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Foundations and choice of risk metrics

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ABSTRACT

Risk metrics are essential for expressing, communicating, and using the results of risk analysis in risk-informed decision-making. The objective of this paper is to shed light on fundamental issues concerning the interpretation and choice of such metrics and to provide practical guidance for this purpose. The motivation is to ensure that decision-makers and stakeholders see the results of risk analysis as legitimate and informative input to the decision process. The main contribution is a clarification of 11 evaluation criteria that can be used as a basis for discussing and evaluating risk metrics in dialog with relevant stakeholders in an analytic-deliberative process. The criteria are summarized in an overall discussion on informative, value-related, and analytical issues that affect the interpretation and choice of risk metrics. Three examples are provided to illustrate: (a) how the criteria can be used to evaluate the metric *fatal accident rate* (FAR), (b) fundamental issues that affect the choice of risk metrics in a controversial decision problem, and (c) the current focus on risk metrics in the Norwegian petroleum industry. The paper concludes that the proposed evaluation criteria can facilitate and enhance the analytic-deliberative process by clarifying the advantages and limitations of the various metrics and promoting acceptability of a chosen set.

1. Introduction

The purpose of risk analysis is to provide information that enables informed decision-making in face of uncertainty. The information may range from qualitative insights on causality and failure modes to quantitative expressions of system performance and overall risk. The focus of this paper is on the interpretation and choice of *risk metrics*. A risk metric serves two important functions: it enables us to talk about risk; to communicate and discuss the results of risk analysis and the aspects of risk that are important to us, and it facilitates decision-making by providing a quantitative measure for risk evaluation. The choice of risk metrics is critical as it directs what kind of information to get from the risk analysis and whether the results are considered as legitimate and informative by decision-makers and stakeholders (NRC, 1996).

The topic of risk metrics entered the arena in the 1960–1970s, when controversial risk analysis reports instigated discussions on the interpretation and acceptability of risk analysis results (e.g., Farmer, 1967; Fischhoff et al., 1981; Gibson, 1976). It was seriously brought on the agenda by a number of publications that problematized the formulation of risk acceptance criteria for regulatory decision-making (e.g., HSE, 1992; Kletz, 1982). Extensive public debates following major accidents and siting controversies in the 1980–1990s brought particular attention to the societal aspects of risk (e.g., Ball and Floyd, 1998; Ballard, 1993; Jorissen and Stallen, 1998). Subsequent contributions have ranged from comparative studies on regulatory practices (e.g., Basta et al., 2007; Duijm, 2009; Gooijer et al., 2012; Jonkman et al., 2011) and technologies (e.g., Burgherr et al., 2012; Colli et al., 2009), to development and evaluation of particular metrics in light of technical or decision-theoretical issues (e.g., Abrahamsen and Aven, 2008; Cox, 2008b; Evans and Verlander, 1997; Frohwein et al., 1999; Hirst and Carter, 2002; Prem et al., 2010).

Risk metrics is an interdisciplinary topic that has been discussed from the perspective of *risk analysis* in terms of technical issues related to the quantification of risk (e.g., Haimes, 2003; Rausand, 2011; Vasseur and Llory, 1999), from that of *risk communication* concerning the framing and presentation of risk to decision-makers and stakeholders (e.g.,NRC, 1996; Renn, 2008), and in relation to the formulation of *risk acceptance criteria* for regulatory decision-making (e.g., CCPS/AIChE, 2009; NORSOK Z-013, 2001). Little attention has, however, been devoted to risk metrics as a topic of its own. A notable exception is Jonkman et al. (2003), who give a technical and applicatory overview of 25 risk metrics for harm to people, the environment, and monetary assets. Another useful overview is provided in CCPS/AIChE (2000), which illustrates the application of 14 metrics for harm to people. What is missing is a consideration of fundamental issues that affect the suitability and acceptability of the different metrics. There is also a call for practical guidelines to aid the interpretation and choice of risk metrics in a specific decision context.

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This paper is a continuation of Johansen and Rausand (2012), who give an explanatory overview of 17 common risk metrics, place them in a decision context, and propose 11 evaluation criteria to aid in their interpretation and choice. The overall objective of this paper is to give a comprehensive overview of fundamental issues concerning the interpretation and choice of risk metrics and provide practical guidance for this purpose. The main contribution is that it explains the 11 evaluation criteria and pinpoints informative, value-related, and procedural issues concerning the choice of risk metrics. The motivation is to ensure that risk analyses are performed and communicated in such a way that decision-makers and affected parties see the results as valuable input to risk-informed decision-making.

The focus of the paper is on engineering risk analysis of socio-technical systems. The topic restricts the scope of the paper to risk as a probabilistically described concept. The paper is further delimited to major accidental events and does not cover continuous exposure to hazardous substances or occupational incidents. The analysis is not restricted to specific sectors or applications, and the results are hence generically applicable. The paper is organized as follows: Fundamental concepts are clarified in Section 2, before the 11 evaluation criteria are explained in Section 3. The criteria are summarized and related to common risk metrics in an overall discussion of informative, value-related, and analytical issues in Section 4, and illustrated by three examples in Section 5. Concluding remarks are given in Section 6.

