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# Maritime transportation risk analysis: Review and analysis in light of some foundational issues

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## ABSTRACT

Many methods and applications for maritime transportation risk analysis have been presented in the literature. In parallel, there is a recent focus on foundational issues in risk analysis, with calls for intensified research on fundamental concepts and principles underlying the scientific field. This paper presents a review and analysis of risk definitions, perspectives and scientific approaches to risk analysis found in the maritime transportation application area, focusing on applications addressing accidental risk of shipping in a sea area. For this purpose, a classification of risk definitions, an overview of elements in risk perspectives and a classification of approaches to risk analysis science are applied. Results reveal that in the application area, risk is strongly tied to probability, both in definitions and perspectives, while alternative views exist. A diffuse situation is also found concerning the scientific approach to risk analysis, with realist, proceduralist and constructivist foundations co-existing. Realist approaches dominate the application area. Very few applications systematically account for uncertainty, neither concerning the evidence base nor in relation to the limitations of the risk model in relation to the space of possible outcomes. Some suggestions are made to improve the current situation, aiming to strengthen the scientific basis for risk analysis.

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## 1. Introduction

Risk analysis methods for maritime transportation have received a growing interest in recent years, even to the extent that international organizations have provided recommendations on the use of specific risk analysis and management tools [1–3]. In parallel, there is a recent focus on foundational issues in scientific environments concerned with risk analysis, with calls for intensifying research on issues such as applied terminology, principles and perspectives for analyzing and managing risk [4–6].

Answering these calls, this paper provides a review and analysis of risk analysis applications addressing the accidental risk of maritime transportation in a sea area, in light of some foundational issues as intended in [5]. A distinction is made between the science of risk analysis (concerning concepts, principles, methods and models for analyzing risk) and the practice of risk analysis (concerning specific applications) [6].

In particular, the applied risk definitions, the perspectives for describing risk, and the scientific approach to risk analysis as a tool for supporting decision-making are in focus. This distinguishes the current work from recent review papers [7–9] as only minimal

attention is given to the structure and content of the methods. Rather, the methods and applications are reviewed on a high level, focusing on some risk-theoretic foundations. The research focuses on providing insight into which risk-theoretical foundations the maritime transportation area has adopted, aiming to facilitate further reflections and discussions within the maritime research community. Thus, the paper aims to support the call by Aven and Zio [5], specifically in the maritime transportation application area.

A systematic method is taken to review and analyze risk applications, considering three issues. In Section 2, a brief review of definitions for risk is provided, focusing on the question how the risk concept is defined in particular applications. In Section 3, a brief summary is given of elements of risk perspectives, focusing on which tools are applied to measure/describe risk and on the scope of the analysis (events or events and consequences). In Section 4, a classification of scientific approaches to risk analysis is presented, utilizing the framework of the realist-constructivist continuum. This concerns the underlying ontological, epistemological and normative commitments to risk analysis as a scientific activity, which amongst other have implications for the evidence types considered in the analysis, the extent of uncertainty treatment and the role of the risk analysis in decision making.

Following the methodological basis, Section 5 presents an overview of maritime transportation risk analysis applications in light of the three above aspects. In Section 6, a further analysis is performed, providing insight in historical developments and cross-dependencies

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between definitions, perspectives and approaches. A discussion is made in Section 7 and a conclusion in Section 8.

## 2. A classification of risk definitions

In Table 1, a brief overview of some categories for definitions of risk is given, based on a historic analysis of the risk concept by Aven [10]. These conceptual classes are here used as a basis to obtain insight in how risk is defined in the application area. Definitions and discussions in [10,11] are used to briefly summarize the nine categories.

Category D1 defines risk as the expected value of the probability of an event occurrence and the utility of the consequences. In D2, risk is defined risk as the probability of an undesirable event, or the chance of a loss. In D3, risk is defined as objective uncertainty, i.e. a probability distribution over an outcome range (known through calculations or from statistical data analysis). Category D4 represents definitions where risk is equal to uncertainty, understood as a statistical variation compared with an average value. In category D5, risk is defined as the possibility of an unfortunate occurrence. D6 defines risk as the combination of the probability of occurrence of an event and consequences, without combining these in one unit as in D1. D7 understands risk as objective states of the world, which are considered existing independent of an assessor. D8 defines risk as the combination of events, consequences and the uncertainties of these, where uncertainty is understood as an assessor's uncertainty about the occurrence of the events/consequences. D9 defines risk as an effect on stated objectives (i.e. a consequence), due to the presence of uncertainty.

## 3. Elements of risk perspectives

In this section, a brief overview is given of some commonly found elements of risk perspectives. A risk perspective is here understood as a way to describe risk, a systematic manner to analyse and make statements about risk, as in [12]. Three aspects are considered: the measurement tools (probabilities, indicators, fuzzy numbers,...), the scope of the analysis (events or events and consequences), and the tools applied to convey information regarding the confidence in the analysis (uncertainty and bias measures). One element of risk measurement tools concerns their interpretability as it has been argued that this is an important aspect of practical decision making [13,14].

Table 2 lists the risk perspective elements applicable to the current research. Each element is outlined by an abbreviation, a definition, a short description of its underlying rationale, and a selection of references where the element is more elaborately discussed.

## 4. A classification of approaches to the science of risk analysis

In a risk analysis, risk is measured/described with the purpose of informing a decision, but views differ about how to do this [38].

**Table 1**  
A classification of risk definitions [10].

Risk definition classes	Abbreviation
D1 Risk=Expected value	R=EV
D2 Risk=Probability of an (undesirable) event	R=P
D3 Risk=Objective uncertainty	R=OU
D4 Risk=Uncertainty	R=U
D5 Risk=Potential/possibility of a loss	R=PO
D6 Risk=Probability and scenarios/(severity of) consequences	R=P&C
D7 Risk=Event or consequence	R=C
D8 Risk=Consequences/damage/severity + uncertainty	R=C&U
D9 Risk=Effect of uncertainty on objectives	R=ISO

Several researchers have argued that much of the controversy about risk analysis as a tool for informing decisions is rooted in fundamentally opposing views on the foundations of risk analysis as a scientific activity and opposing views regarding the nature of the risk concept [39–42].

As the rationale behind these opposing views appears to be less known outside the more theoretically oriented risk research community, and no references have been made to it in the maritime application area, it is considered important to outline some key features. First, a general introduction to the approaches to risk analysis science is given, focusing on the earlier proposed realist-constructivist continuum. Subsequently, a classification of the scientific risk approaches is proposed, which is applied in the subsequent analysis.

### 4.1. Realist, constructivist and proceduralist approaches to risk analysis science

Three broadly differing views on risk analysis can be distinguished: realist, constructivist and proceduralist approaches [39–42]. The outlines given below are intended as a basis for making distinctions, acknowledging that various variations of each approach exist, e.g. related to the types of evidence considered, and the extent of uncertainty treatment.

Risk realists typically consider risk as a physically given attribute of a technology or system, which can be characterized by objective facts. Risk can thus be explained, predicted and controlled by science [40]. Under such approaches, risk is essentially characterized by quantitative (often probabilistic) information regarding events or consequences. Other dimensions sometimes attributed to risk, such as controllability, the voluntariness of exposure and fear, are seen as accidental dimensions and not part of the risk concept per se [39,42,43]. Risk realists work under the presumption that technical analyses are a representation or approximation of an absolute truth, and typically aim at accurate risk measurement. One implication of this reification of risk is the attempt to make a clear distinction between facts and non-epistemic values<sup>1</sup> [39,40]. Another is the strong link between the calculated risk numbers, established risk decision criteria and subsequent decision making, i.e. a risk-based decision making strategy [38,45]. Risk management decisions are seen as rational to the extent they are based on the realist, non-personal factors of technical analysis.

Risk constructivists typically hold that risk is a social construct, attributed to (rather than part of) a technology or system [40]. The risk analysis is presented as a reflection of a mind construct of a (group of) expert(s) and/or lay people. In strong constructivist approaches, risk can be characterized by quantitative (probabilistic) information regarding events or consequences, but these risk dimensions are at par with controllability, fear, the voluntariness of exposure and other psychometric factors. Neither of these are essential parts of the risk concept, and it is a contextual decision which are considered relevant [42,46]. Risk constructivists focus on the cognitive and social dimensions of knowledge claims regarding risk, place more stress on the importance of uncertainty and some argue against a strict separation between facts and values [39]. There often is a strong link to decision making, but risk analyses are used to inform a decision, requiring a managerial decision making where other factors are considered as well [38,45].

An additional distinction can be made related to the role of stakeholders in the risk analysis process. In the realist and

<sup>1</sup> Non-epistemic values are of a moral, political or aesthetic nature, i.e. values which have no relevance to determining whether a claim is true but stem from a reflective consideration of what is good in a given context [44].

**Table 2**

Outline of the elements of risk perspectives applied in maritime transportation risk analysis.

	<b>Definition</b> <b>Rationale of the measurement tool</b>	<b>Ref.</b>
$P_f$	Frequentist probability Fraction of time a specified outcome occurs in an in principle infinite number of repeated tests A distinction is made between $P_f$ as a concept and its measurement $P_f^*$ , which is derived from empirical data, a thought-constructed “repeated experiment” or a repeated evaluation of an engineering or statistical model	[13,15–17]
$P_s$	Subjective probability Degree of belief of an assessor based on evidence available to him/her, i.e. a measure of outcome uncertainty	[13,15–17]
$P_x$	Modelled probability Calculated probability measure based on a data- or judgment-based model, mapping non-probabilistic predictor variables to a probability (or probability-like) scale	[18–20]
$I_{QU}$	Quantitative indicator A ratio- or interval scale measure of a characteristic of the system, used as a proxy of the occurrence of events and/or consequences. The quantitative measure is derived from data, or by applying a model in data	[21–23]
$I_{QL}$	Qualitative indicator A categorical or ordinal measure of a characteristic of the system, used as a proxy of the occurrence of events and/or consequences. The qualitative measure is based on a judgement by an assessor, obtained either through direct judgment or derived from a mathematical model	[21–23]
$F$	Fuzzy number A measure derived from the degree to which a specific instance belongs to a certain category, i.e. the degree of similarity between the instance and the category	[24–26]
$A$	Event A specific (defined) state of the world and how that specified state changes or develops over a time interval	[27]
$C$	Consequence A specific type of event, connected to another event through a causal relation, i.e. under conditions of constant conjunction, temporal succession and spatial propinquity	[27]
$U_{QL}$	Qualitative measure of evidential uncertainty or qualitative measure of the strength of knowledge A linguistic or numerical measure on an ordinal or categorical scale indicating the lack of knowledge (or conversely, the strength of knowledge) for making a measurement or statement	[28–30]
$U_{QU}$	Quantitative measure of evidential uncertainty A numerical measure on an interval or ratio scale, quantifying the epistemic uncertainty related to parameters of a model, e.g. applying imprecise (interval) probability, probability bound analysis, evidence theory or possibility theory	[14,31,32]
$U_{AH}$	Alternative hypothesis-based epistemic uncertainty An expression of epistemic uncertainty, in particular related to model structure, by weighing multiple plausible hypotheses related to a given phenomenon	[33,34]
$B$	Bias A categorical or ordinal measure indicating the direction of deviation from what is believed to be an accurate reflection of the phenomenon, in relation to the applied representation of the phenomenon accepted in a given context	[35–37]

constructivist approaches, risk analysis applications are mainly seen as a process of knowledge transfer from analysts and experts to decision makers. In the proceduralist approach, different stakeholders such as scientists, experts, risk-affected lay persons and policy makers, take part in a process in which risk is characterized through a shared understanding, balancing facts and values [39]. Hence, risk analysis and related decision making is understood through an analytic-deliberative process [47].

#### 4.2. Applied classification of approaches to risk analysis science

The general approaches to risk analysis as a scientific discipline as outlined in Section 4.1 are further distinguished by considering a number of criteria used to classify the risk analysis applications in Section 5. The presented classification distinguishes eight classes, see Table 3 and Fig. 1. Following criteria are considered for classifying risk analysis applications to these classes: (i) focus on an underlying true risk, (ii) reliance on data and models from natural or engineering sciences, (iii) reliance on expert judgment, (iv) reliance on non-epistemic values, (v) reliance on lay people's judgment, (vi) extent of uncertainty assessment, (vii) stakeholder involvement, (viii) consideration of contextual attributes (fear, voluntariness, etc.), and (ix) relation between the risk analysis and decision-making.

