population of 10,000,000 results in an expected fatality of 100 per event. Although the impact of the two scenarios might be the same on the society (same expected risk value), the total number of fatalities per event or accident is a factor in risk acceptance. Air travel may be safer than, for example, recreational boating, but 200–300 injuries per accident in the case of air travel are less acceptable to society in this case. Therefore, the size of the population at risk and the number of fatalities per event should be considered as factors in setting acceptable risk.

The dimension of likelihood that is not shown in Figure 1.1 can be illusive in nature due to two of its aspects: (1) the means of quantification and (2) the effect of time. The most common means of quantification are as follows:

- *Frequency*. It is defined as the count of an outcome of interest from a number of repeated observations of identical experiments or systems. If expressed as a fraction or percentage, it is called *relative frequency*.
- *Rate*. It is commonly defined as the count of an outcome of interest for a system occurring within a time period. The rate itself can be time dependent due to changes in the system's state, for example, due to aging. The term *frequency* is sometimes incorrectly used to mean the rate.
- *Probability*. It is defined as a measure of chance or likelihood.

The effects of time on these three quantification means are discussed, respectively, as follows:

- As for the frequency, by increasing the observation time, an estimate of the frequency tends toward a value, and for cases involving unbiased, consistent estimators, the estimate tends to the true value.
- As for the rate, by increasing the observation time, an estimate of the rate tends toward a value, and for cases involving unbiased, consistent estimators, the estimate tends to the true value.
- As for the probability, we are interested in a probability of an event in a time period. By increasing the length of this time period, this probability tends to one. As long as the event is possible, it has a sure eventual occurrence; otherwise it goes against the premise of being possible. All the example events shown in Figure 1.1 have probabilities tending to one as time extends indefinitely, even for global events including ones leading to human extinction. The length of a time period to reach a probability of one for practical purposes may vary from one event type to another, for example, nuisance events might require a few days at the most, whereas global events might require thousands to millions of years.

2.2.6.2 Risk Matrices or Heat Maps

Risk matrices, also called heat maps, are basically tools for representing and displaying risks by defining ranges for consequence and likelihood as a two-dimensional presentation of likelihood and consequences. According to this method, risk is characterized by categorizing probabilities and consequences on the two axes of a matrix. Risk matrices have been used extensively for screening of various risks. They may be used alone or as a first step in a quantitative analysis. Regardless of the approach used, risk analysis should be a dynamic process, that is, a living process where risk assessments are reexamined and adjusted. Actions or inactions in one area might affect the risk in another; therefore, continuous updating is necessary.

The likelihood metric can be constructed using the categories shown in Table 2.2, and the consequences metric can be constructed using the categories shown in Table 2.3; an example is provided in Table 2.4. The consequence categories of Table 2.2 focus on the health and environmental aspects of the consequences. The consequence categories of Table 2.4 focus on the economic impact and should be adjusted to meet the specific needs of an industry or application. An example risk matrix is shown in Figure 2.2. In the figure, each boxed area is shaded depending on a subjectively assessed risk level. Three risk levels are used here for illustration purposes: low (L), medium (M), and high (H). Other risk levels may be added using a scale of five instead of three, if necessary. These risk levels are known as *severity factors*. The high level can be considered unacceptable risk, the M level can be treated as either undesirable or acceptable with review, and the L level can be treated as acceptable without review.

TABLE 2.2

Likelihood Categories for a Risk Matrix

Category	Description	Annual Probability Range
A	Likely	≥0.1 (1 in 10)
B	Unlikely	≥0.01 (1 in 100) but <0.1
C	Very unlikely	≥0.001 (1 in 1,000) but <0.01
D	Doubtful	≥0.0001 (1 in 10,000) but <0.001
E	Highly unlikely	≥0.00001 (1 in 100,000) but <0.0001
F	Extremely unlikely	<0.00001 (1 in 100,000)

TABLE 2.3

Consequence Categories for a Risk Matrix

Category	Description	Examples
I	Catastrophic	Large number of fatalities and/or major long-term environmental impact
II	Major	Fatalities and/or major short-term environmental impact
III	Serious	Serious injuries and/or significant environmental impact
IV	Significant	Minor injuries and/or short-term environmental impact
V	Minor	First aid injuries only and/or minimal environmental impact
VI	None	No significant consequence

TABLE 2.4

Example Consequence Categories for a Risk Matrix in Monetary Amounts (US$)

