68 million was also identified. The nonstructural plan could be implemented immediately, the \$7.8 billion plan would take 10 years to implement and the other six plans would take 25 years to implement. The risk reduction was summarized qualitatively by a number of stars as shown in Table 22.11 it indicates the extent of overall risk reduction with more stars being more effective.

The risk communication for this rather extensive effort consisted of a series of public meetings held throughout the basins of the Mississippi River and the Great Lakes.

Congress received the report and directed the USACE to develop a plan to prevent upward bound ANS from establishing in the Great Lakes, indicating that this should be done at the site of the Brandon Road Lock and Dam (BRLD). The new risk question

TABLE 22.11
Selected Impacts of Seven Risk Management Options

RMO #	Without Condition	Non-structural	Technologies without Buffer Zone	Technologies with Buffer Zone	Lakefront Hydrologic Separation	Midsystem Hydrologic Separation	Hybrid Cal-Sag Open	Hybrid CSSC Open
Risk Reduction	★	★★	★★★	★★★★	★★★★★	★★★★★	★★★★	★★★★
Cost	\$0	\$68M annually	\$15.5B	\$7.8B	\$18.3B	\$15.5B	\$15.1B	\$8.3B

to be answered was, “What is the most effective way to prevent the establishment of upward bound ANS at Brandon Road Lock and Dam?” Prevention was defined as reducing risk as low as possible.

A quantitative assessment of the probability of establishment was conducted for Asian carp and scud. The Asian carp model results are summarized in the following paragraphs. A numerical model was constructed using Microsoft Excel and Palisade’s @Risk software. The inputs, obtained in an expert elicitation, were used in a model that randomly selected a future Asian carp population size downstream of BRLD. This population provides the propagule pressure that motivates carp to attempt to pass through the waterway from BRLD to Lake Michigan, which is equipped with two electric barriers intended to halt the upstream movement of fish. Experts estimated the number of fish that could pass annually through this stretch of waterway. The model accumulated the numbers of fish overtime and compared that to the expert’s estimate of the colonization threshold. If that threshold was exceeded, colonization is assumed to take place. A simulation of this sequence provided an estimate of $P(\text{colonization})$ which was then multiplied by the expert’s estimate of $P(\text{spread})$ to obtain an estimate of $P(\text{establishment})$ in a second simulation.

Five new risk management options were formulated and compared to a no-new-action scenario. These are:

- Nonstructural plan—includes education, monitoring, and overfishing
- Lock closure—consist of permanently closing the lock
- Electric barrier—includes a flushing lock, an engineered channel, a bubble system, and a new electric barrier to deter the upstream movement of fish
- Complex noise—includes a flushing lock, an engineered channel, a bubble system, and complex noise to deter the upstream movement of fish
- Electric barrier and complex noise—includes a flushing lock, an engineered channel, a bubble system, a new electric barrier and complex noise to deter the upstream movement of fish

Figure 22.5 compares the experts’ estimates that Asian carp will become established in the Great Lakes sometime before or during 2071. One expert has a very high estimate, three experts have low estimates, and two are in between indicating a great deal of difference among the experts. The boxplots show the relative uncertainty of the individual expert.

Figure 22.6 shows six estimates of the $P(\text{establishment})$ value for the without condition and for the five different risk management options from expert 1. The efficacy of the plans can be compared to the without condition. For contrast Figure 22.7 shows six estimates from a different expert.

Although the numerical estimates of $P(\text{establishment})$ are quite different, the ordinal ranking of the effectiveness of the RMOs is identical, not only for these two experts, but for all six experts. Thus, despite the considerable uncertainty about the actual $P(\text{establishment})$ values for each scenario, the results did enable risk managers to say with a high degree of confidence, which measures were most effective in reducing $P(\text{establishment})$. The best reduction comes from lock closure,

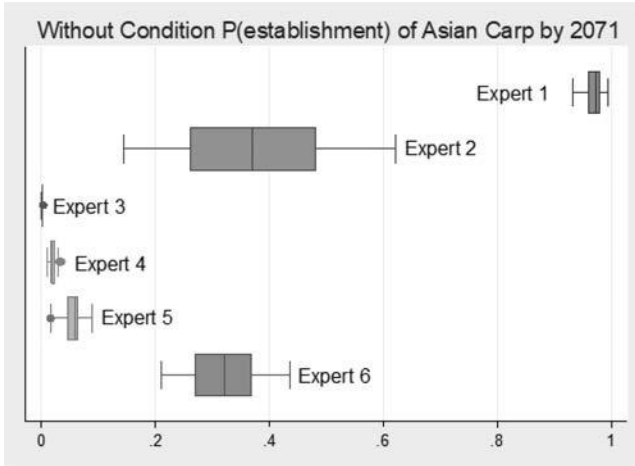


FIGURE 22.5 Comparison of six experts' estimate of the probability of establishment of Asian carp in the Great Lakes by 2071 if no additional risk management measures are implemented.

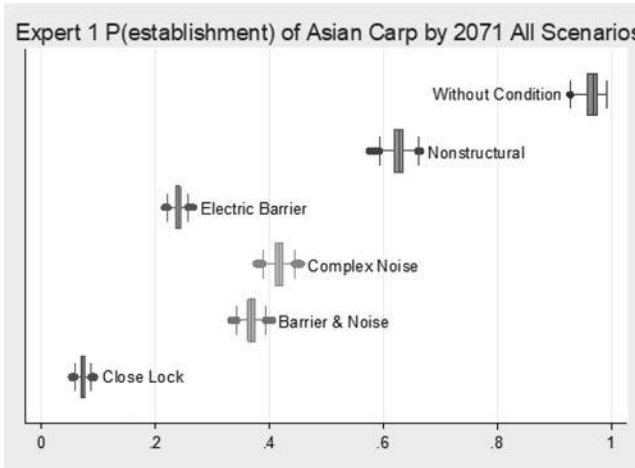


FIGURE 22.6 Estimates of P(establishment) for six different scenarios based on the inputs of expert 1.

followed by the electric barrier, the electric barrier plus complex noise,* complex noise, and nonstructural measures. Congress directed the USACE to reduce the risk of establishment as low as possible. The results of this risk assessment enable risk managers to do that with confidence. The RMO comprising the electric barrier and complex noise was selected as the best option.

* The electric barrier operates continuously in the electric barrier alternative, but it is switched off during the lockage of towboats in the barrier plus noise plans. Hence, this superficially counter-intuitive ranking.

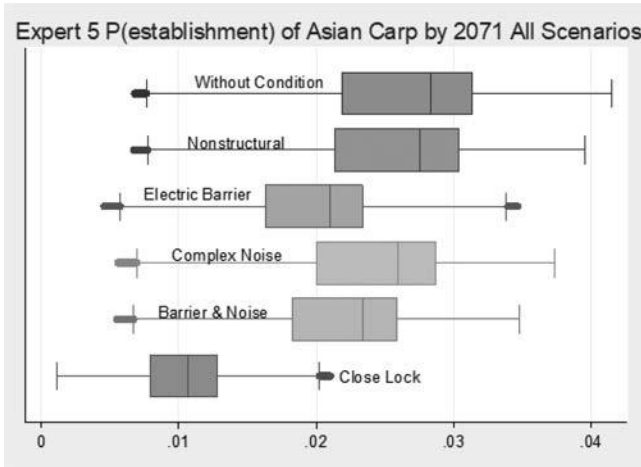


FIGURE 22.7 Estimates of P(establishment) for six different scenarios based on the inputs of expert 5.

22.5 COST RISK

Cost risk provides the opportunity to consider the estimation of a rather routine decision criterion in a way that addresses the uncertainty inherent in many such routine tasks. Costs must be estimated for many business and other functions, and there are risks inherent in over- or underestimating costs. In general, the reward system is not symmetric and underestimates of costs are generally more problematic than overestimates, although a significant overestimate could result in a decision not to undertake an activity. Cost overruns can result in project delays, unfinished projects, poorly designed projects, reallocation of resources, and other adverse budget impacts.

Table 22.12 shows a cost estimate for channel deepening and wetlands creation. Sandy dredged material will be removed from a bay bottom navigation channel and used to fill geotubes, which are like 30- and 45-foot diameter sausage casings. The sand-filled tubes will then be laid parallel to the shoreline and the area behind them will be backfilled with dredged material to create wetlands. All values in the cost estimate are uncertain except the quantity of mobilizations and demobilizations, which is fixed at one.

This project is being built under a grant program with a hard cap of \$20 million. Risk managers want to know:

- What is the probability that costs will exceed \$20 million?
- Because the local authority is responsible for any cost overrun they want to know their maximum exposure to such risk.
- What cost number to enter into their budget system for this project?

Figure 22.8 presents the results of a 10,000-iteration simulation. Table 22.13 presents the five-number summary for costs. The cost ranges from \$13.2 to \$24.6

million. The median cost is \$18.6 million. There is a significant chance this project could exceed the \$20 million grant cap. In fact, 18.8% of all the cost estimates exceed the \$20 million grant cap.

The maximum cost estimate is \$4.6 million greater than the \$20 million cap; that is the project sponsor’s maximum risk exposure. The choice of a cost to use for this

TABLE 22.12
Cost Estimate for Wetlands Creation Project Showing Expected Values

Account Code	Description	Quantity	Unit	Unit Price	Amount
12	Navigation, ports, and harbors				
	Mobe and demobe	1	LS	\$525,000	\$525,000
	Pipeline dredging, reach 1	576,107.33	CY	\$2.78	\$1,603,163
	Pipeline dredging, reach 2	1,022,768.67	CY	\$2.60	\$2,655,363
	Pipeline dredging, reach 3A	1,182,813.33	CY	\$3.16	\$3,738,577
	Pipeline dredging, reach 3B	736,713.33	CY	\$2.76	\$2,034,066
	Scour pad, reach 1	17,550	SY	\$25.69	\$450,831
	Geotubes, 30', reach 1	1,400	LF	\$188.52	\$263,926
	Geotubes, 45', reach 1	4,912	LF	\$222.18	\$1,091,366
	Scour pad, reach 3	38,750	SY	\$25.69	\$995,424
	Geotubes, 45', reach 3	13,940	LF	\$222.18	\$3,097,240
12	Total – Navigation, ports, and harbors				\$16,454,956
30	Engineering and design	8	%		\$1,234,000
31	Construction management	6	%		\$905,000
	Total Project Cost				\$18,593,956

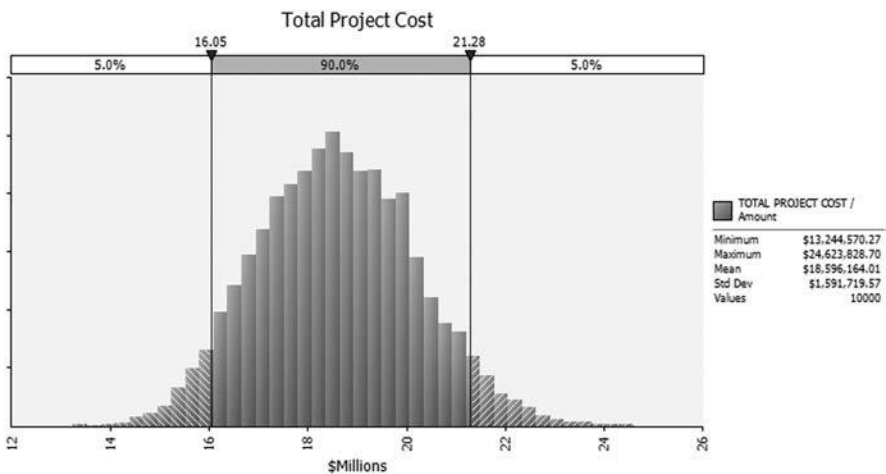


FIGURE 22.8 Results of 10,000-iteration simulation of uncertain costs of a wetlands creation project.

