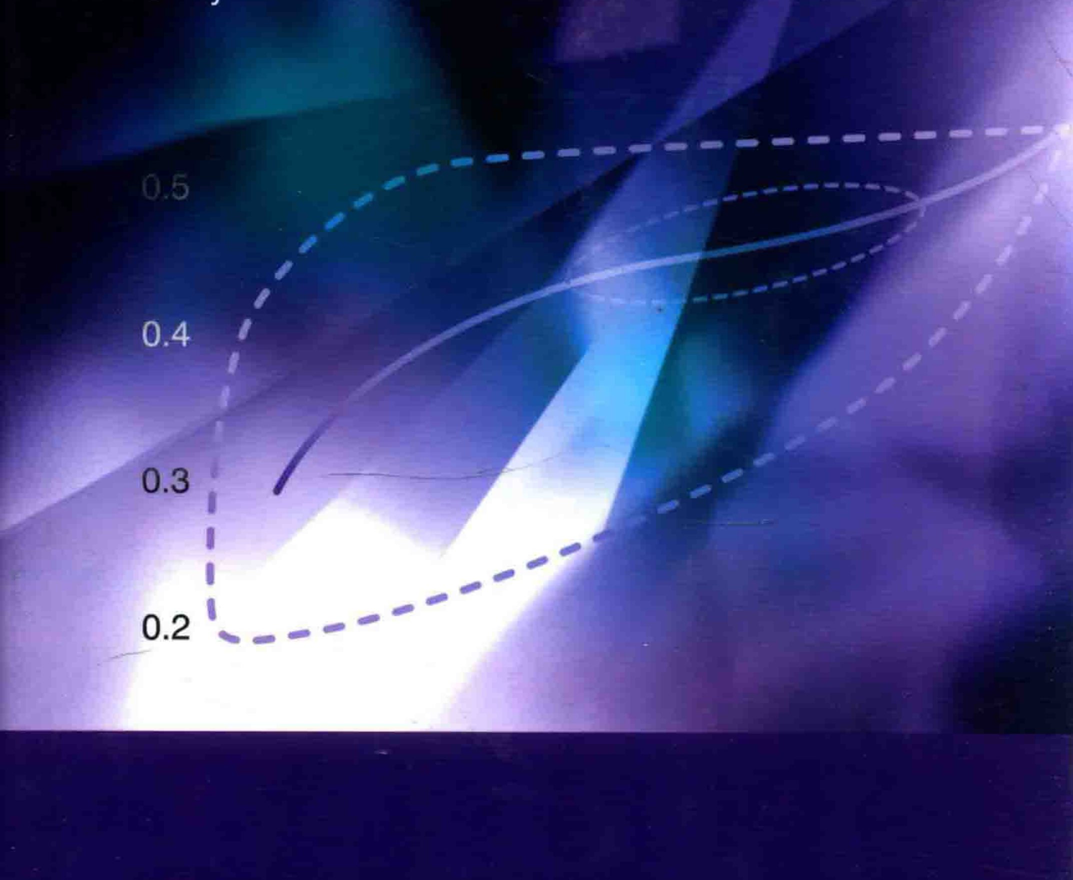
TERJE AVEN | PIERO BARALDI | ROGER FLAGE | ENRICO ZIO

Uncertainty in Risk Assessment

The Representation and Treatment of Uncertainties by Probabilistic and Non-Probabilistic Methods



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Uncertainty in Risk Assessment

Preface

The aim of this book is to critically present the state of knowledge on the treatment of uncertainties in risk assessment for practical decision-making situations concerning high-consequence technologies, for example, nuclear, oil and gas, transport, and so on, and the methods for the representation and characterization of such uncertainties. For more than 30 years, probabilistic frameworks and methods have been used as the basis for risk assessment and uncertainty analysis, but there is a growing concern, partly motivated by newly emerging risks like those related to security, that extensions and advancements are needed to effectively treat the different sources of uncertainty and related forms of information. Alternative approaches for representing uncertainty have been proposed, for example, those based on interval probability, possibility, and evidence theory. It is argued that these approaches provide a more adequate treatment of uncertainty in situations of poor knowledge of the phenomena and scenarios studied in the risk assessment. However, many questions concerning the foundations of these approaches and their use remain unanswered.