The characteristics of the classes are summarized in Table 3, where some references are given to work where (some aspects of) the approaches are more elaborately described. A visual representation of the classification is given in Fig. 1, clearly showing the multi-faceted diversity in approaches to risk analysis.

#### 5. Risk analysis applications for maritime transportation

In this section, a concise overview is given of the maritime transportation risk analysis applications, i.e. applications analyzing the accidental risk of maritime transportation in a given waterway or sea area. The review covers the period from 1970 to 2014, using a total of 58 applications. For each analysis, following characteristics are determined in Tables 4–7:

- (i) the analysis aims and scope;
- (ii) the applied definition of risk, see Table 1;
- (iii) the applied tools to measure risk, see Table 2;
- (iv) whether events (A), or events and consequences (A, C) are accounted for;
- (v) the tools applied to convey information regarding the confidence in the analysis, see Table 2;
- (vi) the applied types of evidence (data, models, expert judgments, layperson judgments, non-epistemic values);
- (vii) the consideration of contextual attributes (fear, voluntary exposure, equity, etc.);
- (viii) the adopted approach to risk analysis science, according to the classification of Table 3.

The risk perspectives are denoted as  $R \sim (x_1, \dots, x_n, y_1, y_2 | z_1, \dots, z_m)$  or  $R \sim (x_1, \dots, x_n \rightarrow y_1, y_2 | z_1, \dots, z_m)$ , where “ $\sim$ ” signifies “is described by”, “ $\rightarrow$ ” means “refers to” and “ $|$ ” represents “conditional to”. For analyses where the actual occurrence of events and/or consequences is measured, the elements are simply listed. For analyses where the occurrence of events and/or consequences is not measured per se, but rather inferred from other measures, the symbol “ $\rightarrow$ ” is used. The

**Table 3**  
Applied classification of approaches to risk analysis science.

RA	Approach	Characteristics	Ref.
I	<b>Strong realist</b>	<ul style="list-style-type: none"> <li>• Risk is considered to exist objectively as a physical attribute of a system, and the analysis is presented as an estimate of this underlying true risk</li> <li>• Exclusively relies on data collected from the system or on engineering / natural science models</li> <li>• Expert judgment is not considered a source of evidence</li> <li>• Evidence uncertainty is not considered</li> <li>• Stakeholders are not involved in analysis process</li> <li>• Strict separation between facts and non-epistemic values</li> <li>• Contextual risk attributes are not considered</li> <li>• Strong relation to established risk decision criteria; risk-based decision making</li> </ul>	[39,43]
II	<b>Moderate realist</b>	<ul style="list-style-type: none"> <li>• Similar as the strong realist approach</li> <li>• Heavily relies on data collected from the system or on engineering / natural science models</li> <li>• Expert judgment considered a source of evidence, but knowledge generated by experts is seen as a last resort and/or is seen as truth approaching</li> <li>• Evidence uncertainty is not considered, or only sporadically mentioned</li> </ul>	[48]
III	<b>Moderate realist with uncertainty quantification</b>	<ul style="list-style-type: none"> <li>• Similar as moderate realist approach</li> <li>• Evidence uncertainty is considered through quantification of uncertainty about parameters of a model</li> </ul>	[35,49,50]
IV	<b>Scientific proceduralist</b>	<ul style="list-style-type: none"> <li>• Relies on data collected from the system, engineering/natural science models, as well as expert and layperson's judgment</li> <li>• Evidence uncertainty may or may not be considered in the analysis</li> <li>• Broad stakeholders process set up to perform risk analysis and decision making</li> <li>• Facts and non-epistemic values are considered relevant in characterizing risk</li> <li>• Contextual risk attributes may or may not be considered</li> </ul>	[39,47]
V	<b>Precautionary constructivist</b>	<ul style="list-style-type: none"> <li>• Similar as moderate constructivist</li> <li>• Evidence uncertainty may or may not be considered in the analysis</li> <li>• Facts and non-epistemic values are considered relevant in characterizing risk</li> </ul>	[35,36]
VI	<b>Moderate constructivist with uncertainty evaluation</b>	<ul style="list-style-type: none"> <li>• Similar as moderate constructivist</li> <li>• Risk exists objectively in the sense of broad-intersubjectivity</li> <li>• Risk is understood as an assessor's uncertainty about events/consequences</li> <li>• Model-based risk analysis accompanied by broad qualitative uncertainty assessment, possibly including quantitative evaluation of alternative hypotheses</li> <li>• Non-epistemic values are excluded from the risk characterization</li> </ul>	[29,51–53]
VII	<b>Moderate constructivist</b>	<ul style="list-style-type: none"> <li>• The analysis is presented as a reflection of an assessor's mental construct</li> <li>• Relies on data collected from the system, engineering / natural science models, as well as expert judgment</li> <li>• Evidence uncertainty is not considered</li> <li>• Stakeholders are not involved in analysis process</li> <li>• Non-epistemic values are excluded from the risk characterization</li> <li>• Contextual risk attributes are not considered</li> <li>• Clear link to decision making, in terms of a managerial review, where other decision criteria are considered along with the risk analysis</li> </ul>	[15,54]
VIII	<b>Strong constructivist</b>	<ul style="list-style-type: none"> <li>• Risk is a social construct, involving factual and psycho-perceptual attributes</li> <li>• Primarily lay person's judgment, which may be informed by expert judgment, data collected from the system and engineering / natural science models</li> <li>• Evidence uncertainty and non-epistemic values may or may not be considered</li> <li>• Contextual risk attributes are considered; and their importance may exceed that of data, models and expert judgment if the analysis is part of a decision process</li> <li>• Risk information is not necessarily part of a decision process</li> </ul>	[39,46,55]

parameters  $x_i$  ( $i=1,\dots,n$ ) are the measurement tools of Table 2, i.e.  $P_s^*$ ,  $P_s$ ,  $P_x$ ,  $I_{QU}$ ,  $I_{QL}$  or  $F$ . The parameters  $y_j$  ( $j=1,2$ ) are related to the scope of the analysis, i.e. events  $A$  or consequences  $C$ . In applications where consequences are not assessed, but it is stated that for performing a full risk analysis, consequences need to be considered, the symbol  $C^*$  is used. The parameters  $z_k$  ( $k=1,\dots,m$ ) are the tools for conveying information regarding the confidence in the analysis, i.e.  $U_{QL}$ ,  $U_{QU}$ ,  $U_{AH}$  and  $B$ , see Table 2. Where the parameter  $z_k$  is placed between brackets [ ], this signifies that the application mentions the need for considering uncertainty, but that it is not systematically assessed.

A note is in place concerning the deduction of the characteristics of the risk analysis applications. Some characteristics are quite

straightforward to assess. For instance, the definitions (when given), are collected directly from the text. Likewise, it is quite straightforward to determine what kind of evidence is considered relevant in the analysis, if uncertainty is assessed and if contextual attributes are considered in the analysis. However, the adopted approach to risk analysis is based on an interpretation. In most cases, it is very difficult to assess what exactly the theoretical basis of the risk assessment is as this is typically not elaborated upon. The characteristics of Table 3 are taken as a guide to make this assessment, but it is acknowledged that some classifications can be subject to discussion. In this context, it is reminded that the analysis is not aimed at a precise delineation of each method. Rather, a broad



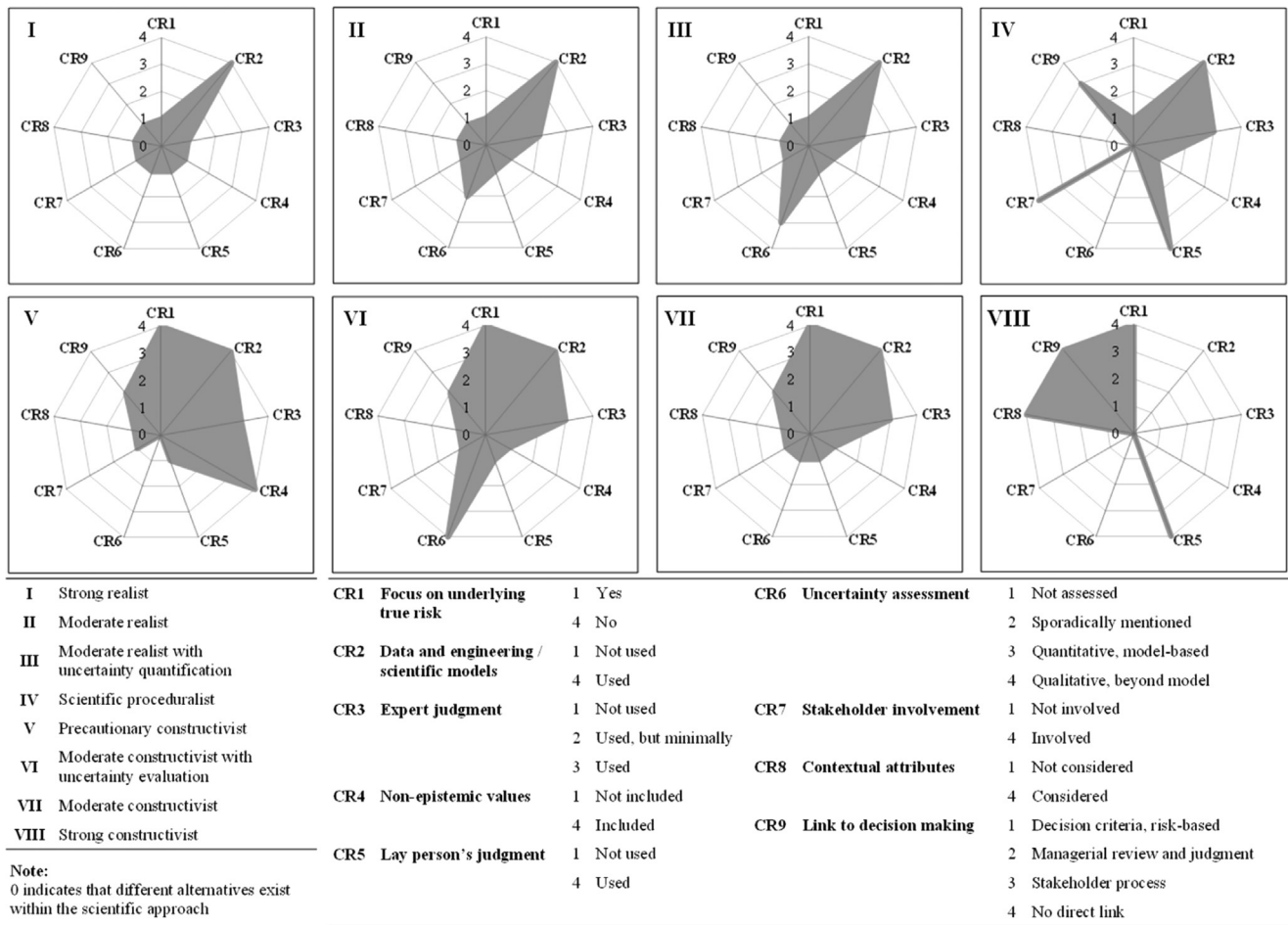


Fig. 1. Conceptual outline of the applied classification of scientific approaches to risk analysis.

Table 4

Summary of risk analysis applications for maritime transportation, period 1970s–2000.

ID Ref	Analysis aim and scope Risk definition	RD	RP	RA	D	M	J	NEV	CA
<b>M1</b> [56]	Study effect of visibility on the number of collisions and groundings in a waterway Not defined								
1974	N/A $R \sim (P_j^*, A)$			I	Y	Y	N	N	N
<b>M2</b> [57]	Determine the expected number of collisions in a sea area Not defined								
1974	N/A $R \sim (P_j^*, A)$			I	Y	Y	N	N	N
<b>M3</b> [58]	Evaluate collision risk in a waterway environment Not defined								
1995	N/A $R \sim (I_{QL}, A)$			II	Y	Y	Y	N	N
<b>M4</b> [59]	Determine the frequency and consequences of collision and grounding in a waterway Not defined								
1995	N/A $R \sim (P_j^*, A, C)$			I	Y	Y	N	N	N
<b>M5</b> [60]	Determine the risk of collision in a waterway Not defined								
1995	N/A $R \sim (P_x, A, C^*)$			I	Y	N	N	N	N
<b>M6</b> [61]	Quantify effect of risk reduction measures on oil spills due to ship accidents Risk is the product of the probability of occurrence and the consequences (p. 236)								
1998	D1 $R \sim (P_j^*, P_x, A, C^*   [U_{QL}])$			IV	Y	Y	Y	N	N
<b>M7</b> [62]	Determine occurrence frequency and consequences of various accident types in a sea area Not defined								
2000	N/A $R \sim (P_j^*, P_x, A, C   [U_{QL}])$			II	Y	Y	Y	N	N
<b>M8</b> [63]	Quantify effect of risk management interventions on risk of oil spills due to ship accidents Not defined								
2000	N/A $R \sim (P_j^*, P_x, A, C)$			IV	Y	Y	Y	N	N

Note: ID=identification number, RD=risk definition (abbreviations as in Table 1), RP=risk perspective (abbreviations as in Table 2), RA=approach to risk analysis science (classification as in Table 3), D=data, M=model, J=judgment, NEV=non-epistemic values, CA=contextual attributes, Y=included in analysis, N=not included in analysis.