TABLE 22.13**Five Number Summary of Costs for Wetlands Creation Project**

	Minimum	25th percentile	Median	75th percentile	Maximum
Project cost	\$13.2 million	\$17.5 million	\$18.6 million	\$19.7 million	\$24.6 million

project depends on the sponsor's risk preferences. If the sponsor is willing to accept a 25% chance of a cost overrun, they would use \$19.7 million as the cost estimate commensurate with that risk. Using the maximum cost could result in a failure to gain approval for the project due to the high local cost.

A great deal of risk work is of this ordinary nature. The risk management decision here is a go/no-go decision along with a decision on what cost estimate to use for that portion of the decision system that requires a number. The risk communication task is limited to internal discussions between the assessors and managers who must make the decision.

22.6 FOOD SAFETY RISK

The Codex Alimentarius defines risk assessment as "A scientifically based process consisting of the following steps: (i) hazard identification, (ii) hazard characterization, (iii) exposure assessment, and (iv) risk characterization." Codex member states follow this conceptual model in assessing a wide range of food safety risks. The U.S. Food and Drug Administration (FDA) conducted a risk assessment of *Vibrio parahaemolyticus* (Vp) in raw oysters following this model in 2005 (CFR, 2005).

The risk assessment was conducted in response to four outbreaks in the United States that caused more than 700 cases of illness. It focused on raw oysters because they are the food predominately linked to illness from this pathogen. The risk assessment estimated levels of Vp in oyster flesh beginning with the harvest of the oysters through postharvest handling, processing, and storage to predict human exposure to Vp from consumption of raw oysters and subsequent illnesses. The number of illnesses were estimated on a per-serving and an annual basis for six regions in the United States and each season for a total of 24 region/season combinations. The baseline model was used to develop with condition scenarios to evaluate the likely impact of potential risk management options on the exposure to pathogenic Vp from consumption of raw oysters as well as subsequent illnesses.

The actual questions used in the risk assessment follow:

1. What is known about the dose-response relationship between consumption of *V. parahaemolyticus* and illnesses?
2. What is the frequency and extent of pathogenic strains of *V. parahaemolyticus* in shellfish waters and in oysters?
3. What environmental parameters (e.g., water temperature, salinity) can be used to predict the presence of *V. parahaemolyticus* in oysters?
4. How do levels of *V. parahaemolyticus* in oysters at harvest compare to levels at consumption?

5. What is the role of postharvest handling on the level of *V. parahaemolyticus* in oysters?
6. What reductions in risk can be anticipated with different potential intervention strategies?

Interestingly, the risk managers did not ask any explicit questions about the risk of illness. The assessment modeled the product pathway as revealed in Figure 22.9, the core of the risk assessment model.

This is a single eater model. The first column full of numbers shows a without condition scenario for one eater and one meal; it is but one of an infinite number of possible scenarios. The water temperature determines the initial bacterial log count/gram of oyster flesh (2.41 log). The outgrowth of the *Vibrio* (0.97 log) is calculated based on the amount of time the oysters remain unrefrigerated and the ambient air temperature.

The sum of the initial bacterial count and the outgrowth yields the count at first refrigeration (3.38 log). The *Vibrio* continue to grow during the cooldown and reach their peak count after cooldown (3.98 log). The bacteria die off during the period of refrigeration and reach their consumption level (3.48 log/g). This is

Gulf Coast Louisiana		Light green cells contain the 'no mitigation' calculation.			
Summer		No mitigation	Parameters		
Water parameters			a_w	0.985	
mean μ	28.650722		b	0.0356	
mean σ	1.3282188		c	0.34	
Water temperature	28.650722 degrees C		T_min	278.5 degree K	
	2.4080866		T_max	319.6 degree K	
Log Vp level in environment	2.408087 log counts/gram		a_w_min	0.921	
min time on water	5		a_w_max	0.998	
likely time on water	9		d	263.64 degree K	
max time on water	11		lag	0 hours	
Time on the water	8.666667 hours		max growth	6 log cfu/gram	
Time unrefrigerated	4.8333333 hours				
Air temperature parameters					
μ	-1.66				
σ	1.33				
Ambient air temp	26.990722 degree C				
sqrt(max growth rate)	0.1901383				
Estimate growth rate in oysters	0.2007189 log counts/hr				
outgrowth1	0.9701415				
Predicted counts at 1st refrigeration	3.378228 log counts/gram				
Duration of cooldown	5 hours		Heat treatment	Freeze treatment	rapid cool mitigation
outgrowth2	0.6021568		four.five log reduction	two log reduction	3.010243
Predicted counts after cooldown	3.980385				
Length of refrigeration time	7.7 days				
Predicted level after die off	3.483585 log counts/gram	-1.016415	1.483585	2.513443	
Grams oysters consumed	383.227 grams				
Total Vp exposure in one meal	1166919.8 log counts	36.90124504	11669.198	124996.9791	
Pathogenic Vp consumed	2929	0	29	314	
	3.4667194 log counts	0	1.462398	2.496929648	
probability of illness	0.0001033	3.35958E-08	1.025E-06	1.10782E-05	
Log(risk)	-3.9857685	-7.473714756	-5.9894151	-4.955532349	
ill? 1=yes 0=no	0	0	0	0	

FIGURE 22.9 Model for the FDA *Vibrio parahaemolyticus* risk assessment.

multiplied by the size of the meal in grams to yield the number of bacteria actually consumed. The number of pathogenic bacteria in this meal is estimated from the total number of *Vibrio** and becomes the dose in a dose-response curve, 2,929 pathogenic *Vibrio* in this example. The resulting response is the probability that the specific meal modeled will make the eater sick. A simple binomial distribution uses this probability and $n = 1$ to simulate whether the eater becomes ill or not. A zero is returned in the bottom cell of the model when there is no illness, a 1 is returned when the eater gets ill.

The model can be run for say 100,000 iterations, and this simulates 100,000 different eating occasions. The number of illnesses divided by the number of meals yields an illness rate or a probability of getting sick from any one meal.

In a single simulation of 100,000 eating occasions 132 became ill, for an illness rate of 0.00132. This rate, which is for oysters harvested from a specific region and time of the year, and the number of oyster eating occasions provides the inputs for a binomial distribution that can be used to estimate the actual number of illnesses. Note that one of the purposes of this model was to evaluate the effectiveness of some RMOs. One of these was a 4.5 log reduction heat treatment, a 2 log reduction freeze treatment, and a rapid cool mitigation. There were other RMOs considered, but these three will meet the purposes of this example.

In the example shown, the log count after die-off is 3.07 under the without condition scenario of no additional risk management measures. That same oyster meal would have had -1.02 , 1.48 , and 2.51 log respectively for the heat treatment, freeze treatment, and rapid cool mitigation as shown in the remaining numerical columns of [Figure 22.9](#). The RMO effect is modeled for the same meal size shown in the without column. The RMO calculations proceed as described above with reduced pathogen loads. The heat treatment reduced the 132 illnesses to zero, freezing reducing the illnesses to 2, and rapid cooling resulted in 16 illnesses.

The questions posed by the risk managers were answered extensively in the interpretation and conclusions of the risk assessment. To illustrate the nature of the responses, [Table 22.14](#) partially answers the question, “What reductions in risk can be anticipated with different potential intervention strategies?”

This table shows a total estimate of 2,826 illnesses from *Vibrio parahaemolyticus* in raw oysters from all regions and seasons. Rapid cooling (immediate refrigeration) reduces this to 391 illnesses, freezing reduces it to 30, and heat treatment essentially eliminates the problem. Risk managers must weigh this information against consumer taste preferences, costs of implementation, industry impacts, and so on to make a risk management decision. The uncertainty in this assessment can be examined extensively. See, for example, the sensitivity analysis found in the original report (FDA 2005).

This risk assessment resulted in harvest restrictions that reduced the number of illnesses. Extensive risk communication efforts were required to make all affected parties aware of the changes.

* Note that in the actual model “Total Vp exposure in one meal” is mistakenly labeled as a log count, it is a cell count.

TABLE 22.14
Predicted Mean Number of Illnesses per Annum from Reduction of Levels of Pathogenic *Vibrio Parahaemolyticus* in Oysters

Region	Predicted Mean Number of Annual Illnesses			
	Baseline	Immediate Refrigeration	2- \log_{10} Reduction	4.5- \log_{10} Reduction
Gulf Coast (Louisiana)	2,050	202	22	<1
Gulf Coast (Non-Louisiana)	546	80	6	<1
Mid-Atlantic	15	2	<1	<1
Northeast Atlantic	19	3	<1	<1
Pacific Northwest (dredged)	4	<1	<1	<1
Pacific Northwest (intertidal)	173	100	2	<1
Total	2,826	391	30	<1

Immediate refrigeration = >immediately after harvest usually yields about 1- \log_{10} reduction.
 Freezing is an example of a process that yields a 2- \log_{10} reduction.
 Mild heat treatments (e.g., 5 minutes at 50°C), irradiation, or ultra high hydrostatic pressure are examples of processes that yield a 4.5- \log_{10} reduction.

22.7 LEVEE SAFETY

Qualitative methods that make limited use of numerical estimates of risk are sometimes called semiquantitative assessments. An example is offered here to illustrate the idea. Hurricanes Katrina and Rita focused national attention on levee safety after the failure of levees in New Orleans. A National Levee Safety Program was implemented to meet three goals:

1. Reduce risk and increase public safety through an informed public empowered to take responsibility for its safety
2. Develop a clear national levee safety policy and standards
3. Maintain a sustainable flood damage reduction system that meets public safety needs

One part of this program includes a levee inventory and a technical risk assessment of each levee. With thousands of levees to consider, it may be useful to develop tools for screening the levees to identify those with the greatest potential risk to humans and property.

This heuristic example presents a technique that could be adapted to such a purpose. It is not the method being used in the National Levee Safety Program. The example begins with an abbreviated version of the three pieces of paper a good risk management process should produce: a problems and opportunities statement, an objectives and constraints statement, and a list of questions to be answered by the

risk assessors. These are the most essential elements for defining a decision context. An example of a semiquantitative risk assessment capable of answering the risk manager’s questions is presented. The manner in which the uncertainty encountered was handled is summarized.

Problems:

1. Locally constructed levees are prone to underperformance or failure resulting in property damage and risk to life.
2. There is a complete lack of data on many of the levees to be evaluated in a national levee safety program.

Objectives:

1. Identify those levees of greatest potential risk to the populations they are to protect.
2. Protect life, health, and safety.
3. Reduce property damage.
4. Identify data gaps.

Questions:

1. Which levees in the region present the greatest potential risk to life and property?
2. Which levees should be subjected to a technical risk assessment first?

Figure 22.10 shows the risk ranger model. Using the basic conceptual model, Risk = Probability × Consequence, to rank the potential risk of the region’s levees in a semiquantitative manner, the challenge is to identify criteria that aid assessment of the probability of an unsatisfactory performance as well as an assessment of the consequences of an unsatisfactory performance. The criteria are shown in the figure along with a sample rating for each criterion.

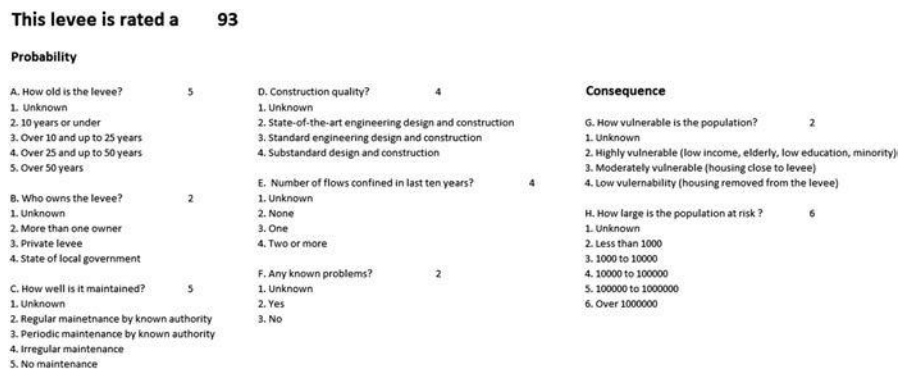


FIGURE 22.10 Levee risk ranger, a semiquantitative risk assessment tool.

