Safety Science 84 (2016) 67–77

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Review

# On the assessment of uncertainty in risk diagrams

Floris Goerlandt [a,b,*], Genserik Reniers [b,c,d]

[a] Aalto University, School of Engineering, Department of Applied Mechanics, Marine Technology, Research Group on Maritime Risk and Safety, P.O. Box 12200, FI-00076 AALTO, Finland
[b] KU Leuven, Campus Brussels, Faculty of Economics and Organizational Sciences, Center for Economics and Corporate Sustainability, Warmoesberg 26, 1000 Brussels, Belgium
[c] UAntwerpen, City Campus, Faculty of Applied Economic Sciences, Prinsstraat 13, 2000 Antwerp, Belgium
[d] TU Delft, Safety and Security Science Group, Faculty of Technology, Policy and Management, Jaffalaan 5, 2628 BX Delft, The Netherlands

ARTICLE INFO

*Article history:*
Received 12 October 2015
Accepted 1 December 2015
Available online 18 December 2015

*Keywords:*
Risk matrix
Risk diagram
Uncertainty
Strength of knowledge
Risk analysis
Risk communication

ABSTRACT

Risk matrices and risk diagrams are widely used tools for analyzing, assessing and visualizing risk in many industries, and are used extensively for risk management purposes. Despite their popularity and wide application, they have recently become the object of discussion and research in scientific environments, which can be seen as part of a wider focus on foundational issues in the risk analysis discipline. Identifying several serious limitations and problems with the risk matrix approach, various authors have proposed extensions, modifications and recommendations for their use. One issue which has been raised recently but has attracted relatively limited scientific attention is the consideration of uncertainty in risk diagrams, i.e. how to visually represent and communicate uncertainty. This paper first reviews the available proposals for this question. Subsequently, the strengths and weaknesses of these proposals are discussed. Finally, some new proposals are made on how to represent uncertainty in risk diagrams in practical applications.



**Contents**

1. Introduction . . . 68
2. Assessing uncertainty in PCDS: risk perspectives . . . 68
   2.1. Background and justification . . . 68
   2.2. Uncertainty-based risk perspectives . . . 69
3. Earlier proposals for visualizing uncertainty in risk diagrams . . . 69
   3.1. PCDS with family of “risk curves” . . . 69
   3.2. PCDS with uncertainty boxes . . . 70
   3.3. Bubble diagrams . . . 70
   3.4. PCDS with prediction intervals and strength-of-evidence assessments. . . . 71
4. Discussion on the existing proposals . . . 71
   4.1. Elements of PCDS with uncertainty treatment . . . 71
      4.1.1. Markers for probability and consequences of risk events . . . 72
      4.1.2. Indicators for uncertainty/strength-of-evidence. . . . 72
      4.1.3. Indicators for surprises/potential for large deviations . . . 72

*Abbreviations:* *A*, event; ADR, assumption deviation risk; *C*, consequence; *E*[*C*|*A*], expected consequences in case an event occurs; *FN*-curve, curve showing the frequency of exceedance (*F*) of a given number of fatalities (*N*); *K*, knowledge on which the analysis is based; PCD, probability–consequence diagram; PCD-USEA$_1$, probability–consequence diagram with Tukey box plots and strength-of-evidence assessments; PCD-USEA$_2$, probability–consequence diagram with uncertainty intervals, strength-of-evidence assessments and assessments of assumption deviation risks; PCD-PISEA, probability–consequence diagram with prediction intervals and strength-of-evidence assessments; $P_f$, frequentist probability; $P_s$, subjective (knowledge-based) probability; *Q*, measure of uncertainty; QRA, quantitative risk analysis; RM, risk matrix; SE, strength-of-evidence; *U*, uncertainty.

* Corresponding author at: Aalto University, School of Engineering, Department of Applied Mechanics, Marine Technology, Research Group on Maritime Risk and Safety, P.O. Box 12200, FI-00076 AALTO, Finland. Tel.: +358 50 343 1186.

*E-mail address:* floris.goerlandt@aalto.fi (F. Goerlandt).

http://dx.doi.org/10.1016/j.ssci.2015.12.001
0925-7535/

4.2. Strengths and weaknesses of earlier proposals . . . 72
5. Proposals for representing uncertainty in risk diagrams . . . 73
5.1. Proposal 1: PCDS with Tukey box plots and strength-of-evidence assessments (PCDS-USEA$_1$) . . . 73
5.2. Proposal 2: PCDS with uncertainty intervals, strength-of-evidence assessments and assessments of assumption deviation risks (PCDS-USEA$_2$) . . . 75
6. Conclusions . . . 76
Acknowledgements . . . 76
Appendix A . . . 76
Appendix B . . . 76
References . . . 76

## 1. Introduction

Risk matrices (RMs) are widely used tools for analyzing, assessing and visualizing risk in many industries, and are used extensively for risk-management purposes. The main benefits attributed to RMs are their intuitive appeal and simplicity: they are perceived to be easy to construct, explain and score (Thomas et al., 2014). Belonging to the class of probability–consequence diagrams (PCDS) as described by Ale et al. (2015), they are easier to interpret than *FN*-curves.[1] Furthermore, RMs are recommended by various international standards and industry guidelines (IMO, 2007; IPIECA/OGP, 2013; ISO, 2010; NHS, 2008).