**Table 5**

Summary of risk analysis applications for maritime transportation, period 2001–2005.

ID Ref	Analysis aim and scope Risk definition							
Year	RD	RP	RA	D	M	J	NEV	CA
<b>M9</b>	Quantify effect of risk reducing measures on transportation risk in a waterway area							
[64]	Risk is defined by combining likelihood of undesirable event and relevant consequences. (p. 128)							
2001	D6	$R \sim (P_f^R, P_x, A, C)$	IV	Y	Y	Y	N	N
<b>M10</b>	Determine frequency, damage and costs of collision and grounding accidents							
[65]	Not defined							
2002	N/A	$R \sim (P_f^R, P_x, A, C)$	II	Y	Y	Y	N	N
<b>M11</b>	Propose a model for collision probability in a waterway area							
[66]	Risk is defined as a product of the occurrence frequencies (or probabilities) and consequences. (p. 1)							
2002	D1	$R \sim (P_f^R, A, C)$	I	Y	Y	N	N	N
<b>M12</b>	Quantify effect of risk reduction measures on oil spills due to ship accidents							
[67]	Risk is a measure of the probability and severity of undesirable events. (p. 27)							
2002	D6	$R \sim (P_f^R, P_x, A, C)$	IV	Y	Y	Y	N	N
<b>M13</b>	Quantify the effect of implementing a Vessel Traffic Monitoring System on accident risk in sea area							
[68]	Not defined							
2002	N/A	$R \sim (P_f^R, P_x, A, C   B)$	V	Y	Y	Y	Y	N
<b>M14</b>	Determine the expected number of accidents and their consequences in a waterway area							
[69]	Risk is a parameter used to evaluate (or judge) the significance of hazards in relation to safety, [...] hazards are the possible events and conditions that may result in severity. (p. 208)							
2005	D5	$R \sim (P_f^R, P_x, A, C)$	I	Y	Y	N	N	N
<b>M15</b>	Identify hazards, assess the risks and evaluate potential mitigation measures in a waterway							
[70]	Risk is the product of the probability of a casualty and its consequences. (p. 1–3)							
2005	D1	$R \sim (I_{QL} \rightarrow A, C)$	IV	N	N	Y	N	N

Note: ID=identification number, RD=risk definition (abbreviations as in Table 1), RP=risk perspective (abbreviations as in Table 2), RA=approach to risk analysis science (classification as in Table 3), D=data, M=model, J=judgment, NEV=non-epistemic values, CA=contextual attributes, Y=included in analysis, N=not included in analysis.

insight into the various applied risk definitions, perspectives and approaches to risk analysis is provided for facilitating further reflections and discussions.

The overview in Tables 4–7 clearly shows that risk analysis in maritime transportation has attracted increasing attention especially over the last decade. It is infeasible to discuss the classifications of risk definition, perspective and approach to risk analysis for all methods. In Appendix A, some methods are discussed in more detail to exemplify the differences.

## 6. Analysis of risk definitions, perspectives and approaches to risk analysis science

In this section, the risk definitions, perspectives and approaches to risk analysis as a science are analyzed, based on the overview presented in Section 5. First, a historic overview is given of the risk definitions and approaches to risk analysis. Then, the relationship between risk definitions and approaches to risk analysis science is analyzed. Finally, the perspectives in risk analysis applications are inspected, grouped by the applied risk definitions and the adopted approaches to risk analysis science.

### 6.1. Historic overview of risk definition and approach to risk analysis

In Fig. 2, a historic overview of the applied risk definitions is given. A wide variety of definitions is found, but in about half of the applications, no explicit definition is provided. Of the nine categories in Section 2, definitions are clustered in the categories D1 ( $R=EV$ ) and D6 ( $R=P\&C$ ), with a few cases found in categories D5 ( $R=PO$ ), D2 ( $R=P$ ), D7 ( $R=C$ ) and D8 ( $R=C\&U$ ). Thus, in the maritime transportation application area, risk has been strongly tied to probabilities. Only weak historic trends can be identified: from 2010 onwards, more applications stipulate a definition, with a continued predominance of categories D1 ( $R=EV$ ) and D6 ( $R=P\&C$ ). Definitions D5 ( $R=PO$ ) are found since 2005, D2 ( $R=P$ ) and D8 ( $R=C\&U$ ) only recently. This

diversity confirms findings in [5] that the scientific risk discipline faces terminological challenges.

The findings furthermore reflect the analysis by Aven [10] that traditional engineering definitions (D1 and D6) and definitions of decision analysts (D1) represent the predominant views on risk in technical application areas. Aven ([10], p. 40) claims that definitions D8 ( $R=C\&U$ ), considering uncertainty rather than probability a fundamental component of risk, have recently replaced probability-based definitions in engineering fields. From our analysis, it is seen that this is only very minimally the case for the maritime transportation application area. In fact, only one such definition is found.

A more policy-oriented issue is that many applications do not follow the suggested definitions by relevant authorities or standardization organizations. In the guidelines for Formal Safety Assessment (FSA), which is commonly seen as the premier scientific method for maritime risk analysis and for formulating maritime regulatory policy [114], risk is defined as “the combination of the frequency and the severity of the consequence” [115], i.e. a categorization in line with class C6. While definitions based on expected values (D1) are close to this view as it consists of the same elements, definitions in line with D5 and D8 represent significantly different risk classes. The ISO-definition, seeing risk as “the effect of uncertainty on objectives” [116], is not found in the application area.

In Fig. 3, a historic overview of the approach to risk analysis science is shown. It is seen that strong realist views (I) on risk analysis are found from the early work in the application area to the present day. Similarly, there has been much work in line with a moderate realist approach (II) to risk analysis over the same time span. Moderate constructivist approaches (VII) are found since about 2007. Scientific proceduralist approaches (IV) were the predominant view around the year 2000, but are overall less prominently found. Few applications are found using approaches where uncertainty is quantified (III), and also precautionary approaches (V) and constructivist approaches with a broad uncertainty evaluation (VI) are exceptions.

The historic overview clearly shows that a wide range of approaches co-exist in the application area, confirming findings in [5,39,40] that there are different paradigms to risk analysis as a scientific activity.

**Table 6**

Summary of risk analysis applications for maritime transportation, period 2006–2010.

ID Ref	Analysis aim and scope		Risk definition					
Year	RD	RP	RA	D	M	J	NEV	CA
<b>M16</b>	Quantify uncertainty in a maritime transportation risk assessment							
[71]	Not defined							
2006	N/A	$R \sim (P_f^*, P_x, A, C^*   U_{QU})$	III	Y	Y	Y	N	N
<b>M17</b>	Determine the relative risk of various navigation areas in a coastal waterway area							
[72]	Risk is [...] the possibility of the occurrence of hazardous accidents or abnormal incidents. (p. 370) Risk is [...] a consequence involved in the damages resulting from a hazardous accident. (p. 370) Risk possesses duplex-characteristics [sic] of possibility (F) and severity (N) [...] frequency (F) can be viewed as the ratio of number of accidents against the number of ship's activities per unit time (p.370)							
2007	D5/D7	$R \sim (F, A, C)$	VII	N	N	Y	N	N
<b>M18</b>	Investigate the effect on collision and grounding risk of introducing a TSS in a sea area							
[73]	Risk is the product of the probability and the consequences of an unwanted event (p. 8)							
2008	D1	$R \sim (P_f^*, A, C)$	I	Y	Y	N	N	N
<b>M19</b>	Determine the accident probability and consequences in a sea area							
[74]	Not defined							
2008	N/A	$R \sim (A, P_f^*, C)$	I	Y	Y	N	N	N
<b>M20</b>	Determine the collision risk in a part waterway through a vessel-conflict technique							
[75]	Not defined							
2009	N/A	$R \sim (P_x, A)$	VII	Y	N	Y	N	N
<b>M21</b>	Propose a meta-model for integrated environmental oil spill risk from ship accidents							
[76]	Not defined							
2009	N/A	$R \sim (P_f^*, P_s, A, C)$	VII	Y	Y	Y	N	N
<b>M22</b>	Quantify effect of risk reduction measures on accident risk in a waterway area							
[77]	Not defined							
2009	N/A	$R \sim (P_f^*, P_x, A, C)$	VII	Y	Y	Y	N	N
<b>M23</b>	Determine the collision risk in a part waterway through a vessel-conflict technique							
[78]	Not defined							
2010	N/A	$R \sim (P_x, A)$	VII	Y	N	Y	N	N
<b>M24</b>	Determine the grounding frequency in a waterway							
[79]	Not defined							
2010	N/A	$R \sim (P_f^*, A, C^*)$	I	Y	Y	N	N	N
<b>M25</b>	Determine expected economic loss due to environmental pollution from oil tankers, for various sea areas							
[80]	Risk is the value of loss under uncertainty, i.e. it is a sum of products of probabilities of occurrence of certain damages. (p. 61)							
2010	C1	$R \sim (A, P_f^*, P_s, C)$	II	Y	Y	Y	N	N
<b>M26</b>	Propose a meta-model for minimizing ecological risks of maritime transportation in a sea area							
[81]	The concept of risk contains both the probability of a certain event and the magnitude of the harm caused if it becomes true							
2010	C6	$R \sim (P_f^*, P_s, A, C)$	VII	Y	Y	Y	N	N
<b>M27</b>	Determine the frequency and consequences of collision in a waterway							
[82]	Not defined							
2010	N/A	$R \sim (P_x, A, C)$	I	Y	Y	N	N	N
<b>M28</b>	Determine the ship collision probability in a sea area							
[83]	Risk is defined as the product of probability of occurrence of an undesired event and the expected consequences. (p. 573)							
2010	C1	$R \sim (P_f^*, P_x, A, C^*)$	I	Y	Y	N	N	N
<b>M29</b>	Calculate maritime accident frequencies in a sea area							
[84]	Risk is the product of the probability/frequency of the unwanted event and its consequences. (p. 10)							
2010	C1	$R \sim (P_f^*, A, C^*)$	I	Y	Y	N	N	N

Note: ID=identification number, RD=risk definition (abbreviations as in Table 1), RP=risk perspective (abbreviations as in Table 2), RA=approach to risk analysis science (classification as in Table 3), D=data, M=model, J=judgment, NEV=non-epistemic values, CA=contextual attributes, Y=included in analysis, N=not included in analysis.

Most of the work is rooted in the idea that a true, mind-independent risk exists in line with realist approaches as outlined in Table 3. Using different modeling approaches, many methods aim to accurately estimate this true risk. While the use of expert judgment has gained steady support, many applications rely heavily on accident and traffic data. Even when judgment is applied, it is often used as if it (should) uncover(s) an underlying true risk. Constructivist views exist, but broad assessments of uncertainty and/or bias, used to convey information regarding the confidence in the analysis, are very rare.

## 6.2. Relation between risk definition and approach to risk analysis science

In Fig. 4, the applied risk definitions are grouped per approach to risk analysis science. It is observed that risk definitions D1 ( $R=EV$ ) are more strongly tied to realist approaches, whereas definitions in line with D6 ( $R=P\&C$ ) are found across the spectrum of approaches to risk science. Applications where risk is not defined also range across the different scientific approaches to risk analysis. The other

applied definitions are less frequently found, precluding insight in the relation to the scientific approaches.