There is a virtual absence of information on many of the nation's levees. Thus, for a screening tool to be useful it must rely on reasonably available data rather than on the higher quality engineering data that will ultimately be required for a technical risk assessment. The logic reflected here is that this tool uses reasonably available data that provide clues to the potential risk associated with the levee. It is presumed that older, private structures that are not built to exacting standards, are poorly maintained, have passed flood flows, and may have known problems are more likely to perform unsatisfactorily or even to fail.

The size and social vulnerability of the population are considered to be the two consequence criteria of most importance in the early screening stages when the focus is on protecting lives.

Evidence is gathered to rate each levee against each criterion. If any entry is unknown, that assessment is flagged as a "data gap" and no rating is provided. Otherwise the choices for each criterion are converted to an order of magnitude. The "riskiest" choice is rated a 1, the second riskiest 0.1, the third riskiest 0.01, etc. An unknown entry is rated a 0. The product of all eight entries is calculated. The largest and smallest possible products are calculated and the range between these two values is normalized over the [0,100] interval. The normalized value is the levee's rating. This is a semiquantitative method that was peer reviewed in a food safety paper by Ross and Sumner (2002). Although the rating is numerical, it remains qualitative in information content. The numerical ratings have only ordinal level information content.

All the levees in the region could be assessed and their semi-quantitative ratings like the overall risk score of 93 in the example enable assessors to answer the risk manager's questions. The levees with the highest numerical ratings have the greatest risk potential. It is understood that this assessment proceeds under conditions of considerable uncertainty. When the very rudimentary data of this tool are not available it is acknowledged that the levee cannot even be ranked. Presumably such an assessment would highlight the need for additional data at some sites, while enabling risk managers to identify those levees that should be subjected to a more rigorous technical risk assessment first.

22.8 ECOLOGICAL RISK

The U.S. Environmental Protection Agency defines ecological risk assessment as "the process for evaluating how likely it is that the environment may be impacted as a result of exposure to one or more environmental stressors such as chemicals, land change, disease, invasive species, and climate change." An ecological risk assessment was completed for the Middle Snake River, Idaho (EPA, 2001), a 100 km stretch of the 1,667 km long Snake River located in southern Idaho. Despite its stated goals to attain water quality standards, establish total maximum daily loads for major pollutants, provide water for hydropower, recreation, and irrigation, recovery of endangered species, and sustained economic well-being, it appears to have been more of a benchmarking risk assessment.

The assessment endpoints used to complete this ecosystem level analysis include the diversity, reproduction, growth, and survival of representative species from three major trophic levels (fish, invertebrates, and plants).

TABLE 22.15
Factors Limiting Reproduction, Growth, and Survival of the Rainbow Trout Population in the Middle Snake River

Factor	Stressor	Lines of Evidence	Risk	Uncertainty	Assumption	Recovery Potential
Number of spawning fish	Loss of adult habitat (e.g., streamside vegetation, overhanging banks, and woody debris)	LJT, Field, PBJ	An increase in the population size is not possible with low or no reproduction	Low, field studies show low numbers of adult fish are present in the Middle Snake River	Lack of habitat is a main factor limiting the size of the adult population	Good if habitat improvements can be improved, but low if a stable annual flow regime is not maintained
Spawning	Sedimentation, high water temperature, and land use on tributaries	HSI, WQS, LJT, Field, PBJ	Population of native fish cannot recover without successful reproduction	Moderate, historic spawning areas in the main channel have not been documented	Poor spawning success attributed to poor water quality conditions	Low, without improving water quality, reducing sedimentation, and controlling land/water use on tributaries
Rearing	Unstable stream flow during the spring and high water temperatures	HSI, WQS, LJT, Field, PBJ	Population cannot recover without successful recruitment	Rearing areas in the main stem of the Middle Snake River identified using habitat suitability indices	Rearing habitat important for maintaining and increasing adult populations	Low, the carrying capacity for native fish was likely permanently reduced by dam construction in the Middle Snake River
Overwintering	Loss of habitat (e.g., deep holes and large woody debris)	LJT, BPJ	Unknown	High, no information available on the amount of overwintering habitat in the main stem	Overwintering habitat can limit the size of the adult population	Unknown
Food supply	Sedimentation and increased water temperature	LJT, Field, PBJ	Poor growth, as invertebrate fauna do not support cold-water fish	Moderate, adequate analysis of sampling information has not been completed	Food supply can limit the size of a rainbow trout population	Low, without improving lotic conditions, lowering water temperature, and controlling sedimentation
Genetic diversity	Hybridization with stocked fish	LJT, PBJ	Poor survival with mixed genotype	Low, effects of hybridization on native fish are known	An adequate population of native fish remains	Good, provided that existing native fish are protected from stocked hatchery fish

The scope of the risk assessment was far too great to lend itself to a succinct summary here. Consequently, this summary will focus narrowly on the risks to rainbow trout. Table 22.15 identifies the factors that limit rainbow trout in the study area. The abbreviations used in the table are: HSI—habitat suitability indices, WQS—water quality standards, Field—field surveys in the Middle Snake River, LIT—literature, BPJ—best professional judgment.

The stressors limiting rainbow trout growth and survival are elevated water temperatures, irregular flows, and excessive sedimentation. The evidence for this includes simulated dissolved oxygen estimates that fall below the standard for spawning for rainbow trout from 19% to 58% of the time during the January 15 to July 15 spawning period. The temperature standard for spawning was exceeded from 58% to 80% of the time. The risks to all life stages of rainbow trout based on calculations of unacceptable habitat conditions are high throughout much of the Middle Snake River. Spawning habitat has also been adversely affected by sedimentation and high temperatures.

The without condition outlook for wild native rainbow trout appears bleak. In light of the habitat requirements and the assessment of the impairment of spawning, rearing, and adult habitat, the Middle Snake River cannot support a viable rainbow trout population. Flow and water temperature have the most environmental influence on trout populations. Management of the river to improve these conditions for this species was identified as a potential solution. The EPA identifies the biggest benefit of this risk assessment as the fact that a number of federal, state, and local environmental agencies and academics, interested citizens, and industrial groups came together to share data, explore, and develop solutions and undertake actions within the watershed.

22.9 SUMMARY AND LOOK FORWARD

Examples of eight risk assessments were summarized. Together they only provide a hint at the range of applications for risk analysis science. Individually they begin to demonstrate the range of tools available to risk assessors.

Looking forward, your challenge becomes finding what is useful in this text and applying it in your own disciplines and communities of practice.

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Appendix A: Using Palisade's DecisionTools® Suite

A.1 INTRODUCTION

Palisade's DecisionTools® Suite* is an integrated set of programs for risk analysis and decision making under uncertainty that run in Microsoft® Excel. The DecisionTools® Suite includes @RISK for Monte Carlo simulation, PrecisionTree for decision trees, and TopRank for “what if” sensitivity analysis. In addition, the DecisionTools® Suite comes with BigPicture for mind mapping and data exploration, StatTools for statistical analysis and forecasting, NeuralTools for predictive neural networks, and Evolver and RISKOptimizer for optimization. All programs work together and are integrated completely with Microsoft® Excel for ease of use and maximum flexibility.

This suite of tools was used to complete the examples found throughout this book. This appendix shifts from an emphasis on risk analysis to how to get started using three of the programs contained in the DecisionTools® Suite. These are TopRank, @RISK, and PrecisionTree. Many of the files used in the creation of this book, as well as additional exercises to help you master some of the techniques described, can be found at <http://www.palisade.com/bookdownloads/taylorfrancis.asp#pra>, a companion site for this book graciously provided by the Palisade Corporation.

The goal of this appendix is to help you learn enough to begin using these analytical tools. Once you begin, you can explore additional capabilities of the software through tutorials, the users' manuals, online help, and users' forums.

The appendix begins with a spreadsheet cost-estimate model that will be familiar to you from the text. The model presented initially is a deterministic model. TopRank is introduced first. You might use it in the early stages of a risk assessment to find out which of your model inputs have the greatest impact on the model output. Next, you learn the basic features of @RISK, Palisade's Monte Carlo process software. Last, you learn the basic event tree structuring capabilities of PrecisionTree.

* Palisade Corporation is the maker of the market-leading risk and decision analysis software @RISK and the DecisionTools® Suite. Virtually all Palisade software adds in to Microsoft® Excel, ensuring flexibility, ease of use, and broad appeal across a wide range of industry sectors. Its flagship product, @RISK, debuted in 1987 and performs risk analysis using Monte Carlo simulation. With an estimated 150,000 users, Palisade software can be found in more than 100 countries and has been translated into five languages. Headquartered in Ithaca, New York, Palisade also maintains offices in London, England; Sydney, Australia; and Rio de Janeiro, Brazil.

A.2 TOPRANK

This section focuses on helping you to begin to make simple use of the TopRank software. It does not address the nature of the computations or the meaning of the outputs. In this section you will learn how to:

1. Identify an output in your model
2. Change the analysis settings
3. Have TopRank identify the inputs to vary
4. Run a what-if analysis
5. Generate results

Figure A.1 presents the spreadsheet cost model prepared in Microsoft® Excel. Total project cost, shown in the bottom right cell, is the output of interest in this model. It is computed by multiplying quantities by unit costs (row-wise) and then summing the amounts. Do not be concerned if you are unfamiliar with the nature of the items included in the cost estimate.

TopRank is an Excel add-in that provides a new tab and the features shown in Figure A.2. The sections that follow make reference to these icon functions.

Description	Quantity	Unit	Unit Price	Amount
Relocations				
Lower 20 pipeline, 653+00	425	LF	\$ 730	\$ 310,250
Remove 8" pipeline, 678+00	1,000	LF	\$ 50	\$ 50,000
Total -- Relocations				\$ 360,250
Navigation, Ports and Harbors				
Mobe and Demobe	1	LS	\$ 500,000	\$ 500,000
Pipeline Dredging, Reach 1	691,328	CY	\$ 2.78	\$ 1,921,892
Pipeline Dredging, Reach 2	1,022,769	CY	\$ 2.60	\$ 2,659,199
Pipeline Dredging, Reach 3A	1,182,813	CY	\$ 3.16	\$ 3,737,689
Pipeline Dredging, Reach 3B	736,713	CY	\$ 2.76	\$ 2,033,328
Scour Pad, Reach 1	17,550	SY	\$ 25.69	\$ 450,860
Geotubes, 30', Reach 1	1,400	LF	\$ 188.52	\$ 263,928
Geotubes, 45', Reach 1	4,912	LF	\$ 222.18	\$ 1,091,348
Scour Pad, Reach 3	38,750	SY	\$ 25.69	\$ 995,488
Geotubes, 45', Reach 3	13,940	LF	\$ 222.18	\$ 3,097,189
Total -- Navigation, Ports and Harbors				\$ 16,750,921
Subtotal				\$ 17,111,171
Engineering and Design	8	%		\$ 1,368,894
Construction Management	6	%		\$ 1,026,670
TOTAL PROJECT COST				\$ 19,506,734

FIGURE A.1 Deterministic Microsoft Excel spreadsheet cost model.



FIGURE A.2 TopRank icons.

Geotubes, 30', Reach 1	1,400	LF	\$ 188,52	\$ 263,928
Geotubes, 45', Reach 1	4,912	LF		
Scour Pad, Reach 3	38,750	SY		
Geotubes, 45', Reach 3	13,940	LF		
Total -- Navigation, Ports and Harbors Subtotal				
Engineering and Design	8 %		\$ 1,368,194	
Construction Management	6 %		\$ 1,026,670	
TOTAL PROJECT COST			\$ 19,506,734	

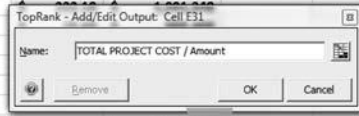


FIGURE A.3 Add output window.