Category	Description	Cost (US$)
I	Catastrophic loss	≥10,000,000,000
II	Major loss	≥1,000,000,000 but <10,000,000,000
III	Serious loss	≥100,000,000 but <1,000,000,000
IV	Significant loss	≥10,000,000 but <100,000,000
V	Minor loss	≥1,000,000 but <10,000,000
VI	Insignificant loss	<1,000,000

Probability category	A	L	M	M	H	H	H
	B	L	L	M	M	H	H
	C	L	L	L	M	M	H
	D	L	L	L	L	M	M
	E	L	L	L	L	L	M
	F	L	L	L	L	L	L
		VI	V	IV	III	II	I
	Consequence category						

FIGURE 2.2
Example risk matrix or heat map.

TABLE 2.5
Expanded Likelihood Categories for a Risk Matrix

Category	Description	Annual Probability Range
AA	Very likely	≥0.8
A	Likely	≥0.1 (1 in 10) but <0.8
B	Unlikely	≥0.01 (1 in 100) but <0.1
C	Very unlikely	≥0.001 (1 in 1,000) but <0.01
D	Highly unlikely	≥0.0001 (1 in 10,000) but <0.001
E	Very highly unlikely	≥0.00001 (1 in 100,000) but <0.0001
F	Extremely unlikely	<0.00001 (<1 in 100,000)

TABLE 2.6
Example Consequence Categories for a Risk Matrix in Monetary Amounts (US$)

Category	Description	Cost (US$)
I	Catastrophic loss	≥10,000,000,000
II	Major loss	≥1,000,000,000 but <10,000,000,000
III	Serious loss	≥100,000,000 but <1,000,000,000
IV	Significant loss	≥10,000,000 but <100,000,000
V	Minor loss	≥1,000,000 but <10,000,000
VI	Insignificant loss	<1,000,000
I+	Insignificant gain	<1,000,000
II+	Significant gain	≥1,000,000 but <10,000,000
III+	Major gain	≥10,000,000

The risk matrix presented so far does not account for potential gains due to nonoccurrence of an adverse event or the occurrence of a favorable event. As an example, the likelihood and monetary categories can be expanded, as shown in Tables 2.5 and 2.6, respectively, to permit the presentation of potential gain. The risk matrix can then be expanded as shown in Figure 2.2. Various events and scenarios can be assessed and allocated to various categories in the figure depending on their impact on the system as far as producing adverse consequences or favorable gains. The potential gains as provided in Figure 2.3 are grouped into illustrative three levels: low expected gain (L+), medium expected gain (M+),

H+	H+	M+	AA						
H+	M+	L+	A	L	M	M	H	H	H
M+	L+	L+	B	L	L	M	M	H	H
			C	L	L	L	M	M	H
			D	L	L	L	L	M	M
			E	L	L	L	L	L	M
			F	L	L	L	L	L	L
III+	II+	I+	Probability categories	VI	V	IV	III	II	I
Gain categories				Loss categories					

FIGURE 2.3
Example risk matrix with potential gains.

and high expected gain (H+). Scenarios that could lead to high expected gain should be targeted by project managers for facilitation and enhancement.

2.2.6.3 Risk Quantified Using Loss or Impact Probability Functions

To quantify risk, we must accordingly assess its defining components and measure the chance, its negativity, and potential rewards or benefits. Risk is commonly approximated by a point estimate as the expected value resulting from the multiplication of the conditional probability of the event occurring by the consequence of the event given that it has occurred as follows:

$$\text{Risk} = \text{likelihood} \times \text{impact} \tag{2.4}$$

The use of the expected value leads to a loss in information in terms of associated dispersion or variability. In Equation 2.4, the measurement scales, as bases for quantifying likelihood, impact, and risk, are as follows: likelihood is measured on an event rate scale in units of count of events per time period of interest, for example, events per year; impact is measured on a loss scale, such as monetary units or fatalities or any other units suitable for analysis or multiple units per event, for example, dollars per event; and risk is the product of (event per unit time) × (loss units per event) producing loss units per unit time. The likelihood in Equation 2.4 can also be expressed as a probability. Equation 2.4 presents risk as an expected value of loss per unit time or an average loss.

The product in Equation 2.4 is sometimes interpreted as the Cartesian product for scoping the space defined by the two dimensions of likelihood and impact for all underlying events and scenarios, which is a preferred interpretation. This interpretation preserves the complete nature of risk. Ideally, the entire probability distribution of consequences should be estimated.