This result implies that the adopted definition does not necessarily provide much information regarding the adopted scientific approach. For example, defining risk through probabilities of events and consequences (D6) can lead to strong realist approaches to risk analysis if the risk concept is literally understood as such. However, the same definition can be used to subsequently introduce a risk measure in an analytic-deliberative decision process. Similar considerations can be made for the other definitions.

From this, it is clear that while providing clarity about definitions and terminology is important in applications, this does not suffice to settle deeper disputes about the feasibility of rationalist, constructivist or proceduralist approaches to risk analysis.

## 6.3. Risk perspectives in relation to risk definitions

In Table 8, an overview is shown of the applied risk perspectives in the applications of Section 5, grouped by risk definition.



**Table 7**

Summary of risk analysis applications for maritime transportation, period 2011–2014.

ID Ref	Analysis aim and scope	Risk definition						
Year	RD	RP	RA	D	M	J	NEV	CA
<b>M30</b>	Determine the ship collision probability in a sea area							
[85]	Risk is defined as the product of the probability of occurrence of an undesired event and the expected consequences. (p. 91)							
2011	D1	$R \sim (P_j^*, A, C^*)$	I	Y	Y	N	N	N
<b>M31</b>	Determine expected oil spill costs due to maritime accidents in a sea area							
[86]	Risk is defined as the product of the probability of occurrence of an undesirable event and the expected consequences (p. 91)							
2011	D1	$R \sim (P_j^*, P_x, A, C)$	I	Y	Y	N	N	N
<b>M32</b>	Quantify effect of risk reduction measures on oil spills due to ship accidents							
[87]	Risk is the complete set of triplets $\{(s_i, l_i, c_i)\}_c$ where $s_i$ describes the context of the accident scenario, $l_i$ the likelihood of an accident occurring in that scenario and $c_i$ a description of the consequences. (p. 251)							
2011	D6	$R \sim (P_j^*, P_x, A, C)$	VII	Y	Y	Y	N	N
<b>M33</b>	Determine the sea areas where collisions are more likely and evaluate effect of speed limits							
[88]	Not defined							
2011	N/A	$R \sim (I_{QU} \rightarrow A)$	II	Y	Y	Y	N	N
<b>M34</b>	Determine effect of a new traffic scheme on the oil spill probability and consequences in a sea area							
[89]	Risk is the frequency of a hazard multiplied by its consequence. The term is, however, often used as a mere probability of an accident/incident with adverse consequences (p. 246)							
2012	D1/D2	$R \sim (P_j^*, A, C)$	I	Y	Y	N	N	N
<b>M35</b>	Quantify effect of risk reduction measures on accident risk in a waterway area							
[90]	Risk is the combination of situations, likelihoods and consequences. (p. 72)							
2012	D6	$R \sim (P_j^*, P_x, A, C)$	VII	Y	Y	Y	N	N
<b>M36</b>	Propose a simulation environment for evaluating the risk in a sea area							
[91]	Risk is the possibility of an adverse event. (p. 58)							
2012	D5	$R \sim (I_{QL}, A)$	II	N	Y	Y	N	N
<b>M37</b>	Determine the risk of oil spill and hazardous substances in a sea area							
[92]	A measure of both the likelihood and consequence, if a hazard manifests itself (p. RMN-14)							
2012	D6	$R \sim (P_j^*, P_s, A, C)$	II	Y	Y	Y	N	N
<b>M38</b>	Determine probability of tanker collisions and probability of an oil spill in a sea area							
[93]	Risk is a set of triplets $\{(s_i, l_i, c_i)\}_i$ , $i=1, 2, 3, \dots$ with $s_i$ the context of the accident scenario, $l_i$ the likelihood of the accident occurring in that scenario and $c_i$ the evaluation of the consequence in the scenario. (p. 381)							
2012	D6	$R \sim (P_j^*, P_s, A, C)$	II	Y	Y	Y	N	N
<b>M39</b>	Investigate the sensitivity and discuss uncertainty about the impact scenarios in tanker collisions							
[94]	Risk is the complete set of triplets $\{(s_i, l_i, x_i)\}_c$ where $s_i$ defines the description of the $i$ th risk scenario path, $l_i$ the likelihood of the path occurrence and $x_i$ represents the consequences of the path. (p. 75)							
2012	D6	$R \sim (P_j^*, P_s, A, C \mid [U_{QL}])$	II	Y	Y	Y	N	N
<b>M40</b>	Determine the collision risk in a waterway							
[95]	Not defined							
2012	N/A	$R \sim (P_x, A)$	II	Y	N	Y	N	N
<b>M41</b>	Determine the probability and consequences of collision between LNG vessel and harbor tug							
[96]	Risk is the product of the probability of a scenario and the consequences of a scenario. (p. 7)							
2012	D1	$R \sim (P_j^*, P_s, A, C)$	II	Y	Y	Y	N	N
<b>M42</b>	Calculate the collision frequency in a waterway							
[97]	Not defined							
2012	N/A	$R \sim (P_j^*, P_s, A, C^*)$	II	Y	Y	Y	N	N
<b>M43</b>	Determine the relative risk of coastal areas, and determine through statistical analysis if risk level is acceptable							
[98]	Risk is the possibility of a harmful event. (p.33) Risk is the consequences of the normal level of event leading to injury. (p.33) Risk is of double characteristics with frequency and consequences degree (p.33)							
2012	D5/D7/D6	$R \sim (P_j^*, I_{QL}, A, C)$	VII	Y	N	Y	N	N
<b>M44</b>	Determine the accidental risk of chemical tanker spills in a given sea area							
[99]	Risk is the probability of something adverse happening multiplied by the consequences. (p. 10)							
2012	D1	$R \sim (P_j^*, P_x, A, C \mid [U_{QL}])$	II	Y	Y	N	N	N
<b>M45</b>	Determine the areas of a waterway where collisions are more likely							
[100]	Not defined							
2012	N/A	$R \sim (P_x, I_{QU} \rightarrow A)$	II	Y	N	Y	N	N
<b>M46</b>	Calculate the collision frequency in a waterway							
[101]	Not defined							
2012	N/A	$R \sim (P_j^*, A, C^*)$	I	Y	Y	N	N	N
<b>M47</b>	Calculate collision frequency with vessels laying at an anchorage							
[102]	Risk is the combination of number of occurrences per time unit and the severity of their consequences (p. 287) Risk is the probability of an event multiplied by its expected damage. (p. 287)							
2013	D6/D1	$R \sim (P_j^*, A, C^*)$	I	Y	Y	N	N	N
<b>M48</b>	Determine the collision risk of maritime traffic in a sea area							
[103]	Risk can be defined as the probability of occurrence of an unwanted event multiplied by the consequences of that same event. (p. 888)							
2013	D1	$R \sim (P_j^*, A, C^*)$	I	Y	Y	N	N	N
<b>M49</b>	Examine the feasibility of data-based generalized linear modeling technique to risk analysis of navigation							
[104]	Not defined							
2013	N/A	$R \sim (P_x, A)$	I	Y	N	N	N	N
<b>M50</b>	Propose a method to quantify uncertainty related to traffic data in maritime risk assessment							
[105]	Not defined							
2013	N/A	$R \sim (P_j^*, A, C^* \mid U_{QU})$	III	Y	Y	N	N	N
<b>M51</b>	Determine the accident risk of maritime transportation in an inland waterway							
[106]	A risk is composed of two elements: an event or accident occurrence probability and its impact, also known as the consequence severity. (p. 96) Risk is often defined as the combination [product] of its probability and consequences (p. 100)							

Table 7 (continued)

ID	Analysis aim and scope								
Ref	Risk definition								
Year	RD	RP	RA	D	M	J	NEV	CA	
2013	D6/D1	$R \sim (P_f^*, P_s, I_{QU}, I_{QL}, A, C)$	VII	Y	Y	Y	N	N	
<b>M52</b>	Propose tools to assess uncertainty and bias in a maritime transportation risk model through a case study								
[107]	Risk is defined through scenarios, probabilities and consequences. (p. 2296)								
2014	D6	$R \sim (P_f^*, P_s, P_x, A, C   U_{QL}, B)$	V	Y	Y	Y	Y	N	
<b>M53</b>	Determine the effect of implementing a navigation service of collision and grounding risk in a sea area								
[108]	Not defined								
2014	N/A	$R \sim (P_s, A, C^*)$	VII	N	N	Y	N	N	
<b>M54</b>	Propose a framework for analyzing risk in a sea area through a case study of RoPax vessels								
[109]	Risk is [...] a condition under which it is possible both to define a comprehensive set of all possible outcomes and to resolve a discrete set of probabilities across this array of outcomes. (p. 143)								
2014	D2	$R \sim (P_f^*, P_s, P_x, A, C   U_{QU})$	III	Y	Y	Y	N	N	
<b>M55</b>	Calculate the frequency of ship sinking due to collision in a waterway								
[110]	Not defined								
2014	N/A	$R \sim (P_f^*, A, C^*)$	I	Y	Y	N	N	N	
<b>M56</b>	Apply a method for analyzing evidence uncertainty through a case study of risk of chemical tanker collisions								
[111]	Risk could be defined and foremost taken as the uncertainty regarding (negative) outcomes. (p. 26)								
2014	D8	$R \sim (P_f^*, P_s, P_x, A, C   U_{QL})$	VI	Y	Y	Y	N	N	
<b>M57</b>	Determine the risk of shipping routes in a sea area								
[112]	Not defined								
2014	N/A	$R \sim (I_{QL}, F \rightarrow A)$	VII	Y	N	Y	N	N	
<b>M58</b>	Apply a failure mode and effects analysis (FMEA) method to ship collision risk in a sea area								
[113]	Not defined								
2014	N/A	$R \sim (F, A, C)$	VII	Y	N	Y	N	N	

Note: ID=identification number, RD=risk definition (abbreviations as in Table 1), RP=risk perspective (abbreviations as in Table 2), RA=approach to risk analysis science (classification as in Table 3), D=data, M=model, J=judgment, NEV=non-epistemic values, CA=contextual attributes, Y=included in analysis, N=not included in analysis

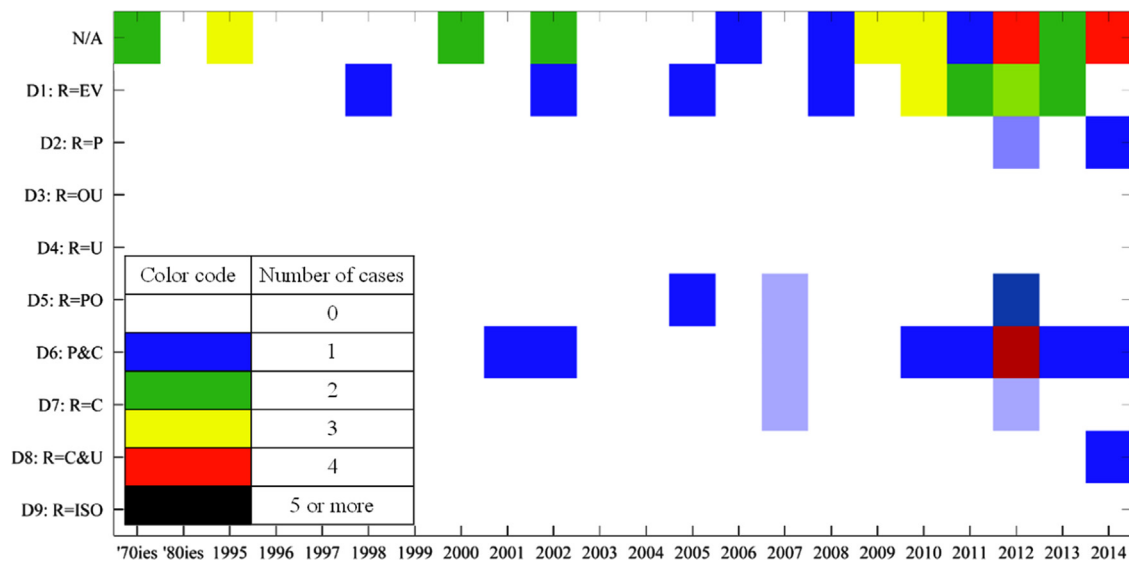


Fig. 2. Historic overview of the applied risk definitions in applications of maritime transportation risk analysis, classification as in Table 1, cases from Tables 4–7.