A.2.1 IDENTIFY MODEL OUTPUT

The output of interest in this model is the total project cost estimate. You must identify each output of interest by placing the cursor in the output cell and selecting the “Add Output” icon (third from left in Figure A.2). When you do, the window shown in Figure A.3 will open. It shows a default name when it opens. The default is chosen by identifying the nearest text to the left of the cell and the nearest text above the cell. You may accept the default or edit it to include the output name you prefer. Repeat this process for every output in the model if you have more than one.

A.2.2 CHANGE THE ANALYSIS SETTINGS

You may want to change the analysis settings before you select the input variables. This is done in the Analysis Cluster (second from the left on the TopRank tab) using the “Analysis Settings” option seen in Figures A.2. This will open the window seen in Figure A.4.

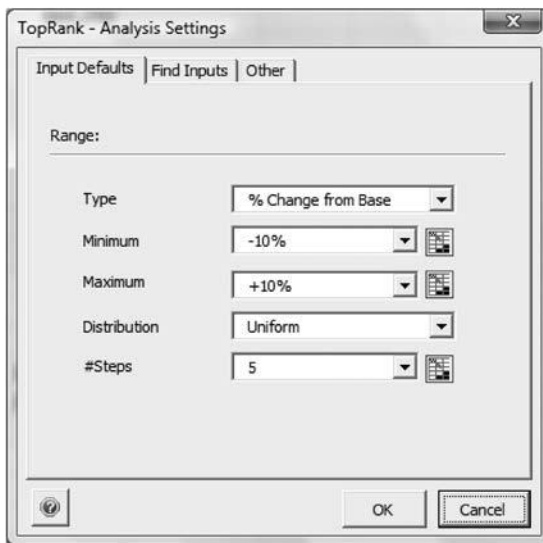


FIGURE A.4 Analysis settings window of TopRank.

You can vary the inputs by a fixed percentage or a fixed amount. The point estimate in the original model is called the base, and all changes are relative to it. You are able to vary the base value up or down symmetrically or asymmetrically. Unless you know why you want a different distribution, use a uniform distribution. You can control the number of intermediate values between the minimum and maximum by varying the number of steps. For this example, the default values are sufficient, $\pm 10\%$, a uniform distribution, and five steps. Just know that you can explore wider or narrower ranges and with different shapes over those ranges. In general, you would define the range to reflect your relative uncertainty. If you can estimate a value within $\pm 10\%$, that is what you use. If you are more uncertain, you might choose $\pm 30\%$ or whatever best bounds your uncertainty.

A.2.3 IDENTIFY THE INPUTS TO VARY

The purpose of your what-if analysis is to identify those inputs that have the greatest potential impact on your output based on the structure of your model. You have two options for identifying inputs. The first is to identify each input as you did the outputs, choosing the “Add Input” icon instead of the add output icon. Alternatively, you can have TopRank automatically identify the inputs to vary based on the structure of your model.

Select the “AutoVary Function” and the “Add AutoVary Functions” as seen in [Figure A.5](#). You will be asked if it is okay to replace the current values in the model (see [Figure A.6](#)), so be sure to keep an original copy of any model you might use with TopRank.

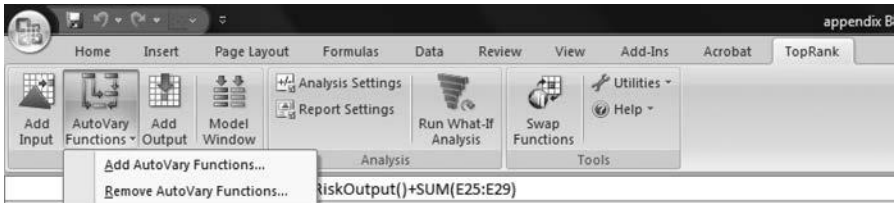


FIGURE A.5 Auto Vary Functions options in TopRank.

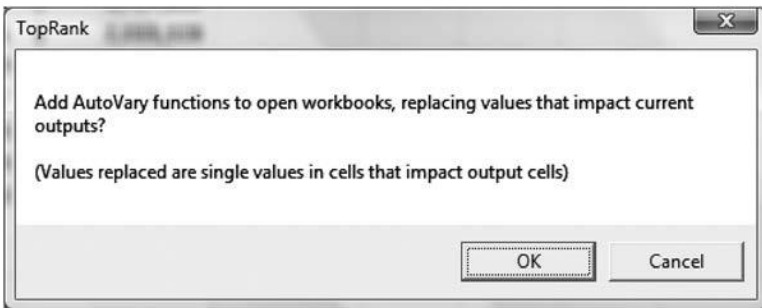


FIGURE A.6 Permission to replace original values with vary functions.

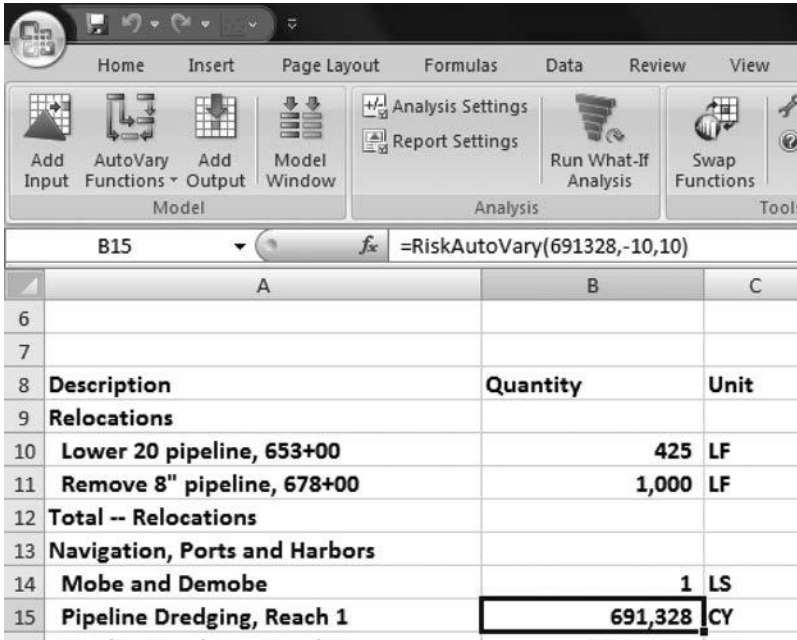


FIGURE A.7 Model cell showing auto vary function in formula window.

Once you select OK, your model will be modified as shown in the formula line of Figure A.7. The cursor is in cell B15, and the formula line shows that although the base value of 691,328 is shown, it has been replaced by a TopRank formula indicating that this value will be varied by ±10%. Each constant in the spreadsheet that is used to calculate the output (total project cost) is replaced by such a formula. Notice that values displayed in the Quantity column have not been modified. Your spreadsheet is now ready for what-if analysis.

A.2.4 RUN WHAT-IF ANALYSIS AND GENERATE RESULTS

Before running your analysis, select the “Reports Settings” icon, found just below the “Analysis Settings” in the Analysis cluster. This allows you to identify the types of graphs you want, as well as the outputs (see tab) and inputs (see tab) for which you’d like to see results. Select the desired options before you run your what-if analysis. Figure A.8 shows this window.

Notice the “Run What-If Analysis” icon in the Analysis cluster of Figure A.7. Select it to run the analysis. Before the analysis runs, you will see a summary of the analysis parameters as shown in Figure A.9. Notice the number of outputs and inputs as well as the variation in your inputs and several other details.

Once you select the “Run” option on Figure A.7, TopRank will write the results to a new workbook. The number of pages in this workbook will vary according to the report settings you selected. This new workbook will contain some of the graphics

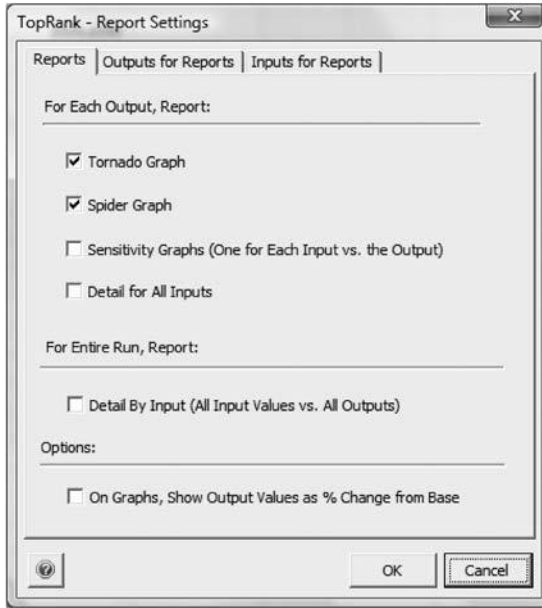


FIGURE A.8 TopRank report settings options.

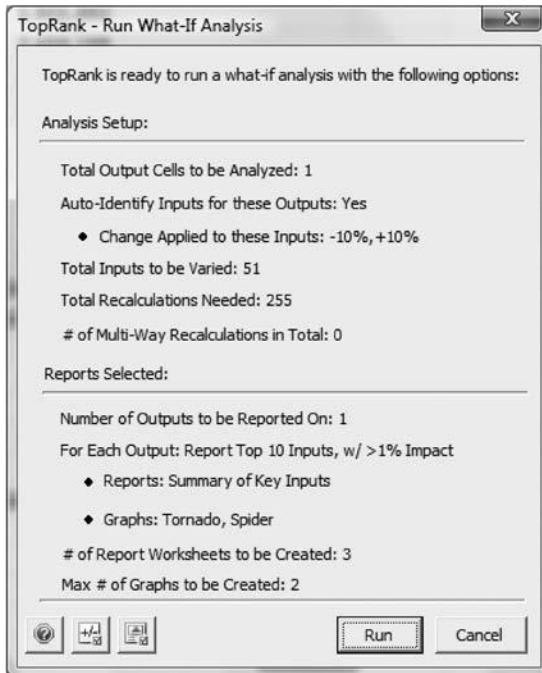


FIGURE A.9 TopRank what-if options.

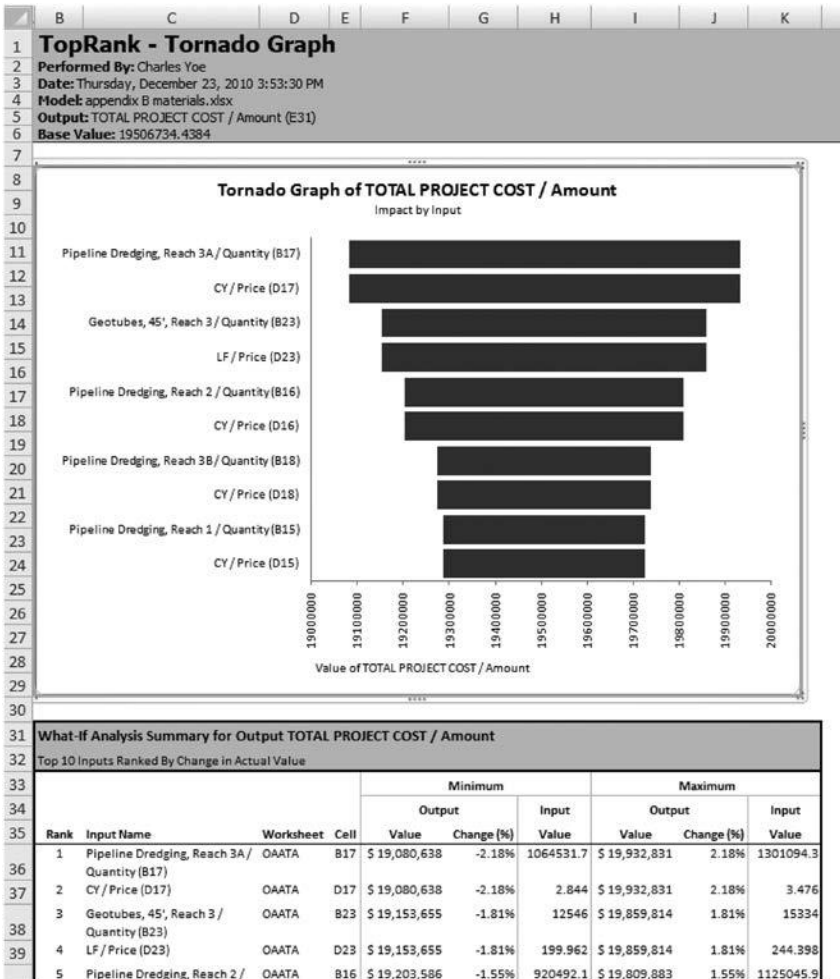


FIGURE A.10 Sample of TopRank tornado graph output.

and outputs discussed in Chapter 17. Figure A.10 shows a partial sample of the output generated using the default settings described in this chapter. The results can be used to help you decide which of your uncertain inputs ought to be entered as a probability distribution.