Notwithstanding its wide application, an increasing body of research has analyzed and discussed the limitations and inconsistencies of the RM approach. Duijm (2015) summarizes critical comments by Franks and Maddison (2006), Cox (2008), Smith et al. (2009), Hubbard and Evans, 2010, Ni et al. (2010), Flage and Røed (2012) and Levine (2012). Following issues are discussed: (i) the consistency between the risk matrix and quantitative measures and the corresponding appropriateness of decisions based on risk matrices, (ii) the subjective classification of consequence and probability, (iii) the (linear or logarithmic) definition of risk scores and its relation to the scaling of the categories, (iv) the limited resolution of risk matrices, resulting in "risk ties", the aggregation of scenarios and consequences for a single event on different areas of concern, and for multiple hazards originating from a single activity, and (v) problems with the use of corporate-wide risk matrix designs (Duijm, 2015). Similar points are made by Hubbard (2009), Kontovas and Psaraftis (2009), Pickering and Cowley (2010) and Thomas et al. (2014).

In response to these identified problems with RMs, several authors have proposed extensions to the approach. Markowski and Mannan (2008) propose the use of fuzzy sets to account for vagueness in the definition of the linguistic ordinal scales. Ni et al. (2010) propose a methodology based on the Borda count, using the likeliness and consequence ranks as independent scores, as well as other arithmetic extensions. Garvey (2009) and Mayer and Reniers (2013) discuss a method to adjust the categorization of the risk ranking, accounting for the decision-makers risk attitude (consequence- or likeliness averseness). Ruan et al. (2015) propose a method to account for decision-makers risk attitude based on the utility theory. Duijm (2015) provides a number of recommendations, including that the coloring should define risk as a monotonously increasing function of consequences and likeliness, the use of logarithmic scaling and the use of continuous PCDS instead of discrete categories, the benefits of which are also discussed by Ale et al. (2015). Duijm (2015) also identifies challenges to the use of continuous probability–consequence diagrams, one of which concerns how to assess uncertainty in the assigned probability and consequence metrics.

[1] An *FN*-curve shows the frequency of exceedance (*F*) of a given number of fatalities (*N*).

This last issue is the research topic of this paper. In particular, previously proposed methods for representing uncertainty in PCDS are summarized and their merits and shortcomings discussed. Subsequently, proposals are made to represent uncertainty in risk diagrams.

This issue strongly relates to risk communication: graphical displays focus attention and serve a special role in getting the right message across, not in the least because detailed analyses in lengthy reports may not always be fully read by decision makers (Abrahamsen et al., 2014). Hence, it is of considerable importance to develop and present ideas to assess, visualize and communicate uncertainty in risk diagrams. The relevance of this research is also supported by Fischhoff (1995), who finds that uncertainties are not always appropriately conveyed in risk communication and by Spiegelhalter et al. (2011), who find that there has been rather little progress on the issue of representing uncertainty.

In the remainder of this paper, our focus is exclusively on continuous PCDS, i.e. qualitative risk matrices are beyond the scope. This limitation follows from arguments from Abrahamsen et al. (2014), Ale et al. (2015) and Duijm (2015) that these allow for a more accurate risk picture. Moreover, risk diagrams are here understood as tools for visualizing the risk picture, not as complete risk analysis tools, see Flage and Røed (2012) and Abrahamsen et al. (2014).

The rest of this paper is organized as follows: Section 2 gives a background for the need for assessing uncertainty, and introduces uncertainty-based risk perspectives. In Section 3, some earlier proposals for representing uncertainty in PCDS are outlined. Their elements, strengths and weaknesses are discussed in Section 4. Section 5 presents two new proposals for visualizing uncertainty in PCDS. Section 6 concludes.

## 2. Assessing uncertainty in PCDS: risk perspectives

### 2.1. Background and justification

Risk is often defined through probabilities, either as an expected value of probabilities and consequences (Campbell, 2005), or as the combination of scenarios, probabilities and consequences (Kaplan, 1997). Aven (2012) has made a historic analysis of the risk concept, finding that in many application areas, the predominant definitions are probability-based. This is confirmed in a recent review of definitions in risk analyses concerned with accidental risk in waterways. This study also shows that risk perspectives (systematic methods to describe risk) corresponding to probability-based definitions typically do not consider uncertainties beyond the probabilistic descriptions (Goerlandt and Montewka, 2015a).

The need for considering uncertainties in making scientific claims has been argued for by Douglas (2009) on grounds that scientists have a responsibility to consider the consequences of error. If evidence is poor and if this may lead to foreseeable changes to the conclusions of an inquiry, these uncertainties need to be made