Only cases where an explicit definition is provided, are retained. The reader is reminded that a risk perspective is here understood as a way to describe risk, a systematic manner to analyse and make statements about risk, see Section 3. Risk descriptions contain measurement tools ( $P_f^*$ ,  $P_s$ ,  $P_x$ ,  $I_{QU}$ ,  $I_{QL}$  and  $F$ , see Table 2), which address an event ( $A$ ) or events and consequences ( $A$  and  $C$ ), and may be supplemented by measures regarding the confidence in the analysis ( $U_{QU}$ ,  $U_{QL}$ ,  $U_{AH}$  and  $B$ , see Table 2).

It is seen that the elements of the risk perspectives are usually well in line with the adopted definition. For example, applications using the definition D1 ( $R=EV$ ) focus on events and consequences as implied in the definition, and use probabilities to describe risk.

A similar conclusion can be drawn from perspectives in applications where definition D6 ( $R=P\&C$ ) is applied.

However, aberrations occur, for example regarding the scope of the analysis. In definition classes D2 ( $R=P$ ) and D7 ( $R=C$ ), the applications analyze events as well as consequences, whereas the definition only focuses on an event, without reference to consequences. Likewise, in definition classes D1 ( $R=EV$ ) and D6 ( $R=P\&C$ ), there are instances where risk is not measured using probabilities (as implied in the definitions), but using indicators (e.g. M15, M43 and M51) or fuzzy numbers (M17).

It is also noteworthy that in applications where definitions D5 ( $R=PO$ ) or D7 ( $R=C$ ) are used, i.e. definitions where no reference

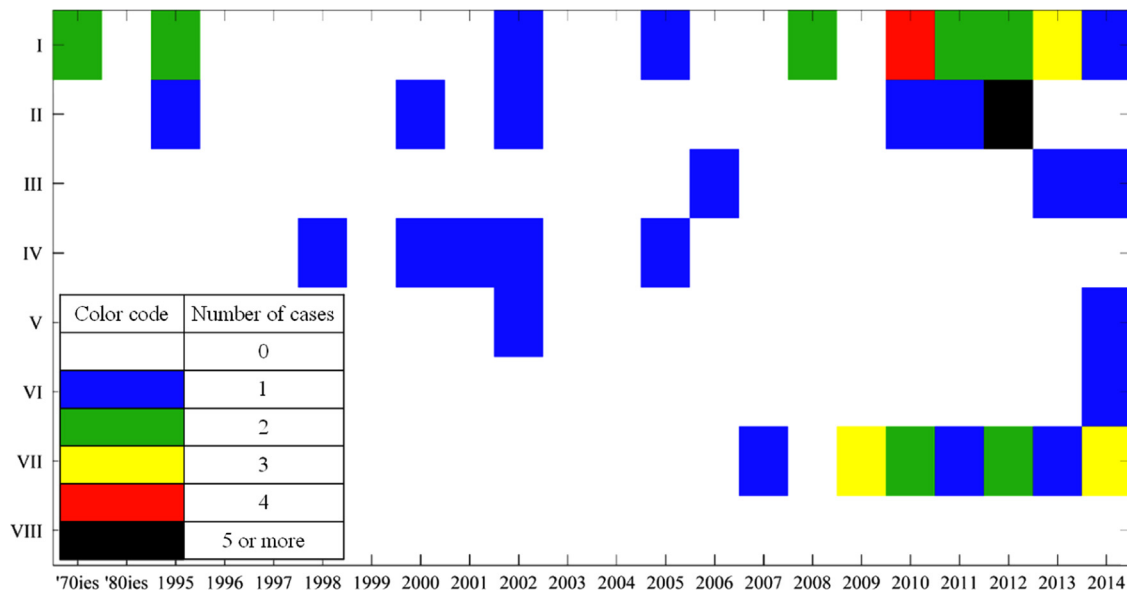


Fig. 3. Historic overview of the adopted scientific approaches to risk analysis in applications of maritime transportation risk analysis, classification as in Table 3, cases from Tables 4–7.

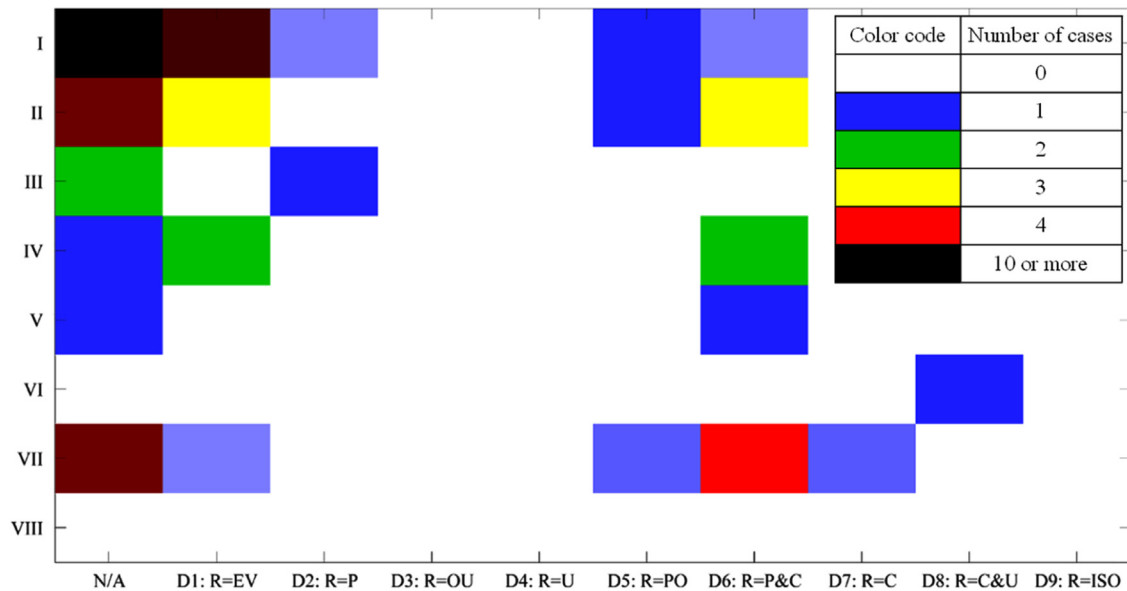


Fig. 4. Relation between applied risk definitions (Table 1) and adopted scientific approaches to risk analysis (Table 3) in applications of maritime transportation risk analysis, cases from Tables 4–7.

is made to a specific measurement tool, indicators (M36, M43) and fuzzy numbers (M17) are relatively more frequently found than in other definition classes.

It is furthermore observed that very few applications take a perspective where measures to assess the confidence in the analysis are considered, irrespective of the risk definition class. Only in the application where risk is defined through uncertainty (M56) a broad uncertainty assessment is performed. In some applications using probability-based definitions, uncertainty is considered through alternative hypotheses (M52, M54) or a broad uncertainty and bias assessment (M54). In definition classes D5 (R=PO) and D7 (R=C), the reviewed applications do not consider uncertainties or biases in the adopted risk perspectives.

Thus, it can be concluded that there generally is a very significant relation between the adopted definitions and the applied risk perspectives, which confirms claims that how one defines and understands risk to a large degree determines how one assesses it [55,117].

#### 6.4. Risk perspectives in relation to approach to risk analysis science

In Table 9, an overview is shown of the applied risk perspectives in the applications of Section 5, grouped by the adopted approach to risk analysis science. This provides insight into how the application area has understood risk analysis, in light of the criteria outlined in Section 4.2, see Table 3.

In the strong realist approaches, risk perspectives consist exclusively of probabilistic risk measures ( $P_f^*$  and  $P_x$ ). The evidence base for these probabilities consists exclusively of data or models. Probabilities of accident occurrences are calculated directly from observed frequencies ( $P_f^*$ , e.g. M19) or through probability models ( $P_x$ , e.g. M5). Uncertainties are not assessed, and the analysis is presented as a representation of a true underlying risk.

Moderate realist approaches show a more diverse spectrum of risk perspectives. While still dominated by probabilistic measures in terms of  $P_f^*$  and  $P_x$ , subjective probabilities  $P_s$  are also applied, e.g. in

**Table 8**

Analysis of applied measurement tools and tools for conveying confidence in analysis by risk definition as in Table 1, cases from Tables 4–7.

Risk definition	ID	Year	$P_f^*$	$P_s$	$P_x$	$I_{QU}$	$I_{QL}$	F	A	C	$C^*$	$U_{QU}$	$U_{QL}$	$U_{AH}$	B
<b>D1: R=EV</b>	M6	1998	x		x				x		x			[x]	
	M11	2002	x						x	x					
	M15	2005					x		x	x					
	M18	2008	x						x	x					
	M25	2010	x	x					x	x					
	M28	2010	x		x				x		x				
	M29	2010	x						x		x				
	M30	2011	x						x		x				
	M31	2011	x		x				x	x					
	M34	2012	x						x	x					
	M41	2012	x	x					x	x					
	M44	2012	x		x				x	x				[x]	
	M47	2013	x						x		x				
	M48	2013	x						x	x					
	M51	2013	x	x		x	x		x	x					
<b>D2: R=P</b>	M34	2012	x						x	x					
	M54	2014	x	x	x				x	x					x
<b>D3: R=OU</b>	-														
<b>D4: R=U</b>	-														
<b>D5: R=PO</b>	M14	2005			x				x	x					
	M17	2007							x	x	x				
	M36	2012					x		x						
	M43	2012	x						x	x	x				
<b>D6: R=P&amp;C</b>	M9	2001	x		x				x	x					
	M12	2002	x		x				x	x					
	M17	2007							x	x	x				
	M26	2010	x	x					x	x					
	M32	2011	x		x				x	x					
	M35	2012	x		x				x	x					
	M37	2012	x	x					x	x					
	M38	2012	x	x					x	x					
	M39	2012	x	x					x	x				[x]	
	M43	2012	x				x		x	x					
	M47	2013	x						x		x				
	M51	2013	x	x		x	x		x	x					
	M52	2014	x	x	x				x	x			x	x	x
	M17	2007							x	x	x				
	M43	2012	x				x		x	x					
<b>D7: R=C</b>	M56	2014	x	x	x				x	x			x		
<b>D8: R=C&amp;U</b>	-														
<b>D9: R=ISO</b>	-														

M7, M10 and M37. However, they are used only as a supplement to applications and models otherwise strongly relying on data and models, and the analyses aim at representing a true underlying risk. Quantitative and qualitative indicators  $I_{QU}$  and  $I_{QL}$  are also used as measurement tools in risk perspectives. Such indicators are defined based on expert judgment (e.g. M33), but they are metrics derived directly from ship traffic data. Alternatively, they are judgments modeled based on experiments involving experts (M3). Uncertainties are typically not assessed, but some applications address some uncertainties (M39 and M44), or state that data or model-related uncertainties should be analyzed (M7).

In moderate realist approaches with uncertainty quantification, the focus is also on frequentist, subjective and/or modeled probabilities  $P_f^*$ ,  $P_s$  and  $P_x$ , but quantitative measures of uncertainty supplement these. In M16, uncertainty is considered through Bayesian simulation, i.e. by sampling probability distributions about parameters of a probability model. In M50, uncertainty is quantified using the Dempster–Shafer evidence theory. In M54, uncertainty is considered in a Bayesian Network framework through the application of alternative hypotheses.

Scientific proceduralist approaches (M6, M8, M9 and M12) combine frequentist probabilities  $P_f^*$  and probabilities modeled based on expert judgment  $P_x$ , using a Bayesian paired comparison technique [20]. Alternatively, qualitative indicators  $I_{QL}$  are applied, based on judgments of experts of different stakeholder groups.

Uncertainties are either summarily addressed (M6), or not considered in the analyses.

Moderate constructivist approaches show a rather scattered landscape of risk perspectives. Various types of probability are applied:  $P_f^*$  as derived from data (e.g. M21),  $P_s$  as degrees of belief of an assessor (e.g. M53) and  $P_x$  as modeled representations of experts' judgments (e.g. M23, M32), where judgments of an assessor are the predominant type of evidence. Compared with realist approaches, relatively more use is made of indicators (e.g. M43, M51) and of fuzzy numbers (e.g. M17, M58). Uncertainties are not considered beyond the probabilities, indicators and fuzzy numbers.

Precautionary constructivist and moderate constructivist approaches with uncertainty evaluation also apply the different types of probability. Judgments, data and models are combined in a model construct, which is supplemented with a systematic assessment of biases (M13), uncertainties (M56) or uncertainties and biases (M52).