When you are done you can select “AutoVary Functions” and then select “Remove AutoVary Functions,” and your model will be restored to its original condition. That is all you need to know to begin to use TopRank. Be sure to explore its other capabilities, especially the multiway what-if analysis that enables you to examine the impacts of combinations of changes in two or more inputs on model outputs. The files used in this section are available for your use at the Palisade link <http://www.palisade.com/bookdownloads/yoe/principles/>.

A.3 @RISK

@RISK is the Excel add-in that enables you to use the Monte Carlo process in a simulation. With @RISK you can replace any point estimate in your model with a probability distribution. In this section you will learn how to:

1. Enter a probability distribution into your model
2. Modify that distribution
3. Identify an output in your model
4. Set up and run a simulation
5. Modify a graph
6. Generate reports

A.3.1 ENTER A PROBABILITY DISTRIBUTION (AND MODIFY IT)

We will use the same model shown in [Figure A.1](#), and for simplicity we will work with the triangular distribution. We begin with a look at the @RISK icons in [Figure A.11](#).

There are four groupings on the @RISK tab: Model, Simulation, Results, and Tools. The model functions are used primarily to set up your model prior to running the simulation, so we will begin there.

Placing your cursor in a cell where you want to insert a distribution, B11 in this case, select the “Define Distributions” icon (first on the far left). You will see something like [Figure A.12](#). Note that the “Define Distributions” window has several tabs. [Figure A.12](#) has the “All” (show all distributions) tab selected. This is the easiest way to select a distribution when you are starting. Simply scroll up or down to find the distribution you need. Note that there is a grayed-out input name and a cell formula at the top of this window when you are working with an existing model. If you begin from scratch in a new spreadsheet, these entries will be blank.

Select the triangular distribution (Triang). Each distribution is represented by a typical shape for that family of distributions. Once selected, you will see something like [Figure A.13](#). Whenever you select a distribution, @RISK will display an example of that distribution in the window that pops up. This particular distribution and the parameters entered (382.5, 425, and 467.5 in this instance) are absolutely meaningless. @RISK uses any preexisting value in the cell as a default base for constructing a distribution to demonstrate what the distribution you chose looks like. Even when you enter a distribution into a blank cell, there are default values provided. These are default parameters chosen by @RISK; do not use them. Replace them with the values you have chosen. You must specify the parameters for any distribution you use.



FIGURE A.11 @RISK icons.

The screenshot displays the @RISK software interface. The background is a spreadsheet with the following data:

	A	B	C	D
B11				
6				
7				
8	Description	Quantity	Unit	Price
9				
10	Relocations			
11	Lower 20 pipeline, 653+00	425	LF	\$
12	Remove 8' pipeline, 678+00	1,000	LF	\$
13	Total -- Relocations			
14	Fish and Wildlife Facilities (Mitigation)			
15	Oyster Reef Creation	0	ACR	\$-
16	Total -- Fish and Wildlife Facilities (Mitigation)			
17	Navigation, Ports and Harbors			
18	Mobe and Demobe	1	LS	\$ 500.0
19	Pipeline Dredging, Reach 1	691,328	CY	\$ 2.
20	Pipeline Dredging, Reach 2	1,022,769	CY	\$ 2.
21	Pipeline Dredging, Reach 3A	1,182,813	CY	\$ 3.
22	Pipeline Dredging, Reach 3B	736,713	CY	\$ 2.
23	Scour Pad, Reach 1	17,550	SY	\$ 25.
24	Geotubes, 30', Reach 1	1,400	LF	\$ 188.
25	Geotubes, 45', Reach 1	4,912	LF	\$ 222.
26	Scour Pad, Reach 3	38,750	SY	\$ 25.
27	Geotubes, 45', Reach 3	13,940	LF	\$ 222.
28	Total -- Navigation, Ports and Harbors			
29	Subtotal			\$ 17,111,171
30				\$ 1,368,894
31	Engineering and Design	8	%	
32				\$ 1,026,670
33	Construction Management	6	%	
34				\$ 19,506,734
35	TOTAL PROJECT COST			

The 'Define Distribution' dialog box is open, showing a grid of distribution icons. The 'BurrIII' distribution is selected. The dialog includes tabs for 'Common', 'Favorites', 'Discrete', 'Continuous', 'ALT Parameters', 'Special', and '@RISK Library All'. The 'Name' field contains 'Lower 20 pipeline, 653+00 / Quantity' and the 'Cell Formula' is '=425'.

FIGURE A.12 @RISK's available distributions accessed through the define distribution icon.

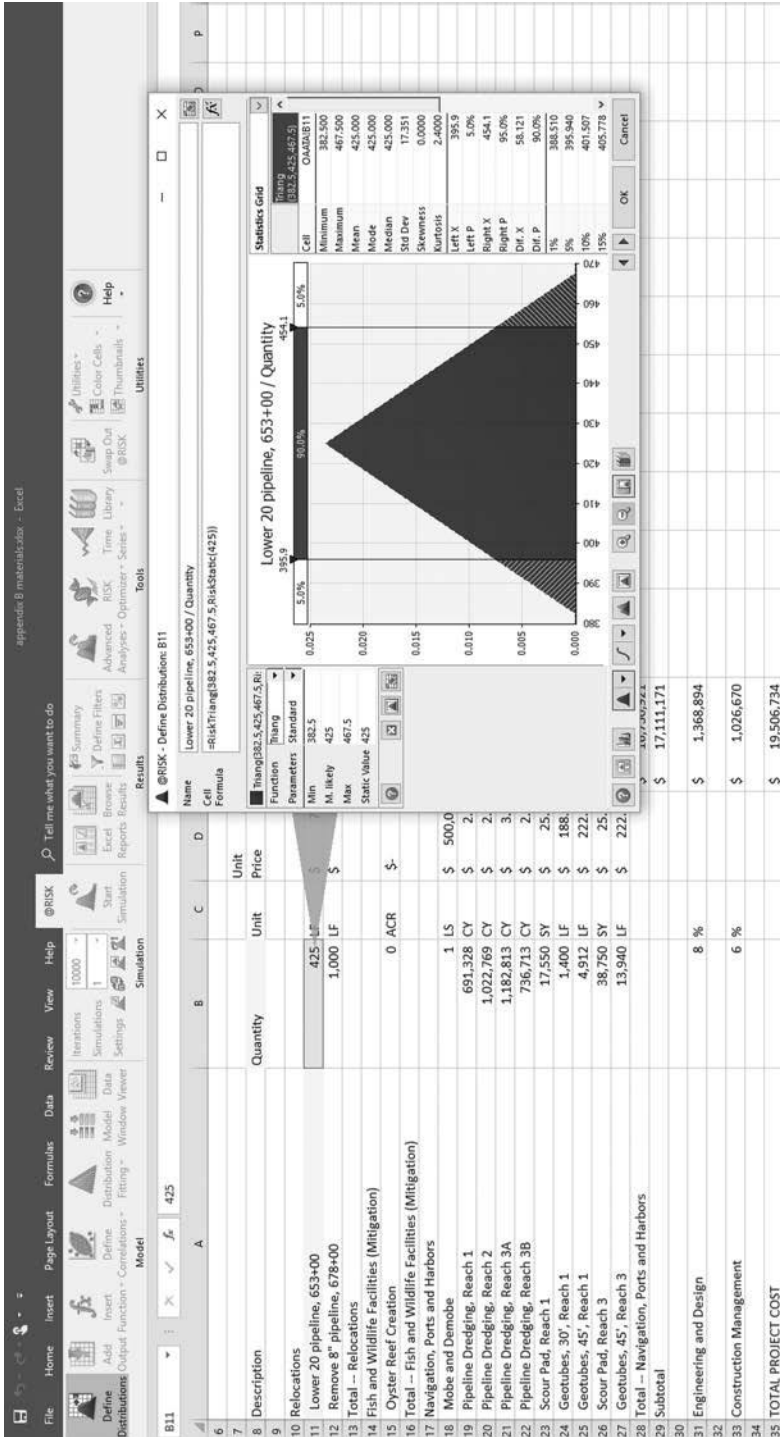


FIGURE A.13 Default view of a triangular distribution with a preexisting cell entry.

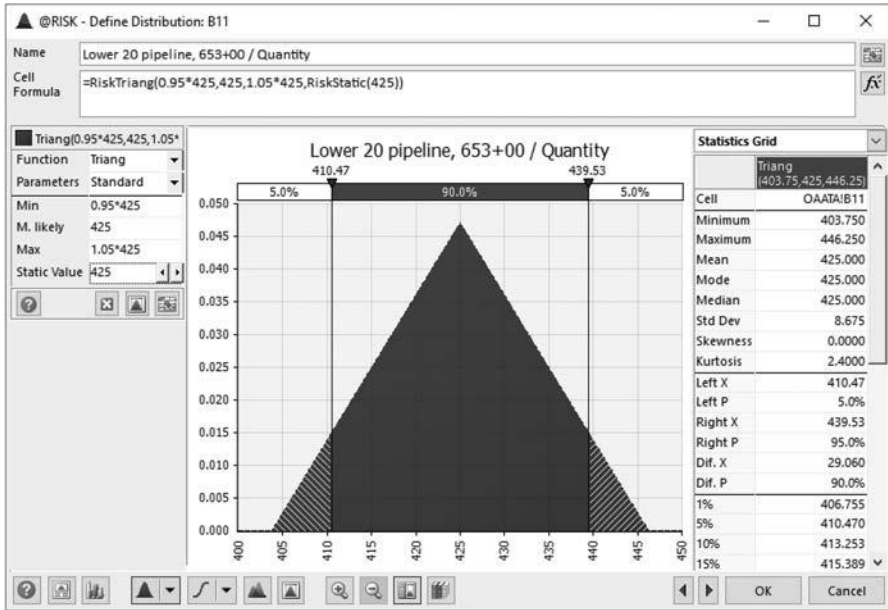


FIGURE A.14 The triangle distribution in @RISK.

Figure A.14 shows a close-up of a typical distribution window. Note the name and cell formula at the top. These can be edited directly in this window. Changing the name of the distribution does not change your spreadsheet text. Once you learn the @RISK syntax, you can type distribution formulas, like that in the cell formula box, directly into a spreadsheet cell. The bulk of the window is taken up by the distribution graph. To the left of it you will find the distribution parameters. The parameters will vary with the distribution, but they are always found here. The “Static Value” is the number displayed in the spreadsheet cell when the Monte Carlo process recalculation is turned off.

First, note that this is the standard format for entering parameters, as numerical values of the variable. In this example the minimum is considered to be 5% less than the point estimate, and the maximum is 5% more. Simple formulas (without equal signs) are typed into the cell to define the distribution. To the right of the graph is a statistics grid.