2. Fundamental concepts and frameworks

In order to facilitate meaningful discussions on risk metrics, it is necessary to clarify what we mean by risk and related concepts. Risk can be defined at three levels: an abstract level, which defines risk as an overall concept (what we analyze), an operational level, which specifies the variables of interest (how we analyze it), and an instrumental level, which concerns the technical expression of risk (how we describe it) (Aven, 2011a; Stallen et al., 1998).

2.1. Abstract definition: elements and types of risk

Risk can be defined as the answer to three questions: (1) What can go wrong? (2) How likely is it? and (3) What are the consequences? (Kaplan and Garrick, 1981). The second question can be phrased in terms of the probability (e.g., see Modarres, 2006) or the uncertainty (e.g., see Aven, 2012) related to the occurrence and severity of an undesired event. The latter gives more flexibility at the operational and instrumental levels of definition, as the answer can be given both probabilistically and non-probabilistically. It furthermore directs attention to the strength of knowledge that lies behind our answer. This paper is not restrictive to any of the interpretations at the abstract level, but is naturally confined at the other levels by its focus on risk metrics.

Different types of risk can be classified based on the type of event and the subject of harm. *Occupational risk* concerns work-related events that cause harm to single workers, whereas *major accident risk* concerns major events that can cause damage to several humans, the environment, or material assets. More generally, *individual risk* can be defined as the the risk to an actual or hypothetical individual related to single or multiple events. This is related to *group risk*, which is the risk to a particular group or society as a combination of individual risk levels and the number of people at risk. We finally define *societal risk* as the risk to a society or population related to a single event that affects multiple persons or assets.

2.2. Operational definition: HE, P, and C

The second level of definition concerns how we operationalize the answers to the three questions of risk in the process of *risk analysis*. In this paper, we delimit the answer to a *set of triplets*, $\{\langle HE, P, C\rangle\}$, where each triplet consists of a hazardous event (HE), its probability of occurrence (P), and a consequence spectrum (C). A useful operational model of risk is the *bow-tie* diagram in Fig. 1, which centers on a specific hazardous event, a path of causes leading up to this event, and a spectrum of potential consequences. A particular trajectory in the bow-tie is called a *scenario*. Since most systems may experience more than one type of hazardous event, risk is given not by a single bow-tie, but a collection of bow-ties that each corresponds to a triplet $\langle HE, P, C\rangle$.

Hazardous event: A hazardous event can be defined as *"loss of control of energy in the system"* (Kjellén, 2000), or *"the first event in a sequence of events that, if not controlled, will lead to undesired consequences (harm) to some assets"* (Rausand, 2011). Due to practical and/or analytical constraints, only a limited selection of hazardous events can be included in the risk analysis (CCPS/AIChE, 2009). The choice depends on the type of system, the hazards considered, and their potential effects. A special concern is extreme events that have very low probabilities, but potentially catastrophic consequences (e.g., see Haimes, 2003; Khan, 2001).

Probability: The probability element can be given as a frequency or by using other probability concepts. The interpretation of probability has crucial implications for risk analysis. Probability can either be seen as a property of the system under study, or as a subjective expression that represents the analyst's degree-of-belief (Lindley, 2006). We take the latter position, which implies that risk is not an inherent system property, but a subjective construct in the mind of the analyst. Probability is then an expression of the analyst's uncertainty related to the occurrence of the hazardous events and its consequences. There are, however, important aspects of uncertainty that are not reflected in the probability statement, such as the strength of knowledge that underlies the probability assessment and the answer to the other two questions. Owing to this, an integral part of answering the three questions of risk is to provide a qualitative characterization of the uncertainty that underlies the numbers (Aven, 2011b, 2013).

Consequence: This is a vector that comprises a variety of outcomes that represent an impact on something humans *value*, along with their associated probabilities (Renn, 2008; Rausand, 2011). The vector represents judgments about what consequence dimensions and outcomes to include, to whom, and at what point in the bow-tie. The most common *consequence dimensions* are harm to humans, the environment, and material assets. One may also consider wider effects such as loss of revenue or social disruption (e.g., see Kim et al., 2012). By *outcomes* we mean the damage or harm, for example, death, injury, permanent disability, or illness. This may be attributed to workers, users, members of the public, or unborn generations (1–4th party, respectively). Damage to the environment may be specified to individual organisms, populations,

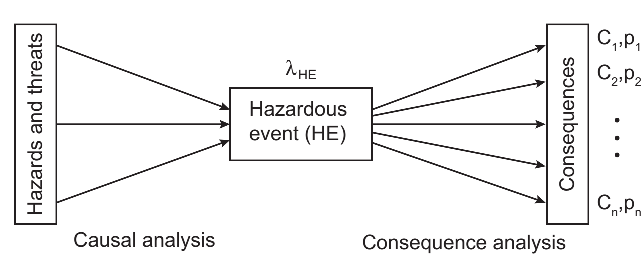

Fig. 1. The bow-tie as a mental model of risk analysis.