## 7. Discussion: Risk analysis science and practice in the maritime transportation application area

In this section, a general discussion is given based on the findings from the previous sections. The following issues are addressed: (i) the need to clarify risk-theoretical issues in applications, (ii) the need to systematically consider uncertainty, and (iii) the need for further reflection on science and practice in the application area.

### 7.1. The need to clarify risk-theoretical issues in applications

A significant finding of the current research is that many applications provide little or no attention to risk-theoretical issues, concerning definitions, perspectives and scientific approaches to risk analysis. Risk is often not explicitly defined, and no attention is paid to how the risk concept is understood. Where risk is defined, the adopted definition is typically presented as if no alternatives exist, or no argumentation is given why the definition is taken. This practice may be problematic for several reasons.

First, the lack of clarity may lead to terminological confusion and definitional conflicts in risk communication [49,118]. Second, several authors have argued that the choice of a definition is not a value-neutral endeavor: including or excluding contextual attributes (voluntariness, fear, equity etc.) in the risk definition has a relation to normative commitments in risk management [119–121]. Third, even if contextual factors are excluded, different definitions can represent an opposing conceptual understanding of risk, from which important differences in risk perspectives can result. As found in Section 6.3, probability-based definitions D1 (R=EV) and D6 (R=P&C) commonly lead to probability-based perspectives, whereas possibility-based definitions like D5 (R=PO) are more frequently found with perspectives applying indicators or fuzzy numbers. Uncertainty-based definitions like D8 (R=C&U) lead to a broader risk perspective where other uncertainty factors (underlying the risk model or beyond the modeling scope) are assessed as well. The adapted terminology thus guides, supports, but may also limit which elements are considered in describing risk.

In the application area, there is typically no explicit attention given to the scientific approach underlying risk analysis applications, i.e. it is not clarified whether a realist or constructivist risk foundation is adopted. In fact, no work is found in the maritime application area where these distinctions are introduced or referred to. Nonetheless, as clear from Table 3, the differences are important, for several reasons.

First, considering risk analysis as a science focusing on a 'true', mind-independent underlying risk (realist approaches) or as a

**Table 9**

Analysis of applied measurement tools and tools for conveying confidence in analysis by scientific approach to risk analysis as in Table 3, cases from Tables 4–7.

Scientific approach to risk analysis	ID	Year	$P_f^*$	$P_s$	$P_x$	$I_{QU}$	$I_{QL}$	$F$	$U_{QU}$	$U_{QL}$	$U_{AH}$	$B$
<b>I Strong realist</b>	M1	1974	x									
	M2	1974	x									
	M4	1995	x									
	M5	1995			x							
	M11	2002	x									
	M14	2005			x							
	M18	2008	x									
	M19	2008	x									
	M24	2010	x									
	M27	2010			x							
	M28	2010	x		x							
	M29	2010	x									
	M30	2011	x									
	M31	2011	x		x							
	M34	2012	x									
	M46	2012	x									
	M47	2013	x									
	M48	2013	x									
	M49	2013			x							
	M55	2014	x									
<b>II Moderate realist</b>	M3	1995					x					
	M7	2000	x	x							[x]	
	M10	2002	x	x								
	M25	2010	x	x								
	M33	2011				x						
	M36	2012					x					
	M37	2012	x	x								
	M38	2012	x	x								
	M39	2012	x	x							[x]	
	M40	2012			x							
	M41	2012	x	x								
	M42	2012	x	x								
	M44	2012	x		x						[x]	
	M45	2012			x	x						
<b>III Moderate realist with uncertainty quantification</b>	M16	2006	x		x				x			
	M50	2013	x						x			
	M54	2014	x	x	x							x
<b>IV Scientific proceduralist</b>	M6	1998	x		x						[x]	
	M8	2000	x		x							
	M9	2001	x		x							
	M12	2002	x		x							
	M15	2005					x					
<b>V Precautionary constructivist</b>	M13	2002	x	x								x
	M52	2014	x	x	x						x	x
<b>VI Moderate constructivist with uncertainty evaluation</b>	M56	2014	x	x	x						x	
	M17	2007						x				
<b>VII Moderate constructivist</b>	M20	2009			x							
	M21	2009	x	x								
	M22	2009	x		x							
	M23	2010			x							
	M26	2010	x	x								
	M32	2011	x		x							
	M35	2012	x		x							
	M43	2012	x									
	M51	2013	x	x		x	x					
	M53	2014		x								
	M57	2014					x	x				
	M58	2014						x				
	-											
<b>VIII Strong constructivist</b>	-											

reflection of a mental construct (constructivist approaches) result in different risk analysis and subsequent decision making processes. In the former, risk analysis is a process of fact finding, i.e. an impersonal process governed by data collection and processing, and calculation of quantitative risk metrics using models from engineering and natural sciences. Decision making is strongly linked to the risk analysis, often using predefined risk acceptance criteria or mathematical techniques such as optimization or rational choice models, i.e. decision making is risk-based. In the latter, risk analysis can be understood as a process of problem finding, where judgments of a group of analysts are informed by data and models, possibly supplemented with

uncertainty and/or bias descriptions, providing insight in the strength of evidence for making the judgments. Decision making here has a link to the risk analysis results, but it is an evaluative process in which apart from the quantitative risk metrics, uncertainties and contextual attributes such as public trust, equity and psychometric factors can be considered [38,42].

Second, the different commitments to risk analysis science possibly held by the different actors in a risk management problem (decision makers, analysts, experts, lay people) can lead to important challenges in communicating about risk. Hence, clarity about the foundations is of great importance for practical decision making [122].



Third, clarity about the different approaches to risk science is important from a scientific perspective as well, in relation to the scientific review process. As in risk communication, if the authors and reviewers do not share a common understanding of risk analysis as a scientific activity, this can lead to misunderstandings and misguided expectations. Thus, clarity on the adopted scientific basis is important to improve the reviewing process in scientific risk journals [6].

## 7.2. The need to systematically consider uncertainty

One significant finding of the review and analysis in Sections 5 and 6 is the lack of uncertainty treatment in the application area. Only three applications are found where uncertainty is quantified (M16, M50 and M14), and qualitative assessments of uncertainties and/or biases are equally rare (M13, M52, M56). However, in all three applications analyzed in more detail in Appendix A, important uncertainties which are not addressed in the actual applications, have been found.

In our view, the systematic consideration of uncertainty is a fundamental issue in risk analysis, which goes beyond the quantification of uncertainty of parameters or model structure. Two aspects are important. First, uncertainty related to the evidence for making statements about risk and for constructing the risk model should be considered, known as “evidence uncertainty” [30]. Second, uncertainty related to the occurrence of the events/consequences, in relation to the representation by a risk model should be considered. This is known as “outcome uncertainty” [30], and can be accounted for through a (qualitative) assessment of uncertainty factors beyond the model space.

Quantification and propagation of parameter uncertainty (as in M16, M50), or accounting for structural uncertainty through alternative hypotheses (M54) can provide confidence in the sense of bounding model-based uncertainties. However, it is questionable in how far such quantification can in practical settings account for all relevant evidential and outcome uncertainty. This would in principle require that a quantitative uncertainty measure is defined about all parameters and structural assumptions of the entire model, which are propagated over the entire model space [123]. Such a procedure is infeasible in practice, such that uncertainty is considered only about a selection of parameters (M16, M50) or about selected structural assumptions (M54). It is not clear in how far such uncertainty quantification adequately captures all decision-relevant uncertainty, because such procedures cannot account for uncertainties stemming from the omission of potentially relevant factors and because a purely quantified uncertainty analysis may fail to uncover the strength of evidential support for various model elements. We thus favor a broad assessment of the evidence base, as well as a systematic consideration of uncertainties beyond the model, as in [28,29]. Evidential biases, when present, can be assessed as well, as in [36,37].

Uncertainty treatment has been proposed as a validity criterion for quantitative risk analysis [124]. Another reason for the need to consider uncertainty is the responsibility of scientists to consider the consequences of error when informing public policy, which requires awareness and openness about the limitations in data and information, the inadequacies of models and opposing judgments [125].

## 7.3. Suggestions for improvement of the current situation

### 7.3.1. Clarity about fundamental issues in applications

As discussed in Section 7.1, it is important to provide clarity about the conceptual understanding of risk, the adopted risk definition and perspective, and insight in the scientific approach taken to risk analysis. Fig. 5 provides a schematic overview of

concepts relevant for performing a risk analysis, which can be useful for clarifying the foundations in applications.

First, the risk analysis is embedded in a decision context, which sets the stage for the analysis by specifying the scope and focus of the analysis, but also by providing limitations in terms of resources (time, money, expertise) for performing the analysis. Where value judgments are required, the decision context can also inform the analysts to prefer conservative or optimistic inferences, so the decision context and the risk analysis are not necessarily independent [126].

Second, the risk analysis is conditional to a scientific approach to risk analysis as a science, and a reasoned choice is required between realist, proceduralist and constructivist approaches, as outlined in Table 3. There is potential for disagreement between various stakeholders in agreeing on the scientific approach, but a reasoned discussion on a philosophical rather than on a personal level may contribute to a decision. This can be facilitated by considering the relevant literature, see Table 3.

Third, the conceptual understanding of risk and the object of inquiry are considered. This means that clarity is needed about what risk per se is, how it connects to other concepts relevant in the analysis and what ontological, epistemological and normative implications this understanding has. As with the scientific approach to risk analysis, different conceptual interpretations of risk exist and disagreements may occur, but a reasoned choice can be made by considering the relevant literature, e.g. [4,27,49,52,55,120]. Similarly, an understanding of the object of inquiry is needed, to facilitate which aspects are relevant for the application.

Fourth, the risk measurement process is systemized. A risk definition stipulates specific features of the concept which are considered important in a specific application, and suitable risk measures are defined. A risk perspective is delineated, systemizing which measurement tools are applied, whether events or events and consequences are analyzed and how the confidence in the measurement is conveyed to decision makers, see Table 2. The risk perspective is thus the practically applied elements to describe risk, in line with the adopted conceptual understanding and definition. The operationalization of the object of inquiry specifies which features of the event and/or consequence are considered relevant for the specific application, i.e. the events/consequences are constructed in view of the intended use of the risk model [127]. When considered in the risk perspective, a method for conveying the confidence in the measurement is applied, e.g. using a qualitative uncertainty assessment [28], an assessment of the strength of evidence [29] or an assessment of biases in the risk model and evidence [36,37]. The measurement is conditional to an evidence base, which consists of data, information, models, expert knowledge and assumptions.

The outline of Fig. 5 is a simplification, but distinguishing the conceptual level of risk and its object, the measurement in a particular application, the evidence for making the measurement, the underlying scientific commitment to risk analysis as a science and the relation to a decision context are important aspects to more clearly articulate the foundations adhered to in a specific application.

### 7.3.2. Increased focus on foundational issues in the application area

Another finding resulting from the current work is that the maritime transportation application area would benefit from intensifying research on foundational issues, as well as increased reflection on proposed risk analysis methods. Various frameworks have been proposed for analyzing maritime transportation risk, e.g. [62,63,78,109]. Furthermore, many risk analysis applications have been presented in the literature, see Section 5. However, there has been very little scientific research and discussion on the proposed frameworks and methods.

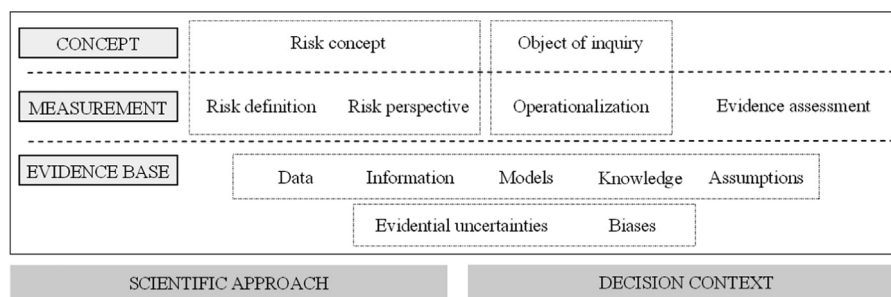


Fig. 5. Outline of concepts for clarifying the risk analysis applications.

A (non-exhaustive) list of issues requiring further scientific attention is given in [5], e.g. concerning research on the risk-conceptual basis, methods for assessing and communicating uncertainty and the causality of accident occurrence. Similar issues have been identified as requiring attention in revising the guidelines for Formal Safety Assessment (FSA), for decision making and rule development at the International Maritime Organization (IMO) level [128]. Thus, rather than being only academic exercises, research for strengthening the risk analysis foundations can also have repercussions for maritime policy.