Look at the distribution parameters area on the left again. If you click on the cell that says “Standard” just to the right of the word “parameters,” the window in Figure A.15 will appear. This is a bit advanced for a simple getting-started introduction, but it is a useful feature that allows you to truncate your distributions or, for example, to define your distribution using percentile values (Alternate Parameters). Remember where this is and you can grow into it later. There are many other icons on the distribution window, but for now, select “Okay” and you have entered a distribution. Repeat this process for every input you will represent with a probability distribution.

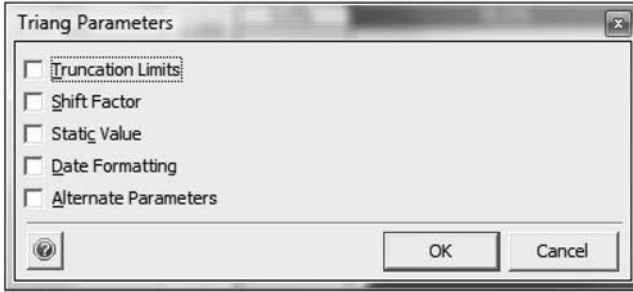


FIGURE A.15 Distribution parameter modification options in @RISK.

A.3.2 IDENTIFY AN OUTPUT

You identify outputs in exactly the same way as you did for TopRank.

A.3.3 SET UP AND RUN A SIMULATION

After you have entered all the distributions you intend to use in your simulation and identified all your output cells (remember that any intermediate calculations you want to monitor must be identified as outputs), it is time to move to the simulations grouping. Hit F9. Do the numbers in your model change? If not, the Monte Carlo process recalculation is not turned on (it need not be turned on to run a simulation). Find the icon with a pair of dice under the word “Simulations” in the Simulations cluster. It is the “Random/Standard Static F9 Recalc” icon, and it enables or disables your ability to iterate your model by striking the F9 key.

For a fast start, put your cursor in an output cell and set the number of iterations to the desired number (say 1,000 for now) and then select the “Start Simulation” icon. The simulation will begin and you can monitor its progress as seen in [Figure A.16](#). If you put the cursor in an output cell you will also see the output distribution forming.

You have now run a simulation using @RISK. [Figure A.17](#) shows a sample output. It is that simple. Now, we will double back and explore some more features.

A.3.4 MODIFYING A GRAPH

Display your output graph. If it has closed, place your cursor in the output cell and select “Browse Results” from the results cluster. Right click inside the graph frame and select “Graph Options.” You will see the window shown in [Figure A.18](#).

The Distribution tab enables you to alter the graph format. Choose a cumulative ascending distribution. Note that when you use the automatic, probability density, or relative frequency options, you can vary the number of bins used to define your graph. As noted in the text, this can have a strong influence on the appearance of your data at times.

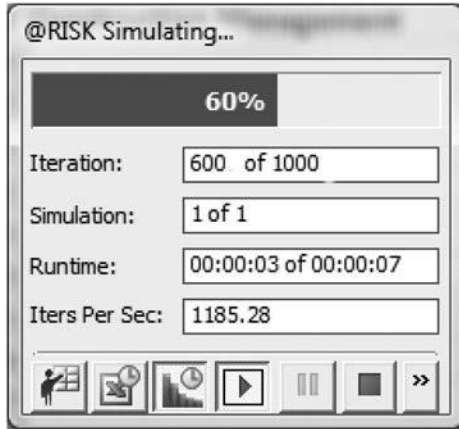


FIGURE A.16 Simulation progress window in @RISK.

The Title tab enables you to enter a title and control the font style and color. The X-Axis and Y-Axis tabs enable you to enter labels on the axes and to control their range as well. You have the option of eliminating grid lines, scale factors, and tick labels if you desire. With the Curves tab, you can alter the style, fill, and color of each distribution in your graphic. You can eliminate the legend or modify what appears in it with the Legend tab. Delimiters can be removed by the Delimiters tab, and new markers can be added with the Markers tab. Figure A.19 shows a transformation of the information shown in Figure A.17 using the graph options tabs with markers added.

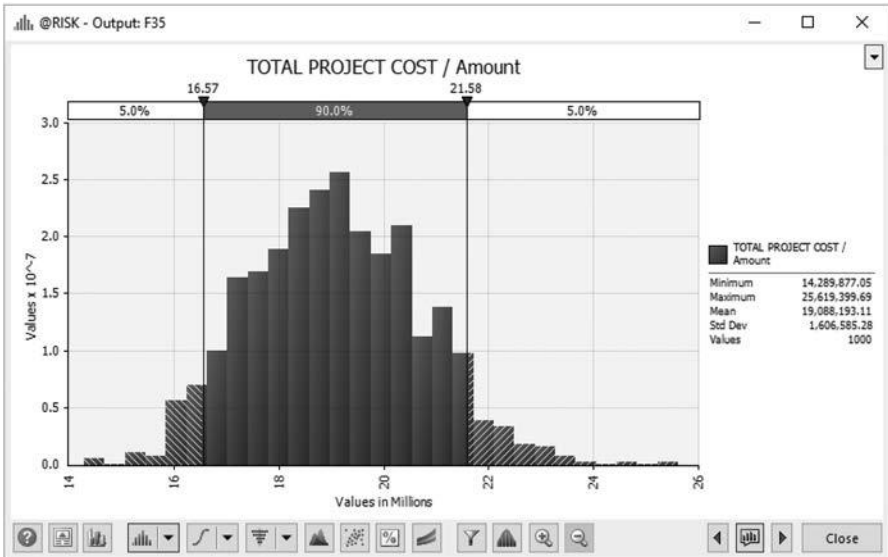


FIGURE A.17 Sample model output distribution in @RISK.

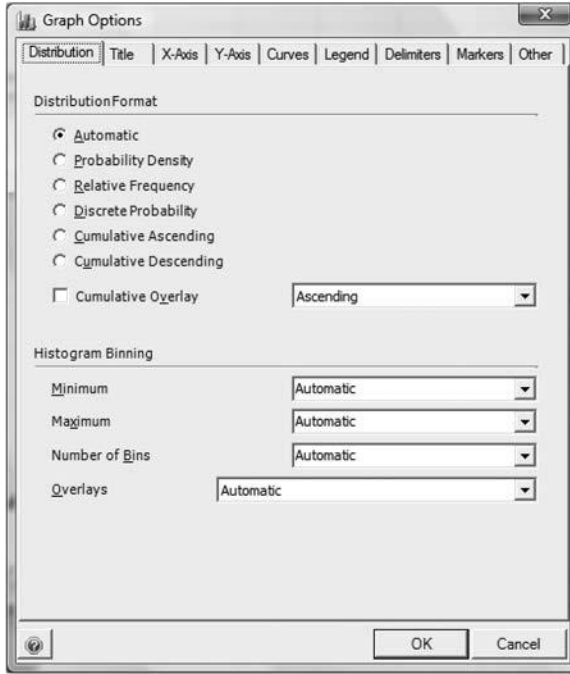


FIGURE A.18 Graph options in @RISK.

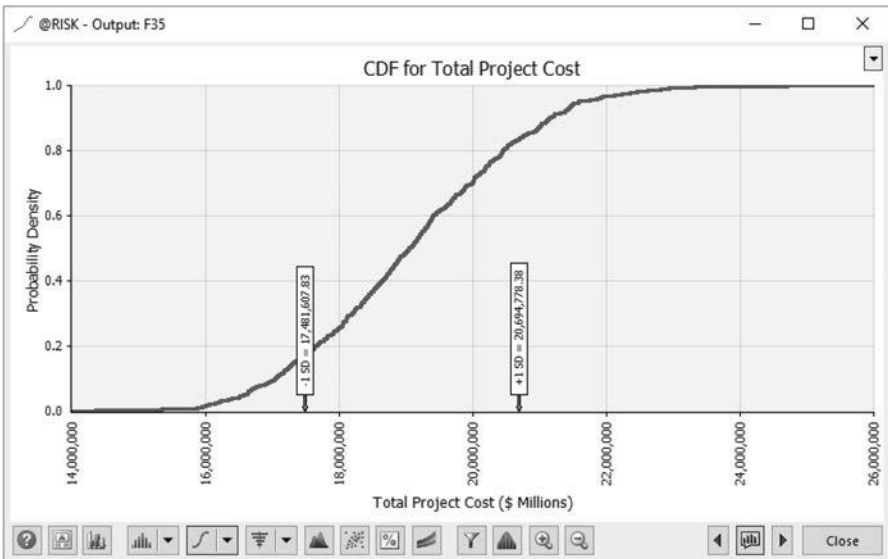


FIGURE A.19 Transformation of the data in Figure A.17.

A.3.5 MORE RESULTS

The small icons on the right side of the results cluster will make the results of the simulations available to you. The first one, “Simulation Detailed Statistics,” provides descriptive statistics and percentiles in 5% increments for every output and input in your model. You may also query your simulation data to learn specific percentile values (e.g., the 99.5 percentile) or to learn the percentile of any given value (\$19,000,000). This feature enables you to describe the CDF for any variable in your simulation. The “Simulation Data” icon makes every iteration value for every input and output available.

A.3.6 SIMULATION SETTINGS

Now let us look back in the simulations cluster at the small icons there. The first one, “Simulation Settings,” is important to understand. Four of its tabs are illustrated in Figure A.20. The first of these allows you to set the number of iterations and simulations you will run and to turn the Monte Carlo process on or off. These features are also directly available in the simulation cluster.

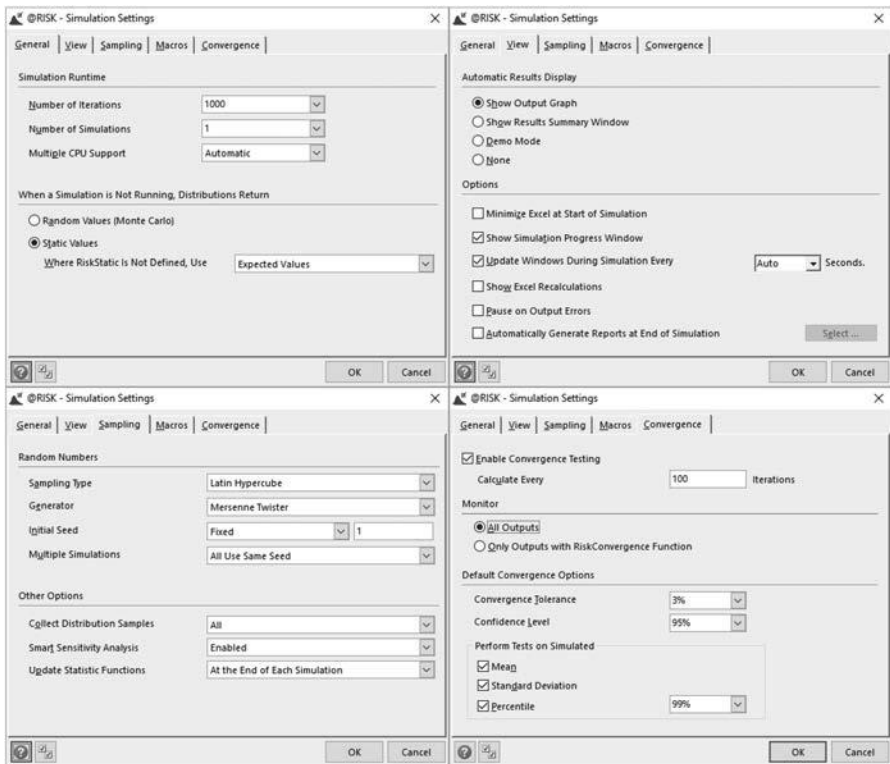


FIGURE A.20 Four of the simulation setting icon tabs in @RISK.