In this book, we present a critical review and discussion of methods for the representation and characterization of the uncertainties in risk assessment. Using examples, we demonstrate the applicability of the various methods and point to their strengths and weaknesses in relation to the situation addressed. Today, no authoritative guidance exists on when to use probability and when to use an alternative representation of uncertainty, and we hope that the present book can provide a platform for the development of such guidance. The areas of potential application of the theories and methods studied in the book are broad, ranging from engineering and medicine to environmental impacts and natural disasters, security, and financial risk management. Our main focus, however is, on engineering applications.

The topic of uncertainty representation and characterization is conceptually and mathematically challenging, and much of the existing literature in the field is not easily accessible to engineers and risk analysts. One aim of the present book is to provide a relatively comprehensive state of knowledge, with strong requirements for rigor and precision, while striving for readability by a broad audience of professionals in the field, including researchers and graduate students.

Readers will require some fundamental background in risk assessment, as well as basic knowledge of probability theory and statistics. The goal, however, has been to reduce the dependency on extensive prior knowledge, and key probabilistic and statistical concepts will be introduced and discussed thoroughly in the book.

It is with sincere appreciation that we thank all those who have contributed to the preparation of this book. In particular, we are grateful to Drs. Francesco Cadini, Michele Compare, Jan Terje Kvaløy, Giovanni Lonati, Irina Crenguza Popescu, Ortwin Renn, and Giovanna Ripamonti for contributing the research that has provided the material for many parts of the book, and to Andrea Prestigiacomo for his careful editing work. We also acknowledge the editing and production staff at Wiley for their careful and effective work.

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Part I

INTRODUCTION

1

Introduction

Risk assessment is a methodological framework for determining the nature and extent of the risk associated with an activity. It comprises the following three main steps:

- Identification of relevant sources of risk (threats, hazards, opportunities)
- Cause and consequence analysis, including assessments of exposures and vulnerabilities
- Risk description.

Risk assessment is now widely used in the context of various types of activities as a tool to support decision making in the selection of appropriate protective and mitigating arrangements and measures, as well as in ensuring compliance with requirements set by, for example, regulatory agencies. The basis of risk assessment is the systematic use of analytical methods whose quantification is largely probability based. Common methods used to systematically analyze the causes and consequences of failure configurations and accident scenarios are fault trees and event trees, Markov models, and Bayesian belief networks; statistical methods are used to process the numerical data and make inferences. These modeling methods have been developed to gain knowledge about cause–effect relationships, express the strength of these relationships, characterize the remaining uncertainties, and describe, in quantitative or qualitative form, other properties relevant for risk management (IAEA, 1995; IEC, 1993). In short, risk assessments specify what is at stake, assess the uncertainties of relevant quantities, and produce a risk description which provides information useful for the decision-making process of risk management.

In this book we put the main focus on quantitative risk assessment (QRA), where risk is expressed using an adequate representation of the uncertainties involved. To further develop the methodological framework of risk assessment, we will need to explain in more detail what we mean by risk.

Uncertainty in Risk Assessment: The Representation and Treatment of Uncertainties by Probabilistic and Non-Probabilistic Methods, First Edition. Terje Aven, Piero Baraldi, Roger Flage and Enrico Zio.

This introductory chapter is organized as follows. Following Section 1.1, which addresses the risk concept, we present in Section 1.2 the main features of probabilistic risk assessment (PRA), which is a QRA based on the use of probability to characterize and represent the uncertainties. Then, in Section 1.3, we discuss the use of risk assessment in decision-making contexts. Section 1.4 considers the issue of uncertainties in risk assessment, motivated by the thesis that if uncertainty cannot be properly treated in risk assessment, the risk assessment tool fails to perform as intended (Aven and Zio, 2011). This section is followed by a discussion on the main challenges of the probability-based approaches to risk assessment, and the associated uncertainty analysis. Alternative approaches for dealing with uncertainty are briefly discussed.

