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A framework for risk analysis of maritime transportation systems: A case study for oil spill from tankers in a ship–ship collision

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ABSTRACT

This paper proposes a framework for risk analysis of maritime transportation systems, where risk analysis is understood as a tool for argumentative decision support. Uncertainty is given a more prominent role than in the current state of art in the maritime transportation application area, and various tools are presented for analyzing uncertainty. A two-stage risk description is applied. In the first stage, Bayesian Network (BN) modeling is applied for probabilistic risk quantification. The model functions as a communication and argumentation tool, serving as an aid to thinking in a qualitative evidence and assumption effect assessment. The evidence assessment is used together with a sensitivity analysis to select alternative hypotheses for the risk quantification, while the assumption effect assessment is used to convey an argumentation beyond the model. Based on this, a deliberative uncertainty judgment is made in the second risk analysis stage, which is supplemented with a global strength of evidence assessment. The framework is applied to a case study of oil spill from tanker collisions, aimed at response capacity planning and ecological risk assessment. The BN-model is a proactive and transferable tool for assessing the occurrence of various spill sizes in a sea area. While the case study uses evidence specific to the Gulf of Finland, the model and risk analysis approach can be applied to other areas. Based on evaluation criteria and tests for the risk model and risk analysis, it is found that the model is a plausible representation of tanker collision oil spill risk.

1. Introduction

In risk research, there is a recent focus on foundational issues. Calls have been made for devising risk analysis frameworks, focusing on issues such as how to understand and describe risk, and how to use risk analysis in decision making (Aven and Zio, 2014). Furthermore, there have been calls for devising methods for communicating uncertainty in risk analysis (Psaraftis, 2012).

In the maritime transportation application area, some theoretical frameworks exist, e.g. based on system simulation (Harrald et al., 1998), traffic conflict technique (Debnath and Chin, 2010) and Bayesian Networks (BNs) (Montewka et al., 2014a). Recent research has however shown that a wide range of definitions, perspectives and approaches to risk analysis co-exist, whereas typically little or no attention is given to risk-theoretic issues in applications. Furthermore, uncertainty typically is not considered (Goerlandt and Montewka, 2015).

In light of the above, this paper introduces a framework for risk analysis of maritime transportation systems, where uncertainty is given a more prominent role than in the current state of the art in the application area. Specific attention is given to the risk-theoretical basis (risk concept, perspective and use of risk analysis in decision making), and to the tools for analyzing uncertainties and biases beyond the model-based quantification. Bayesian Networks are applied as a modeling tool.

Subsequently, the framework is applied to a case study involving the oil spill risk from tankers in a ship–ship collision, aimed at providing insight in the possible occurrence of given spill sizes in this accident type in a given sea area. Such information is useful for response capacity and fleet organization planning (COWI, 2011; Jolma and Haapasaari, 2014; Lehikoinen et al., 2013) and for assessing the risk of biological impacts of oil spills (Lecklin et al., 2011).

While major oil spills from tankers are rare occurrences, the transportation of oil remains one of the main concerns for the various stakeholders in marine environmental protection (Dalton and Jin, 2010). This is due to their potentially major impact on marine ecosystems (Bi and Si, 2012), important socio-economic impacts on communities dependent on coastal resources (Garcia Negro et al., 2009; Miraglia, 2002) and high acute costs involved in clean-up operations (Montewka et al., 2013). Oil spills in harbor

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approaches or in narrow shipping waterways can also lead to a blockade, which can incur high costs to the world economy (Qu and Meng, 2012). Thus, adequate accident prevention measures (Hänninen et al., 2014; van Dorp and Merrick, 2011) and oil spill preparedness planning are important to enhance maritime safety and for marine environmental protection (IMO, 2010; Taylor et al., 2008).

Several methods and analyses have been proposed for assessing the oil spill risk from shipping activities in a sea area. Lee and Jung (2013) combine historic data with qualitative risk matrices for ranking likeliness and consequences. Quantitative methods for analyzing oil spill risk include event-trees and traffic flow theory or system simulation combined with ship collision damage modeling or accident statistics (Akhtar et al., 2012; COWI, 2011; Gucma and Przywarty, 2008; Li et al., 2012; Montewka et al., 2010b; van Dorp and Merrick, 2011). The work presented in this paper extends this literature by presenting a ship–ship collision oil spill risk analysis based on a Bayesian Network model.

This paper is organized as follows: In Section 2, a description of the applied understanding of the risk concept and the adopted two-stage risk perspective is given. A reflection is made on the intended use of the risk analysis. In Section 3, the methodological basis for the risk analysis framework is briefly outlined, focusing on the tools applied to describe risk. In Section 4, the case study to which the risk analysis framework is applied is introduced. The first risk analysis stage for the case study is presented in Section 5, and the second stage in Section 6. In Section 7, a discussion is given on the evaluation of the results, both concerning the risk model and the risk analysis as such. The utility of the tools for contextualizing the risk quantification is discussed in Section 8, and Section 9 concludes. For reasons of brevity, much of the data and models underlying the risk model and analysis is presented in Appendices.