The View tab lets you control what you see during a simulation. The “Pause on Output Errors” option can be especially helpful when you are verifying your model. The “Random Numbers” options on the Sampling tab are useful to know. Generally, you will leave the sampling type on Latin Hypercube; the alternative is Monte Carlo, and these two sampling techniques are discussed in [Chapter 15](#).

You have a choice of many different random number generators. Most users rely on the default generator shown in the figure. Of special interest is the initial seed option. You can choose this seed randomly or use a fixed seed. There may be times when you are running the exact same model with relatively subtle changes in selected inputs that reflect the effect of a risk management option. In these instances, it would be useful to compare without and with RMO conditions, all other things being equal. Choosing a fixed seed ensures that your model generates the same random values for unchanged input distributions. Thus, any changes in outputs are attributable to the RMO and not to random differences in values selected for input cells. If you use a fixed seed, you have the option of entering the seed. A “1” is shown in [Figure A.20](#). Choose something simple and easy to remember. Collecting data from your input distributions can slow your simulation down when you have a lot of inputs and a large number of iterations. You have the option (Monitor) of collecting all, some, or none of your input distributions.

The Convergence tab gives you an alternative to running your model for a fixed number of iterations. With large and slow models, it may be helpful to just run your model until a few parameters of special interest have stabilized. The current example has but one output. Imagine, for the moment that it is but one of several model outputs and we want to stop the simulation when its mean and standard deviation converge. [Figure A.21](#) shows how to identify these outputs.

Place your cursor in the cell of the desired output. Select the “Add Output” icon. When the familiar window opens with the output name, click on the small function icon (f_x) and the output properties box opens. Choose the Convergence tab and check the box to define custom convergence settings. Here you can identify convergence as an absolute amount or a percentage. You can also identify the parameters from the output distribution to use in your convergence monitoring.

[Figure A.21](#) says, once the identified statistics (mean and standard deviation) stop changing by more than 3% (with a 90% confidence interval) every 100 iterations (you can change this option as well), the simulation will stop. This can save time with some models while providing you with the level of precision you desire. Less commonly, you may be working with a model where you cannot be sure that convergence is reached with, say, 10,000 iterations. In such a case you may want to use convergence rather than a fixed number of iterations.

There are many more useful features of @RISK. Correlations, distribution fitting, and other sensitivity analyses are features you can grow into once you begin to use the software. Exercises explaining these more advanced features are found at the Palisade Web site, <http://www.palisade.com/bookdownloads/taylorfrancis.asp#pra> as well as all the files used in this section. Before moving on to consider PrecisionTree, note that the “Excel Reports” icon enables you to export results from and descriptions of your model to a Microsoft® Excel spreadsheet.

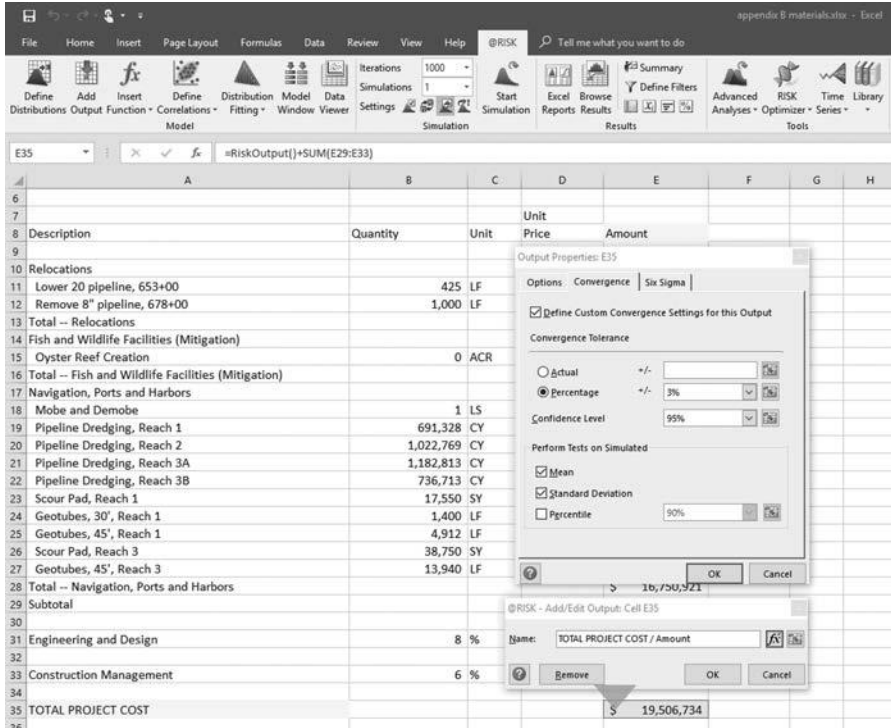


FIGURE A.21 Custom convergence settings for model outputs.

A.4 PRECISIONTREE

PrecisionTree supports risk assessment in Microsoft® Excel using decision trees, event trees, and influence diagrams. Decision trees enable you to visually map complex decision problems in an organized and sequential manner. The decision tree software can also be used, along with @RISK, to build powerful event-tree models commonly used in risk assessment as described in Chapter 16.

The description of PrecisionTree, which follows, introduces you to the use of the software for event-tree models. Overlooking the decision tree capability of this software does not do justice to the full range of features available to you with PrecisionTree. The simple event-tree example that follows does, however, expand the range of applications for this tool.

A new example is used for this discussion. Consider a risk management activity that is concerned about the likelihood of Aquatic Nuisance Species (ANS) reaching and spreading throughout a lake. The necessary sequence of events is that the ANS reach the lake from their originating waterway, that they survive in the lake, and that they find enough life requisites to establish a breeding colony. They would then have to spread from that breeding colony throughout the lake.

In this section you will learn how to:

1. Build a tree model
2. Use @RISK to change the probability inputs in the model
3. Recognize other features of PrecisionTree

A.4.1 BUILDING A SIMPLE EVENT TREE MODEL

Figure A.22 shows the icon set used by PrecisionTree. Notice that PrecisionTree enables you to build and use influence diagrams. This capability is not explored in this discussion, but a discussion of influence diagrams can be found in [Chapters 16 and 19](#). This discussion focuses on how one would use the software to build an event tree.

To begin a new tree model, place your cursor in a cell and select the “Decision Tree” icon. This will open a box that asks you to identify the cell in which you'd like to begin your model. See [Figure A.23](#). You can use any cell in your spreadsheet. If you have no clear need for another starting point, cell A1 works fine.

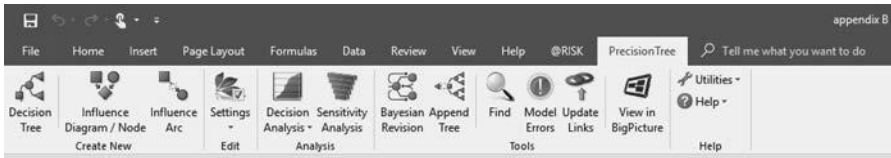


FIGURE A.22 PrecisionTree icon set.

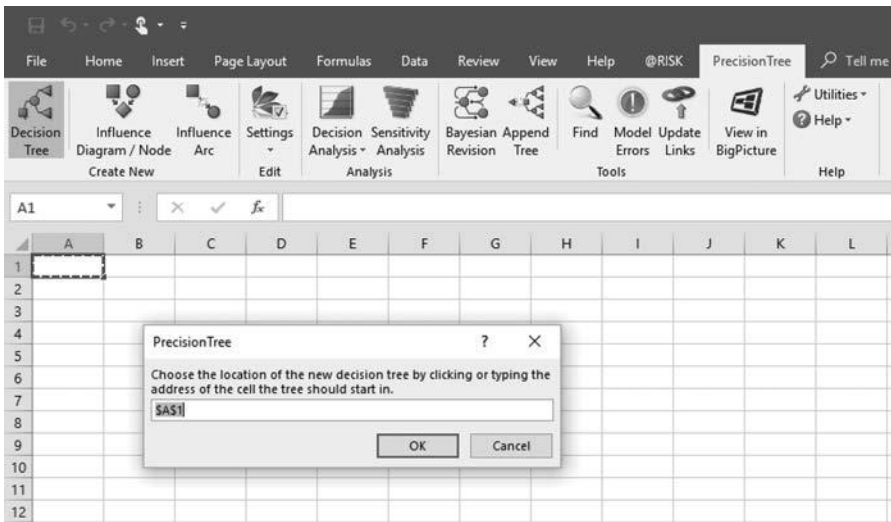


FIGURE A.23 Starting a PrecisionTree model.

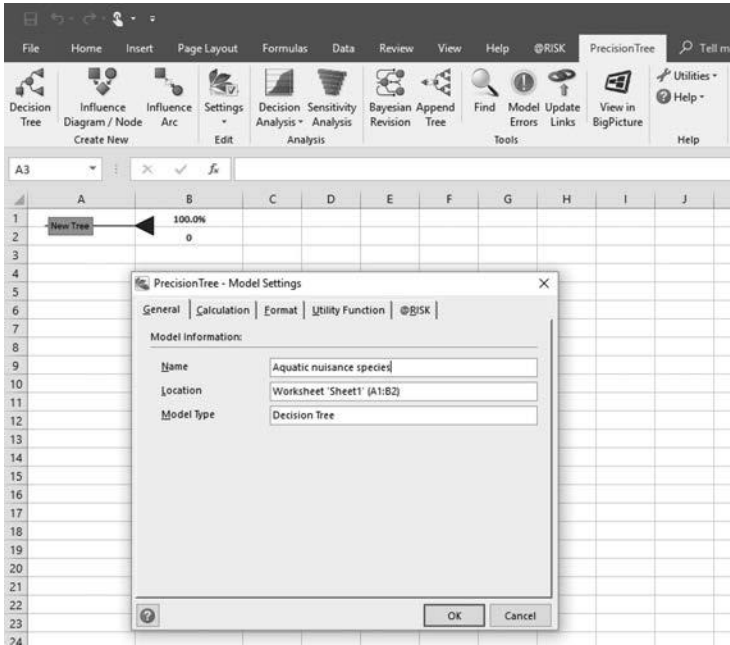


FIGURE A.24 Naming your tree model in PrecisionTree.

After you identify the starting point for your model, a new tree will appear, as seen in [Figure A.24](#). The first thing you will have to do is name your model. Simply click on the box that says “New Tree” and the window shown in [Figure A.24](#) will open. Type the name as shown and click “Okay.” Note that there are five tabs in this window. You will want to explore these tabs when you are ready to build and use decision trees. With your model named, you are ready to build your model.

Click on the triangle endpoint to begin to build your model. This is how you expand your model, by clicking on endpoints along the pathways you wish to expand. When you click on an endpoint, the “Decision Tree Node Settings” window of [Figure A.25](#) will appear. Notice there are five different kinds of nodes you can add to your model at this point. For an event tree, all nodes will be chance nodes. When the Chance node is selected, the default number of branches from the node is two. To add additional branches, select the plus sign icon on the right border of the window. Use the x icon to delete branches and the up and down arrows to rearrange the order of the branches. Two nodes will be fine for this example. Enter the name for your node and relabel the branches. Probabilities of 50% are default values. If you know the values you want to use you can enter them now. Just leave them as is for the moment. When you click on “OK,” you will see the tree expanded as shown in [Figure A.26](#).