## 8. Conclusion

In this paper, a review and analysis has been presented of risk definitions, perspectives and approaches to risk analysis science in the maritime transportation application area. A classification of risk definitions, an overview of risk measurement tools and tools for conveying information regarding the confidence in the analysis and a classification of scientific approaches to risk analysis have been used as a research method.

The main conclusions of this work are as follows. First, many applications lack clarity about foundational issues concerning the scientific method for risk analysis. Definitions for key terminology are often lacking, perspectives are not introduced and no attention is given to the scientific approach underlying the analysis. Second, the analysis of applications in light of the foundational issues introduced in Sections 2–4 shows that a large variety exists in the underlying principles for risk analysis in the application area. Definitions are mostly based on probabilities, but a minority of applications uses possibility- or uncertainty-based definitions. Many different risk measurement tools are applied, risk analyses focus either on events or on events and consequences, and uncertainties/biases are only in a minority of applications systematically considered. Applications are found across the range for scientific approaches to risk analysis, from strong realist over scientific proceduralist to moderate constructivist. Realist-based approaches are dominant.

Some suggestions are made to improve the current situation, focusing on the adopted terminology and principles underlying the risk analysis applications, and the need for a systematic consideration of uncertainty/bias in qualifying the risk measurement.

It is hoped that this work can increase focus on fundamental concepts and principles underlying future maritime transportation risk analysis applications, and that it can act as a catalyst for increased research and discussion for strengthening the scientific basis for risk analysis. To the extent our analysis and discussion has contributed to this end, the aim of this paper has been achieved.

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## Appendix A. Example applications

In this section, a selected number of risk analysis applications are addressed in more detail to exemplify the differences in the adopted risk perspectives and approaches to risk analysis science. As it is infeasible to discuss all methods in detail, three examples are taken, representing the most commonly found approaches to risk analysis science, applying different risk perspectives. Focus is on the elements found in risk perspectives and the approach to risk analysis science. Furthermore, some uncertainties are identified in the methods (which are not addressed in the original applications) to show the relevance of uncertainty treatment, and the interpretability of the results is addressed. This last point has been raised as a concern for practical decision making: it should be possible to explain how to interpret the risk measurements [13,14].

Application M4 is represents the strong realist approach, see Table 3. A probabilistic estimate of frequency and consequences of collisions and groundings in a waterway is made. The method is recommended by maritime authorities and regulatory organizations [1–3], and has been influential to other work realist approaches (e.g. M10, M28, M34, M48), has been used in an uncertainty quantification approach (M50) and to estimate baseline probabilities in a precautionary constructivist approach (M13).

Application M33 is chosen to illustrate the moderate realist approach to risk science, see Table 3. Expert judgment is applied to define a set of quantitative indicators, which are measured directly from maritime traffic data. The method has sparked further work in M45. Indicators are rather rare measurement tools in the application area and hence are interesting to consider.

M23 is chosen to exemplify the moderate constructivist approach. The risk model is constructed based on expert judgments of the risk levels of vessel interactions, from which a probability-like measure is derived to measure the risk of collision in traffic data. Ordinal probit regression modeling is applied in this vessel conflict technique. This method has sparked further work, e.g. M45.

### A.1. Method M4: $RA=I$ , $R \sim (P_f, A, C)$

The method aims at estimating the collision and grounding frequency and consequences in a waterway, with a sequence of events as shown in Fig. A1. Three events are distinguished: ship–ship encounter, collision, and structural damage. The number of encounters  $N_G$  is measured using traffic data and an encounter detection method. The frequency of collision accidents is measured using a frequentist probability derived from accident data. Consequences are calculated using engineering models, but it is

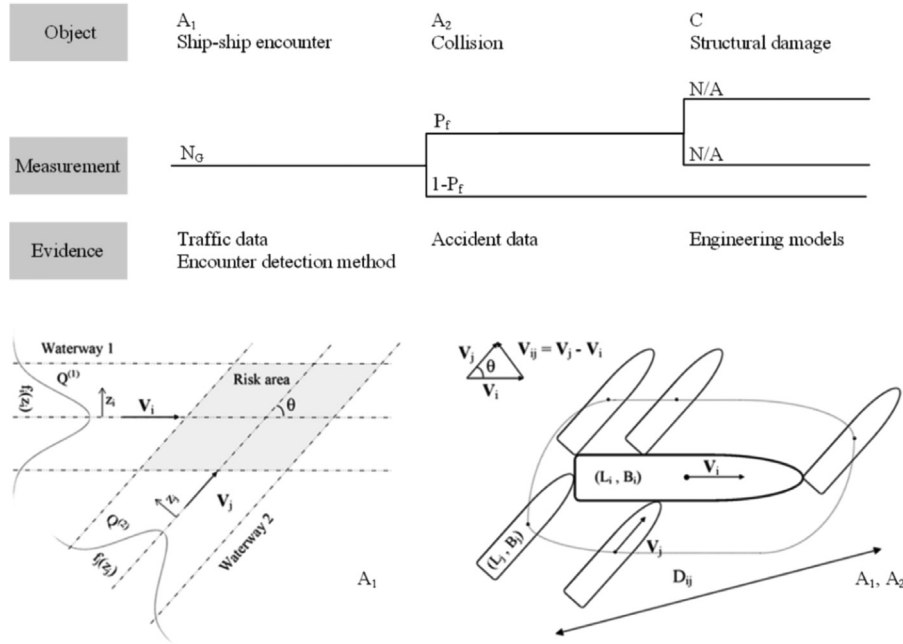


Fig. A1. Schematic overview of risk analysis application M4, based on [59].

not specified how exactly probabilities are derived. Here, focus is on the collision frequency  $f$  (involving  $A_1$  and  $A_2$  of Fig. A1), calculated as follows:

$$f = N_G P_C \quad (A1)$$

where  $N_G$  is the number of encounters in a waterway area and  $P_C$  the probability of accident in an encounter.

For crossing waterways, the number of encounters is calculated from the distribution of ship traffic in a waterway as follows, which is established using AIS data<sup>2</sup>, see Fig. A1:

$$N_G^{CR} = \sum_i \sum_j \frac{Q_i^{(1)} Q_j^{(2)}}{V_i^{(1)} V_j^{(2)}} D_{ij} V_{ij} \frac{1}{\sin \theta} \quad (A2)$$

with  $V_{ij}$  the relative speed between the vessels and  $D_{ij}$  the apparent collision diameter:

$$D_{ij} = \frac{L_i^{(1)} V_j^{(2)} + L_j^{(2)} V_i^{(1)}}{V_{ij}} \sin \theta + B_j^{(2)} \sqrt{1 - \left( \sin \theta \frac{V_i^{(1)}}{V_{ij}} \right)^2} + B_i^{(1)} \sqrt{1 - \left( \sin \theta \frac{V_j^{(2)}}{V_{ij}} \right)^2} \quad (A3)$$

$Q_i^{(1)}$  and  $Q_j^{(2)}$  are the flow rates of vessels of subclasses  $i$  and  $j$ .  $L$  and  $B$  represent ship length and width,  $V$  the ship speed and  $\theta$  the angle between the waterways. The cross-waterway traffic distributions  $f_i^{(1)}(z_i)$  and  $f_j^{(2)}(z_j)$  integrate to unity for crossing encounters, but for overtaking and meeting encounters, the shape of these distributions affects the number of calculated encounters. The procedure is based on the assumption of blind navigation, i.e. under the premise that neither ship takes an evasive action prior to collision.

The probability of an accident given an encounter is calculated from accident statistics and is estimated as  $P_C = 1.2 \times 10^{-4}$  [59]. This is a frequentist probability  $P_f^*$ , because it is derived purely from data, see Table 2.

The approach focuses on a true underlying risk, calculated using traffic-flow analysis ( $A_1$ ), accident data ( $A_2$ ) and engineering models

(C). No expert judgment is applied and no uncertainty is assessed. Decision making is strongly linked to the risk model: “[...] it should be possible to derive *probability-based* codes for [...]” ([59], p. 153). From this, it is concluded that a strong realist scientific approach to risk analysis is adhered to, see Table 3.

Focusing on the interpretability of the risk model, it is found that it is not straightforward to provide a meaning to the model elements. The measurement of event  $A_1$  (ship-ship encounter) clearly is a strong simplification of a real encounter process, which is difficult to relate to actual encounters. The event  $A_2$  (ship-ship collision) is likewise measured using a strong simplification, which is difficult to reconcile with actual collision accidents. In normal operation and in ship-ship collision accidents, at least one of the ships makes evasive action [129,130].

Interpreting the risk measurement tools also presents some conceptual challenges. The probability  $P_C$  has been explained as “the probability that an accident will occur if the ship is on collision course” ([97], p. 2). This seems intuitive enough, but assigning this probability to a model parameter ( $A_2$ , see Fig. 5) representing a blind navigation collision is inconsistent: in principle, the accident data should then only consider cases where neither ship made an evasive action. Moreover, interpreting the frequentist probability  $P_C$  is difficult, as such probabilities are defined through an infinite repetition and require a specification of what is understood under “similar” events [13]. It can be questioned whether a risk analysis should focus on mathematical constructs such as  $N_G$  and  $P_f$  [124].

Even though uncertainty is not addressed in M4, some important uncertainties can be identified, see Table A1. A simple uncertainty rating scheme is applied, proposed in [28] and briefly outlined in Appendix B. Each uncertainty factor is assessed using four criteria, leading to an overall uncertainty rating Table A1.

Take for example ME<sub>3</sub>, the relation between the flow rate and the frequency of collisions. Based on traffic flow theory, the number of encounters is quadratic with flow rate, so it seems a plausible assumption. Given the use of the same assumption in other applications (e.g. M10, M13, M28, M34, M48, M50), but contested in others (e.g. M42, M56), the agreement about the model element is ambiguous. There is very little data supporting the claim that increases in traffic density in fact result in more

<sup>2</sup> AIS is a system where navigational parameters are transmitted from ships to one another and to shore stations, allowing for improved situational awareness. It provides a rich data source for studies in maritime transportation, containing detailed information about vessel movements.

**Table A1**  
Uncertainties underlying risk analysis M4.

Model element		CR <sub>1</sub>	CR <sub>2</sub>	CR <sub>3</sub>	CR <sub>4</sub>	Uncertainty rating
ME <sub>1</sub>	Encounter detection method	N	N	Y/N	N	M–H
ME <sub>2</sub>	Collision probability equal for all encounters	Y/N	N	Y/N	N	M–H
ME <sub>3</sub>	The relation between the flow rate and the frequency of collisions is quadratic	Y	N	Y/N	N	M–H

Note: CR<sub>1</sub>=the assumptions are seen as very reasonable, CR<sub>2</sub>=much relevant data are available, CR<sub>3</sub>=there is broad agreement/consensus among experts, CR<sub>4</sub>=the phenomena involved are well understood, Y=yes, N=no, L=low, M=medium, H=high.

collision accidents. Moreover, the phenomenon is not well understood in maritime transportation, with varying approaches to assess the relation leading to significantly different results [12]. Related research in road traffic has shown that the relation between traffic density and accident occurrence is complex, involving a heuristic balancing of economy, risk-taking behavior and comfort of road users. Areas with more traffic conflicts may even be safer due to increased awareness [131]. In maritime transportation research, an investigation on the relation between grounding accidents and traffic density has also shown that no clear dependency can be found [132]. For these reasons, ME<sub>3</sub> is considered to involve medium to high uncertainty.

#### A.2. Method M33: $RA=II$ , $R \sim (I_{QU} \rightarrow A)$

This method uses three risk indicators to analyze the risk of collision in a Traffic Separation Scheme (TSS) area<sup>3</sup>. A speed dispersion index ( $I_{QU,1}$ ), an acceleration/deceleration index ( $I_{QU,2}$ ) and a vessel conflict index ( $I_{QU,3}$ ) provide quantitative information regarding the possibility of a collision in a given area, as schematically shown in Fig. A2. The identification of indicators considered relevant to assessing collision risk is based on judgments of navigational experts.  $I_{QU,1}$  and  $I_{QU,2}$  are situational characteristics obtained directly from traffic data, whereas  $I_{QU,3}$  is obtained from traffic data, using a ship domain model [88]. It is interesting to note that the event occurrence itself is not modeled, but its likeliness is inferred from the values of the indicators. Also, the risk perspective makes no reference to consequences of the collision accident.