1.1 Risk

1.1.1 The concept of risk

In all generality, risk arises wherever there exists a potential source of damage or loss, that is, a hazard (threat), to a target, for example, people, industrial assets, or the environment. Under these conditions, safeguards are typically devised to prevent the occurrence of the hazardous conditions, and protection is put in place to counter and mitigate the associated undesired consequences. The presence of a hazard does not in itself suffice to define a condition of risk; indeed, inherent in the latter there is the uncertainty that the hazard translates from potential to actual damage, bypassing safeguards and protection. In synthesis, the notion of risk involves some kind of loss or damage that might be received by a target and the uncertainty of its transformation in actual loss or damage, see Figure 1.1. Schematically we can write (Kaplan and Garrick, 1981; Zio, 2007; Aven, 2012b)

$$\text{Risk} = \text{Hazards/Threats and Consequences (damage)} + \text{Uncertainty}. \qquad (1.1)$$

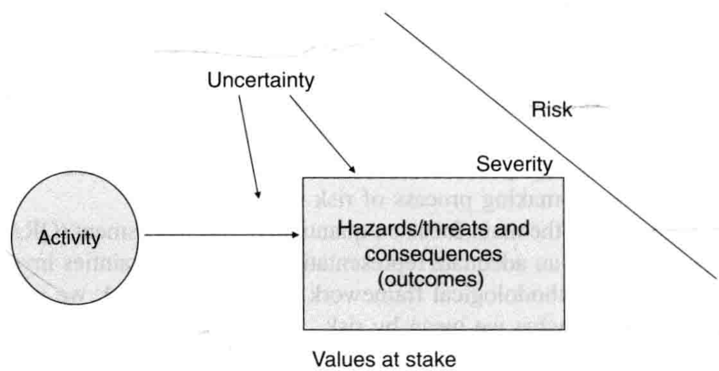

Figure 1.1 The concept of risk reflecting hazards/threats and consequences and associated uncertainties (what events will occur, and what the consequences will be).

Normally, the consequence dimension relates to some type of undesirable outcome (damage, loss, harm). Note that by centering the risk definition around undesirable outcomes, we need to define what is undesirable, and for whom. An outcome could be positive for some stakeholders and negative for others: discussing whether an outcome is classified in the right category may not be worth the effort, and most of the general definitions of risk today allow for both positive and negative outcomes (Aven and Renn, 2009).

Let A denote a hazard/threat, C the associated consequences, and U the uncertainties (will A occur, and what will C be?). The consequences relate to something that humans value (health, the environment, assets, etc.). Using these symbols we can write (1.1) as

$$\text{Risk} = (A, C, U), \tag{1.2}$$

or simply

$$\text{Risk} = (C, U), \tag{1.3}$$

where C in (C, U) expresses all consequences of the given activity, including the hazardous/threatful events A. These two risk representations are shown in Figure 1.2.

Obviously, the concept of risk cannot be limited to one particular measuring device (e.g., probability) if we seek a general risk concept. For the measure introduced, we have to explain precisely what it actually expresses. We also have to clarify the limitations with respect to its ability to measure the uncertainties: is there a need for a supplement to fully describe the risk? We will thoroughly discuss these issues throughout the book.

A concept closely related to risk is vulnerability (given the occurrence of an event A). Conceptually vulnerability is the same as risk, but conditional on the occurrence of an event A:

$$\text{Vulnerability} \mid A = \text{Consequences} + \text{Uncertainty} \mid \text{the occurrence of the event } A, \tag{1.4}$$

where the symbol $\mid$ indicates "given" or "conditional." For short we write

$$\text{Vulnerability} \mid A = (C, U \mid A). \tag{1.5}$$

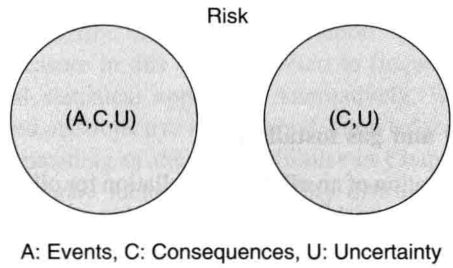

Figure 1.2 The main components of the concept of risk used in this book.

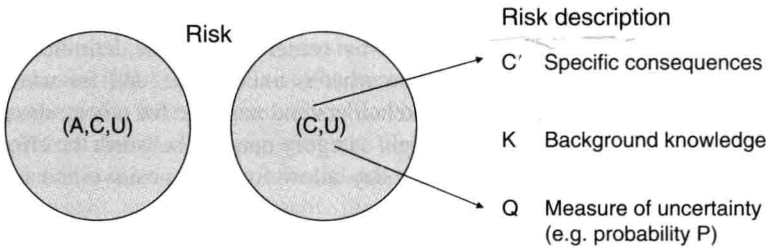

Figure 1.3 Illustration of how the risk description is derived from the concept of risk.