Beneath the branch you see a 0; this is another default value. If you used other quantities in the model like dollars of damage or numbers of fish they would be

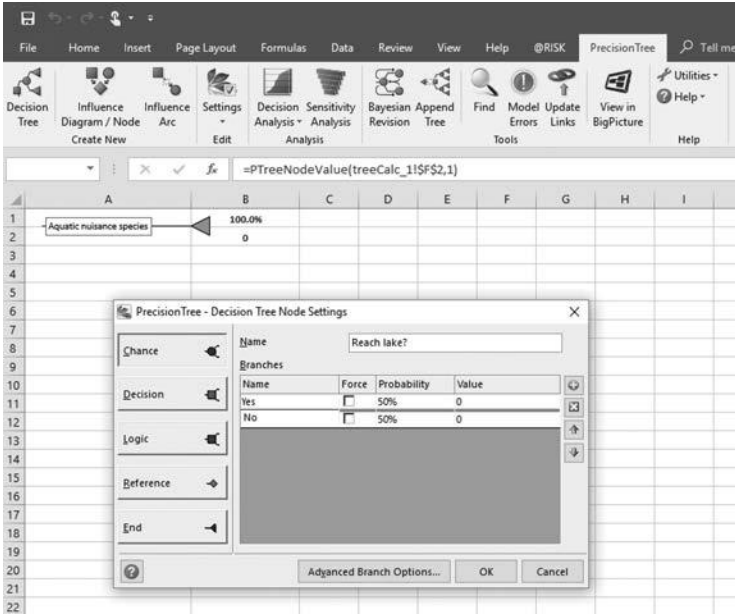


FIGURE A.25 Decision Tree Node Settings.

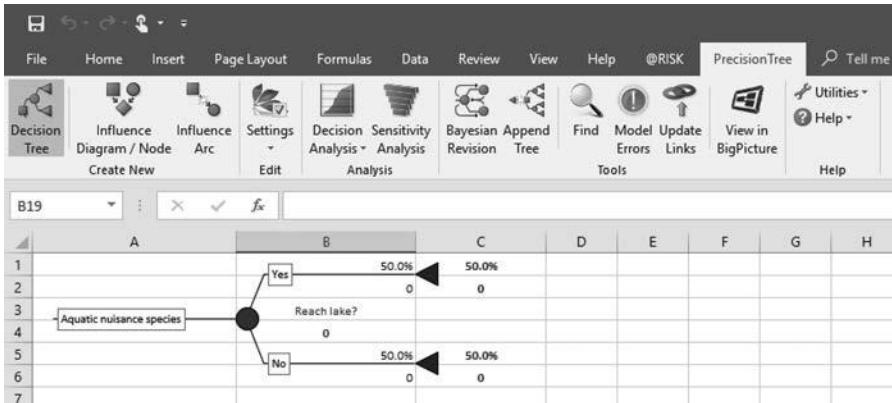


FIGURE A.26 First node with yes/no branches.

entered here. Repeat this process as often as necessary to complete your model. The completed example model is shown in Figure A.27. Each node’s name is given in the form of a question. Note that each of the branches is labeled yes or no, to answer the question. All “No” values result in endpoint nodes. “Yes” nodes continue, except for the very last one. Notice probabilities are multiplied along each pathway to calculate the probability of arriving at any one given endpoint. These probabilities

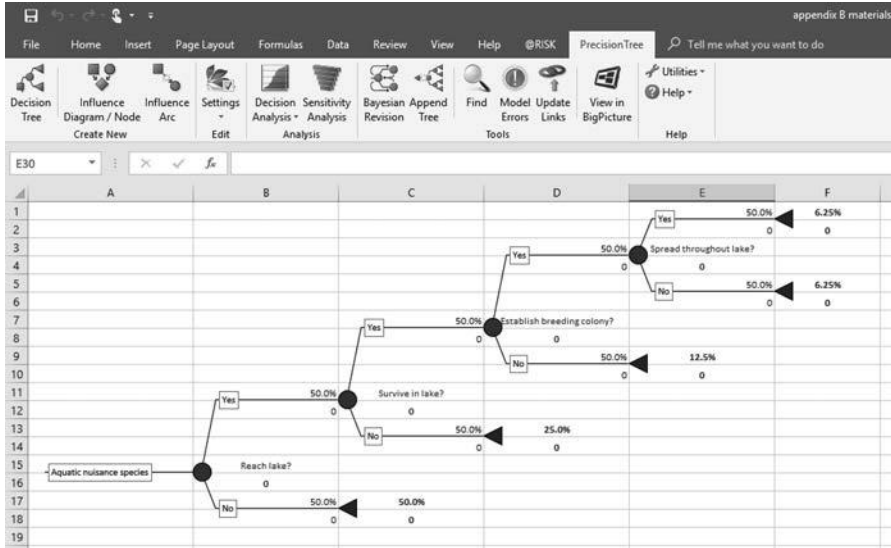


FIGURE A.27 First iteration of a built event tree.

are based on PrecisionTree’s default values, and we now need to return to the task of entering the actual values for our model.

A.4.2 USE @RISK IN MODEL

You can change the probability along a branch by entering that cell (B11) and typing in a new value. You must take care to make sure the probability values you enter obey all the relevant laws of probability. PrecisionTree’s tree structuring features can be combined with @RISK’s Monte Carlo process features to yield a very powerful tool.

Figure A.28 shows a probability value being entered as a distribution. In this instance it is a Pert distribution, where the minimum probability the ANS will actually reach the lake from their originating waterway is 0.6, the most likely probability is 0.7, and the maximum probability is estimated to be 0.85. Because the value for cell B11 will vary according to the distribution entered here, it is important to ensure that the probabilities of the yes and no branches always sum to 1. The easiest way to do this with two branches is to go into cell B17 and type $= 1 - B11$. This ensures that B17 always reflects the complement to cell B11.

If you use more than two nodes with distributions, you will want PrecisionTree to handle the normalization of probabilities along multiple branches to avoid mistakes. Figure A.29 shows you how to do this. From the PrecisionTree tab go to the Edit cluster and select “Settings” and then “Model Settings” to get to the window shown. Now choose the Calculations tab and the Chance Probabilities pulldown. Select “Automatically Normalized” this will assure that if the sum of probabilities on all your branches is not equal to one they will be rescaled to do so for all model calculations.

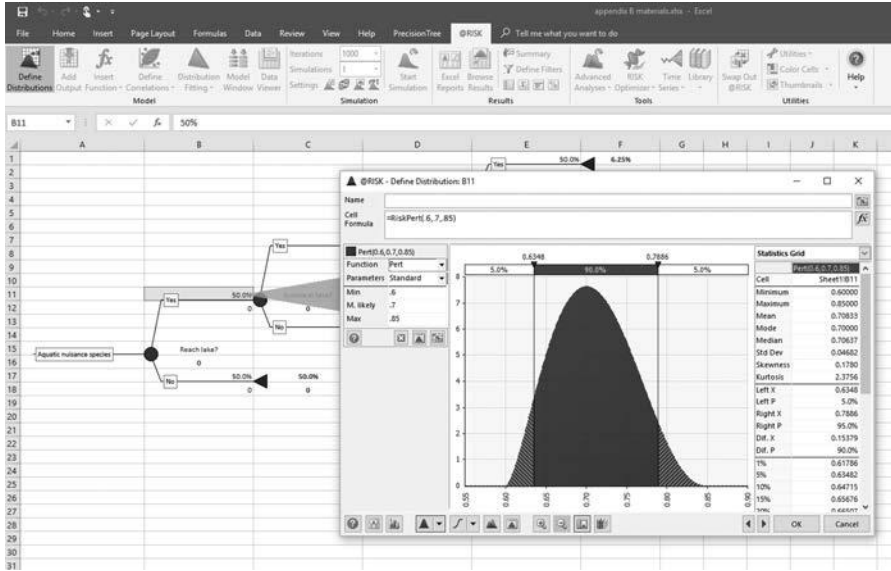


FIGURE A.28 Entering a probability distribution into an event-tree cell.

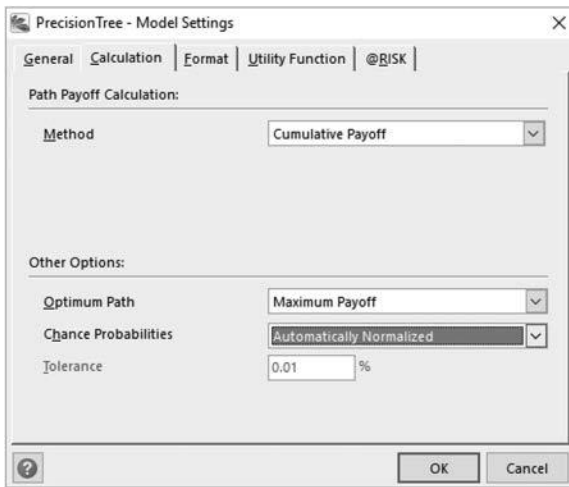


FIGURE A.29 PrecisionTree settings for normalizing probabilities in nodes with multiple branches.

A.4.3 OTHER PRECISIONTREE FEATURES

Figure A.30 shows the model again after probability distributions have been entered for each yes branch in the model with corresponding complementary probabilities in the no nodes. Cell B17 is seen in the function box as = 1 – B11. The probability

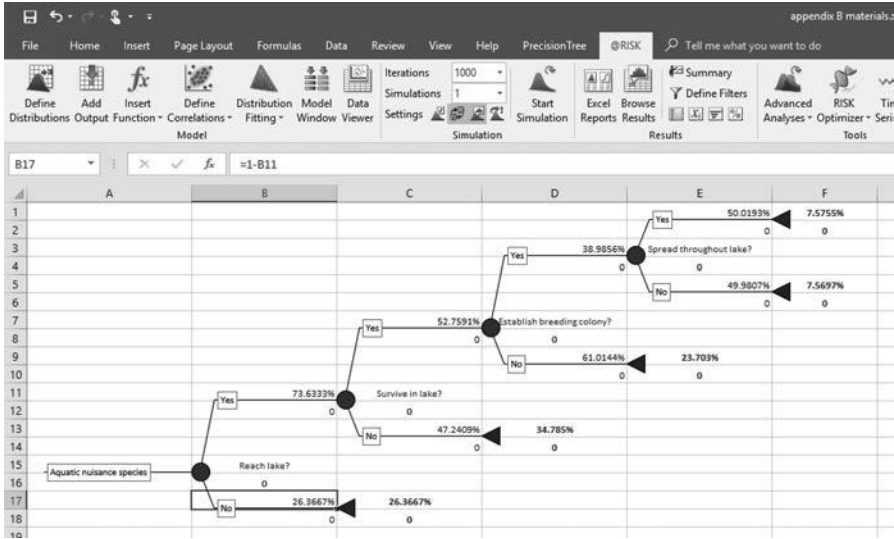


FIGURE A.30 Event tree with probability distributions on one node and complement probabilities on the other node.

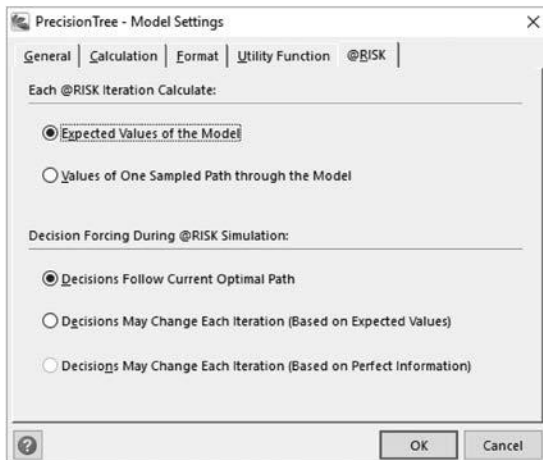


FIGURE A.31 PrecisionTree settings to obtain model output results when inputs are entered as probability distributions.

values shown reflect a single random iteration of the probability values. Cell F1 is, nominally, a cell of interest as it displays the probability that the ANS will spread throughout the lake given the preceding events. Add this cell to the outputs and a simulation can be run to characterize the uncertainty about this value. However, to get simulation results go to the Edit cluster and select “Settings” and then “Model

Settings.” Choose the @RISK tab and select the “Expected Values of the Model” radio button as seen in [Figure A.31](#).

With these brief introductions, you are ready to begin to use and to learn more about the powerful risk assessment tools available in the Palisade DecisionTools® Suite. Excellent tutorials can be found among the Palisade web resources or on YouTube.

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