2. Framework for risk analysis: risk-theoretic foundations

Risk analysis is an established tool for informing decisions. However, there are many different views on what risk is and how to define it (Aven, 2012; Hampel, 2006), how to measure/describe it (Aven, 2010a; Kaplan, 1997), and how to use risk analysis in decision making (Apostolakis, 2004; Aven, 2009). Therefore, this section provides a brief overview of the adopted conceptual understanding of risk, which systematic perspective is taken to describe risk and how to use the risk analysis results in decision making.

2.1. Risk concept: how risk is understood

Many definitions of the risk concept exist, involving constituents such as probability, uncertainty, possibility, events and/or consequences (Aven, 2012; Hampel, 2006). In the current application, risk is understood as referring to the possible but uncertain occurrence of a situation where something of human value is at stake. The terminological diversity of risk has philosophical roots, with opposing views on the nature of risk rooted in realism or constructivism (Shrader-Frechette, 1991). In the current understanding, risk is not considered a reality existing in itself, but a construct shared by a social group, informed by available evidence (Aven and Renn, 2009; Thompson and Dean, 1996). It is thus not a physical attribute of a system, existing by itself, but a concept attributed to a system in the mind of an assessor (Goerlandt and Montewka, 2015; Solberg and Njå, 2012).

2.2. Risk perspective: how risk is described

Understanding risk as above, a risk description is a reflection of a mind construct of analysts and experts (Aven and Guikema, 2011; Rosqvist, 2010; Watson, 1994), which may be more or less intersubjectively objective (Aven, 2010b). There is no reference to an underlying "true" risk, opposed to other risk description frameworks, such as the one presented by Kaplan (1997). In this section, the systematic manner to describe risk, i.e. the risk perspective, is outlined.

It is well-established that in the complex, distributed maritime transportation system, knowledge is not equally available about all parts of the system (Montewka et al., 2014b; Yan et al., 2014). Relying on poor evidence may lead to erroneous conclusions and misguided decisions, e.g. about risk acceptability or the choice between risk control alternatives. Because scientists have the responsibility to consider the consequences of error (Douglas, 2009), uncertainty has a central role in the current framework.

Moreover, in many analysis and modeling contexts, it is unavoidable to make simplifying assumptions which lead to conservative or optimistic biases in the analysis (Vareman and Persson, 2010). Such assumptions ultimately rely on value judgments (Diekmann and Peterson, 2013; Wandall, 2004). Because such value judgments may not be acceptable to all stakeholders (Hermansson, 2012), their effect is considered in the framework through considering biases.

Another issue is that the information presented to stakeholders and decision makers should be interpretable, i.e. it should be possible to explain what the presented numbers and descriptions mean (Aven, 2011a).

Based on the above, the current framework applies a two-stage risk description, as illustrated in Fig. 1. The general method and perspectives for analyzing risk is presented in the following sections. The intended use of the risk analysis in decision making is discussed in Section 2.3. The methodological aspects of the tools for analyzing risk are presented in Section 3.

2.2.1. Stage 1: Quantitative risk modeling with extended uncertainty/bias evaluation

In the first risk analysis stage, case-specific background knowledge is established. This concerns data, information, models and judgments and is conditional to a decision context, which sets limits to the available resources (time, money, expertise) and may act as a guide to selecting conservative or optimistic modeling choices (Vareman and Persson, 2010).

Using the evidence, a risk model is constructed to quantify risk, using the established background knowledge. This is supplemented with an extended qualitative assessment of uncertainties and biases. Together with a sensitivity analysis, model variables for which to prioritize alternative hypotheses are identified and their effect quantified using the risk model. The effect of assumptions on the quantitative risk results is finally qualitatively assessed.

The perspective applied in the first stage of the risk analysis is based on a combination of the precautionary perspective (Rosqvist and Tuominen, 2004) and the uncertainty-based perspective (Aven, 2010a; Aven and Zio, 2011; Flage and Aven, 2009). In the precautionary perspective, frequentist probability P_f and subjective probability P_s are used to describe events and consequences. This is supplemented by a qualitative assessment of model biases B, i.e. whether conservative or optimistic modeling choices are made. In the uncertainty-based perspective, the occurrence of events and consequences is quantified using subjective probabilities P_s. Structural uncertainty is quantified using alternative hypotheses in the model construction U_{AH} and/or through a qualitative assessment of uncertainties U_{QL}.