1.1.2 Describing/measuring risk

The risk concept has been defined above. However, this concept does not give us a tool for assessing and managing risk. For this purpose we must have a way of describing or measuring risk, and the issue is how.

As we have seen, risk has two main dimensions, consequences and uncertainty, and a risk description is obtained by specifying the consequences C and using a description (measure) of the uncertainty, Q. The most common tool is probability P, but others exist and these also will be given due attention in the book. Specifying the consequences means identifying a set of quantities of interest C' that represent the consequences C, for example, the number of fatalities.

Now, depending on the principles laid down for specifying C' and the choice of Q, we obtain different perspectives on how to describe/measure risk. As a general description of risk we can write

$$\begin{aligned} &\text{Risk description} = (C', Q, K), \\ &(\text{or, alternatively}, (A', C', Q, K)), \end{aligned} \tag{1.6}$$

where K is the background knowledge (models and data used, assumptions made, etc.) that Q and the specification C' are based on, see Figure 1.3. On the basis of the relation between vulnerability and risk previously introduced, the vulnerability given an event A is analogously described by $(C', Q, K|A)$.

1.1.3 Examples

1.1.3.1 Offshore oil and gas installation

Consider the future operation of an offshore installation for oil and gas processing. We all agree that there is some "risk" associated with this operation. For example, fires and explosions could occur leading to fatalities, oil spills, economic losses, and so on. Today we do not know if these events will occur and what the specific consequences will be: we are faced with uncertainties and, thus, risk. Risk is two dimensional, comprising events and consequences, and associated uncertainties (i.e., the events and consequences being unknown, the occurrences of the events are not known and the consequences are not known).

When performing a risk assessment we describe and/or quantify risk, that is, we specify (C', Q, K). For this purpose we need quantities representing C' and a measure of uncertainty; for the latter, probability is introduced. Then, in the example discussed, C' is represented by the number of fatalities, $Q=P$, and the background knowledge K covers a number of assumptions that the assessment is based on, for example, related to the number of people working on the installation, as well as the models and data used for quantification of the accident probabilities and consequences. On this basis, several risk indices or metrics are defined, such as the expected number of fatalities (e. g., potential loss of lives, PLL, typically defined for a one-year period) and the fatal accident rate (FAR, associated with 100 million exposed hours), the probability that a specific person will be killed in an accident (individual risk, IR), and frequency–consequence (f–n) curves expressing the expected number of accidents (frequency f) with at least n fatalities.

1.1.3.2 Health risk

Consider a person's life and focus on the condition of his/her health. Suppose that the person is 40 years old and we are concerned about the "health risk" for this person for a predetermined period of time or for the rest of his/her life. The consequences of interest in this case arise from "scenarios" of possible specific diseases (known or unknown types) and other illnesses, their times of development, and their effects on the person (will he/she die, suffer, etc.).

To describe risk in this case we introduce the frequentist probability p that the person gets a specific disease (interpreted as the fraction of persons that get the disease in an infinite population of "similar persons"), and use data from a sample of "similar persons" to infer an estimate p^* of p. The probability p can be considered a parameter of a binomial probability model.

For the consequent characterization, C', we look at the occurrence or not of a disease for the specific person considered, and the time of occurrence of the disease, if it occurs. In addition, we have introduced a probability model with a parameter p and this p also should be viewed as a quantity of interest C'. We seek to determine p, but there are uncertainties about p and we may use confidence intervals to describe this uncertainty, that is, to describe the stochastic variation in the data.

The uncertainty measure in this case is limited to frequentist probabilities. It is based on a traditional statistical approach. Alternatively, we could have used a Bayesian analysis based on subjective (judgmental, knowledge-based) probabilities P (we will return to the meaning of these probabilities in Chapter 2). The uncertainty description in this case may include a probability distribution of p, for example, expressed by the cumulative distribution function $F(p')=P(p \le p')$. Using P to measure the uncertainties (i.e., $Q=P$), we obtain a risk description (C', P, K), where p is a part of C'. From the distribution $F(p')$ we can derive the unconditional probability $P(A)$ (more precisely, $P(A|K)$) of the event A that the person gets the