A plot of occurrence probabilities and consequences is a *risk profile* or a *Farmer curve*. An example Farmer curve is given in Figure 2.4 based on a nuclear case study provided herein for illustration purposes (Kumamoto and Henley 1996). It should be noted that the abscissa provides the number of fatalities and the ordinate provides the annual frequency of exceedance for the corresponding number of fatalities. These curves are sometimes constructed using probabilities instead of rates. The curves represent the average or

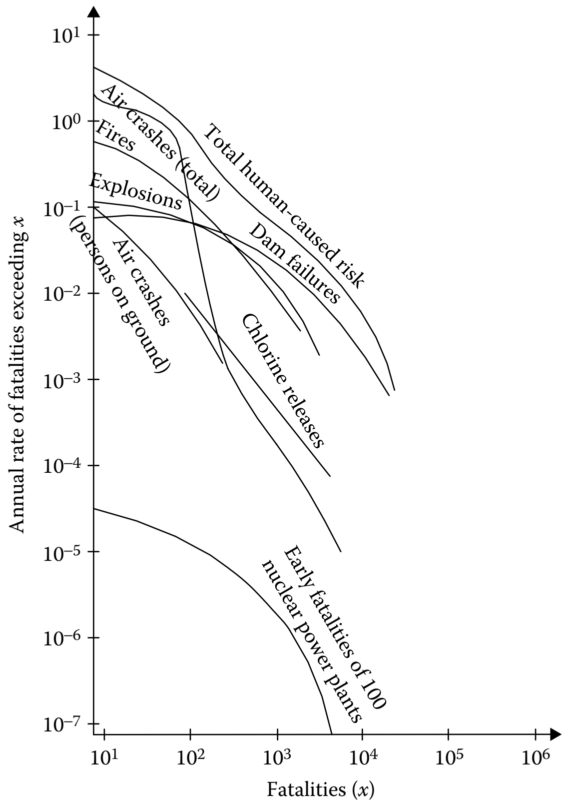

FIGURE 2.4
Example risk profile.

best estimate values. Figure 2.5 shows another example representing the gross margin of an investment project covering both potential loss and profits. This figure was generated using Monte Carlo simulation and presents the results in the form of a relative frequency histogram (i.e., the bar chart) and smoothed cumulative probability distribution (i.e., the solid curve). The figure shows that the loss probability is 0.047 and the probability of profits exceeding $200 million is 0.353.

Sometimes, bands or ranges are provided to represent uncertainty in these curves, and they represent confidence intervals for the average curve or the risk curve. Figure 2.6 shows examples of curves with bands (Kumamoto and Henley 1996). This uncertainty is sometimes called *epistemic uncertainty* or *meta-uncertainty*.

In cases involving deliberate threats, the occurrence probability (p) of an outcome (o) can be decomposed into an occurrence probability of an event or threat (t), a probability of success (s) given a threat ($s|t$), and an outcome probability given the occurrence of a successful event ($o|t,s$). The occurrence probability of an outcome can be expressed as follows using conditional probability concepts discussed in Appendix A on fundamentals of probability theory and statistics:

$$p(o) = p(t)p(s|t)p(o|t,s) \tag{2.5}$$

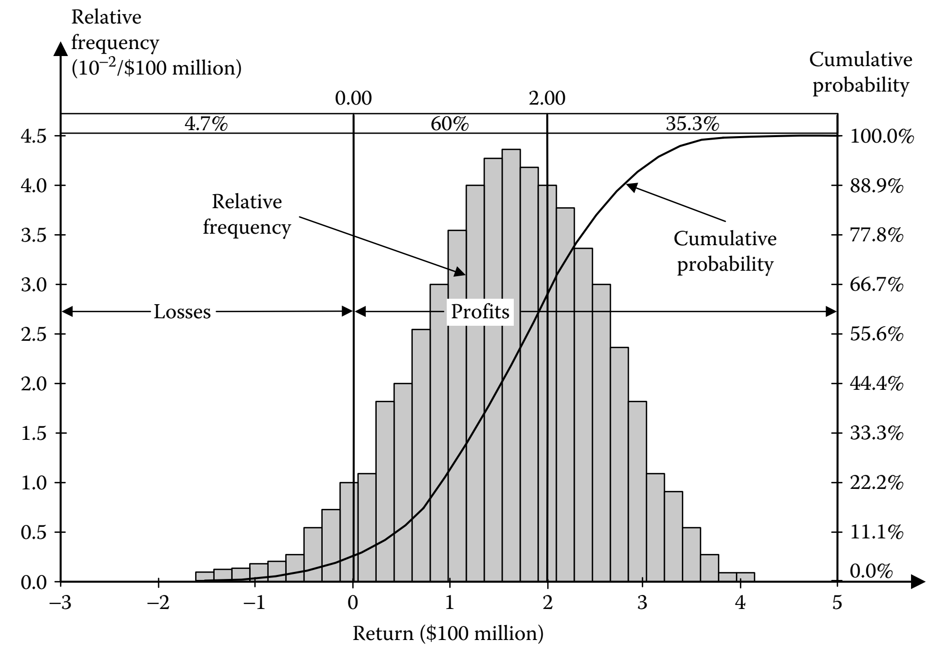

FIGURE 2.5
Example project risk profile.

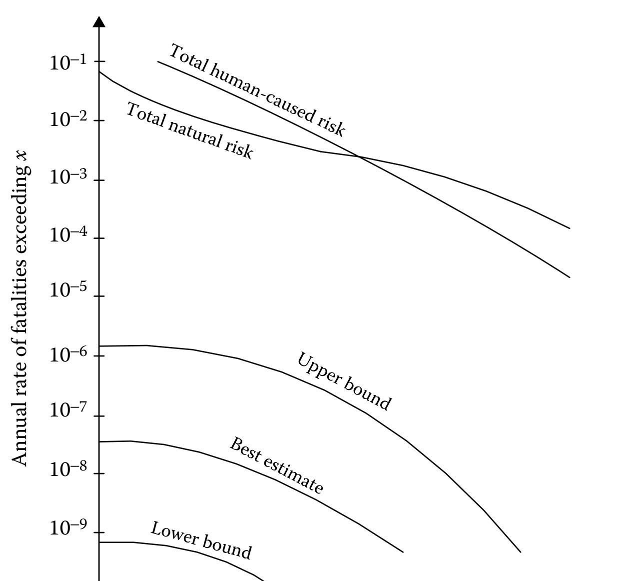

FIGURE 2.6
Uncertain risk profile. (Adapted from Imperial Chemical Industries Ltd., 1971.)

In this context, threat is defined as a hazard or the capability and intention of an adversary to undertake actions that are detrimental to a system or an organization's interest. In this case, threat is a function of only the adversary or competitor, and usually cannot be controlled by the owner of the system. The adversary's intention to exploit a situation may, however, be encouraged by vulnerability of the system or discouraged by an owner's countermeasures. The probability $p(o|t)$ can be decomposed further into two components: success probability of the adversary and conditional probability on this success in terms of consequences. This probability $p(o|t)$ can then be computed as the success probability of the adversary times the conditional probability of consequences given this success.

Risk register is a record of information about identified risks, sometimes called *risk log*.

Risk profile is a description of any set of risks that may relate to an entire organization, part of the organization, or a group of stakeholders or a region or a project.

Risk aggregation is the combination of a number of risk profiles into one risk profile to develop a more complete understanding of an overall risk; whereas *risk segregation* is the decomposition of an overall risk profile into a number of underlying risk profiles.

2.2.7 Asset Security and Protection

Asset is an item of value or importance. In the context of critical infrastructure and key resource (CI/KR) protection, a CI/KR asset is something of importance or value that if targeted, exploited, destroyed, or incapacitated could result in large-scale injury, death, economic damage, and destruction of property, or could profoundly damage a nation's prestige and confidence. Assets include physical elements (i.e., tangible property), cyber elements (i.e., information and communication systems), and human or living elements, (i.e., critical knowledge and functions of people).

Identifying critical assets requires defining the features that define criticality. Categories of critical assets are relatively broad and inclusive as shown in Table 2.7. The criticality of an asset should be based on features such as the impact of total destruction of or significant damage to an asset on the following:

- Public service and the operation of government
- Local, regional, and national economy
- Surrounding population
- National security
- Environment

It is noted that critical assets are identified primarily based on the consequences of a successful attack by an adversary rather than the probability that the attack will be successful. However, other asset features that should be considered include:

- Asset softness, that is, accessibility and inability to limit it
- Softness of targets within an asset
- Other specific features of these targets