The application is understood to adopt a moderate realist approach to risk analysis science. Even though expert judgment is applied in devising the indicators, the application is rooted in the idea that risk is a measureable property of the system. This follows from the reasoning applied for making the indicators: “[existing] risk reduction solutions are generally based on the qualitative and subjective judgment from experts. There is no existing study to quantitatively evaluate ship collision risks [...]” ([88], p. 2030). Quantification is taken as an alternative to subjectivity, implying that the quantification provides better decision support than qualitative, subjective judgment. Even though expert judgment is applied to identify risk indicators, the analysis heavily relies on data. No uncertainty is assessed.

For the interpretation of the risk measurement tools, we consider the acceleration/deceleration index  $I_{QU,2}$ . This is introduced as follows: “[...] acceleration and deceleration happen under the condition that ships are about to cross, overtake, meet, or turn, namely, scenarios with collision potentials. Higher degree of acceleration indicates more frequent occurrence of scenarios with collision potentials.” ([88], p. 2031). The indicator  $I_{QU,2}$  in a

traffic area  $k$  is calculated as follows, see Fig. A2:

$$I_{QU,2,k} = \frac{\sum_{i=1}^{I_k} \sum_{j=1}^{J_{i,k}} a_{k,i,T_j}^2}{I_k} \quad (A4)$$

where  $a_{k,i,T_j}$  represents the acceleration of a consecutive pair of data records,  $J_{i,k}$  the number of records of vessel  $i$  in a TSS area  $k$  and  $I_k$  the number of ship trajectories found in TSS area  $k$ . The acceleration or deceleration of consecutive records for vessel  $i$  in leg  $k$  at time  $T_j$  is given by:

$$a_{k,i,T_j} = \frac{SOG_{k,i,T_j} - SOG_{k,i,T_{j-1}}}{T_j - T_{j-1}} \quad (A5)$$

where  $SOG_{k,i,T}$  is the speed over ground of vessel  $i$  in leg  $k$  at time  $T$ . The AIS data contains the time  $T$  and the speeds  $SOG$  for the individual ships.

Interpreting  $I_{QU,2}$  is not straightforward, but it is possible. The number represents the total acceleration/deceleration intensity of all ships in a given area in a given time period. The number itself is a mathematical construct, but it is an information carrier which refers to an object which can be given a meaning.

Even though uncertainty is not addressed in M33, some important uncertainties can be identified, see Table A2. The uncertainty rating scheme introduced in Appendix B is applied here as well, focusing on  $I_{QU,2}$ . It is clear that important evidential uncertainties underlie the risk model Table A2.

ME<sub>1</sub> addresses the fact that Eq. (A4) measures acceleration, which includes more navigational operations than collision avoidance. When ships are involved in collision evasive maneuvering, it is feasible that they slow down, either voluntarily or due to hydrodynamic forces in the turning maneuvers. However, acceleration/deceleration is not only because of collision evasive actions. Other reasons can be speed adjustments to meet the ETA<sup>4</sup> of pilot boarding or harbor entry, and involuntary speed fluctuations may occur due to tidal and wave action. In this sense, the indicator's specificity can be questioned as it obfuscates the relation between the indicator  $I_{QU,2}$  and collision occurrence, leading to measurement uncertainty.

ME<sub>2</sub> addresses the fact that formula Eq. (A4) does not account for the unequal sizes of the TSS areas. An uncertainty results from this in relation to the number of AIS records in this area, as illustrated in Fig. A2. Consider a specific ship trajectory, which in AIS data is available as a set of points. If the number of data points in TSS area  $k_m$  is systematically more (or less) than the number in area  $k_n$ , because e.g. the areas are not of equal size, this means that the summation in Eq. (A4) is performed for a higher (or lower) number of data points. It follows that larger (smaller) TSS areas will result in a higher (lower) value for the indicator, not because of higher collision risk but because of the larger considered area. Eq. (A4) does not include a compensation mechanism for this, hence the values of indicator  $I_{QU,2}$  are not dimensionally consistent across sea areas. This leads to uncertainty about the specificity of the measurement.

<sup>3</sup> A TSS area is an area where ship traffic is regulated, such that vessels are required to follow certain sea lanes.

<sup>4</sup> ETA: estimated time of arrival.



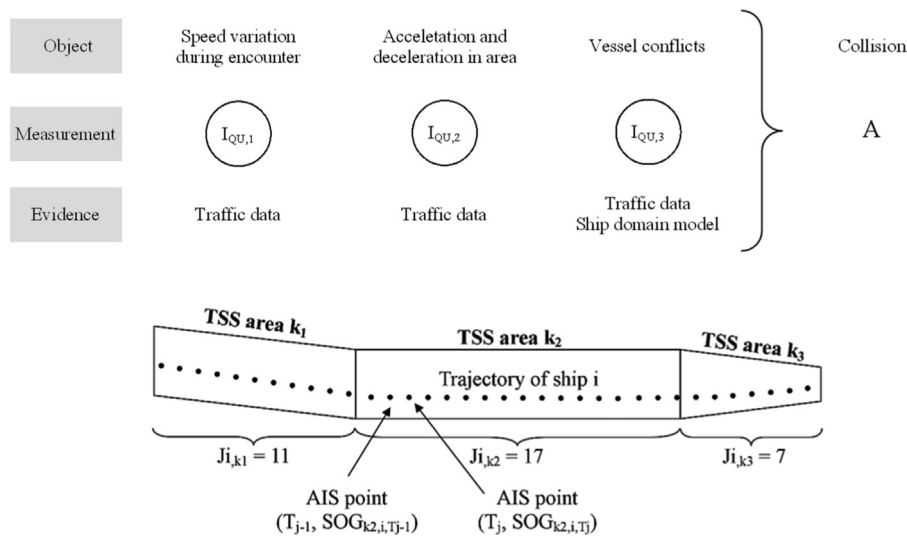


Fig. A2. Schematic overview of risk analysis application M33, based on [88].

Table A2

Uncertainties underlying risk analysis.

Model element		CR <sub>1</sub>	CR <sub>2</sub>	CR <sub>3</sub>	CR <sub>4</sub>	Uncertainty rating
ME <sub>1</sub>	$I_{QU,2}$ (Eq. (A4)) measures accelerations, not only collision-avoidance maneuvers	Y/N	N/A	Y/N	Y/N	M
ME <sub>2</sub>	The areas $k$ for which $I_{QU,2}$ (Eq. (A4)) is calculated are not of equal size	N	N/A	Y/N	N/A	M–H

ote: CR<sub>1</sub>=the assumptions are seen as very reasonable, CR<sub>2</sub>=much relevant data are available, CR<sub>3</sub>=there is broad agreement/consensus among experts, CR<sub>4</sub>=the phenomena involved are well understood, Y=yes, N=no, L=low, M=medium, H=high.

### A.3. Method M23: $RA=VII$ , $R \sim (P_x, A)$

This method uses a vessel conflict technique to analyze the risk of collision in a waterway area. The basic idea is that the severity of non-collision traffic encounters can be ranked, and that this information can be used to derive the probability of a collision. For this, a procedure schematically shown in Fig. A3 is used. First, a vessel conflict operator is constructed based on an ordered probit regression modeling of expert judgments. Experts are asked to assess the risk level in vessel interactions based on the proximity indicators DCPA<sup>5</sup> and TCPA<sup>6</sup>, for day and night conditions and for different vessel sizes. The risk levels are interpreted as in Fig. A3, and a mathematical operator  $C(t)|S$  is defined. Second, this operator is applied in vessel traffic data for encounters involving a vessel conflict, and a measure  $C'_{max}$  is calculated. Finally, the collision probability  $P_x(A)$  is mathematically derived from the fitted distribution  $f(A4)$  to the empirical distribution  $p(C'_{max})$ . The threshold value  $\tau_{HR}$  corresponds to the separation between serious and non-serious conflicts, i.e. based on the risk score  $RS_m$  corresponding to the “High risk” level. For details about the calculation procedure, see [78]. The application makes no reference to consequences of the collision accident, i.e. the risk perspective focuses on an event.

The application is understood to adopt a moderate constructivist approach to risk analysis science. While the method relies on data to determine collision risk, the basis of the method is a modeled representation of judgments by navigational experts, i.e. a mental construct of an assessor. The constructivist approach is also reflected in the proposed validation method. Considering the risk model to be used as an evaluative, diagnostic tool to assess the effect of changes in a traffic area, no demands are placed on the

method to correlate with observed accident frequencies. Rather, the model results are compared with direct expert judgments of the risk level in different waterway areas, stressing the centrality of judgment in risk analysis. Uncertainties are not assessed.

Interpreting the risk measurement is difficult, as it is a derived measure from a fitted distribution based on data collected through running an expert judgment based model in traffic data. Even though an interpretation is given to the risk levels, see Fig. A3, this is not unambiguous.  $P_x(A)$  is calculated using the threshold value  $\tau_{HR}$ , corresponding to the action level “immediate actions needed”, i.e. a level which does not per se imply a collision occurrence. However,  $P_x(A)$  is calculated from serious conflict cases (with  $C'_{max} > \tau_{HR}$ ), which are defined as “encounter[s] that may pose risk of a certain collision” ([78], p. 143). These definitions provide ambiguous information for interpreting the risk measurement tool:  $P_x(A)$  claims to be the probability of collision, but it is derived from a risk level corresponding to “encounters requiring immediate action”, also defined as “encounters which may pose risk of a certain collision”. This circularity and inconsistency in the basic definitions obfuscate what precisely is measured, and what the measurement means.

Even though uncertainty is not assessed, at least one important uncertainty can be identified. This relates to the structure of the vessel conflict operator, which assumes a linear combination of TCPA and DCPA:

$$r = \hat{\beta}_1 DCPA + \hat{\beta}_2 TCPA \quad (A6)$$

Here, DCPA and TCPA are instantaneous values of the spatial and temporal proximity indicators in a vessel interaction, and  $\hat{\beta}_i$  ( $i=1,2$ ) are estimated coefficients based on ordinal regression modeling of questionnaire-based expert judgments. From research on vessel domain analysis, it is known that in practice, navigators allow a smaller or larger distance between the vessels depending on the encounter angle [133–135]. Hence, navigators interpret the collision risk not only in terms of DCPA and TCPA, but also in relation to the

<sup>5</sup> DCPA: distance to closest point of approach.

<sup>6</sup> TCPA: time to closest point of approach.



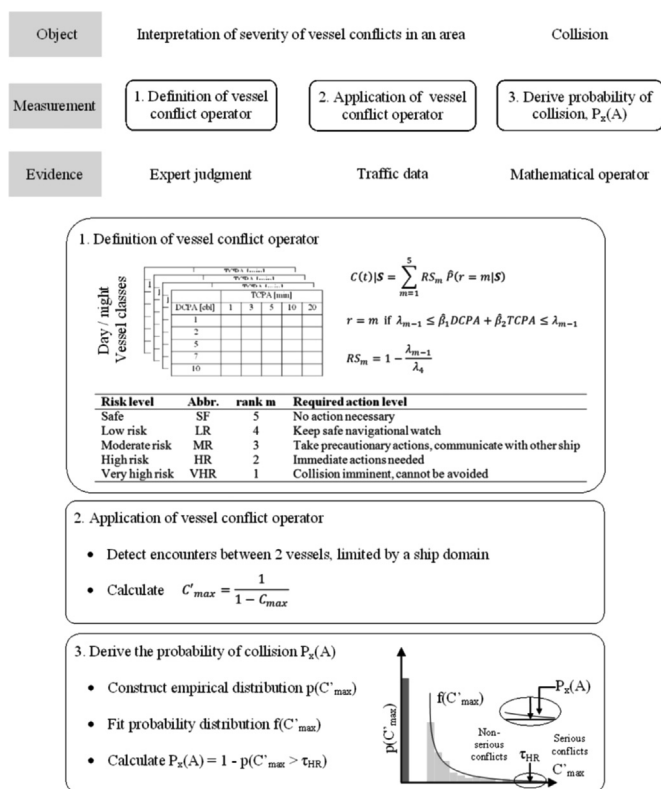


Fig. A3. Schematic overview of risk analysis application M8, based on [78].

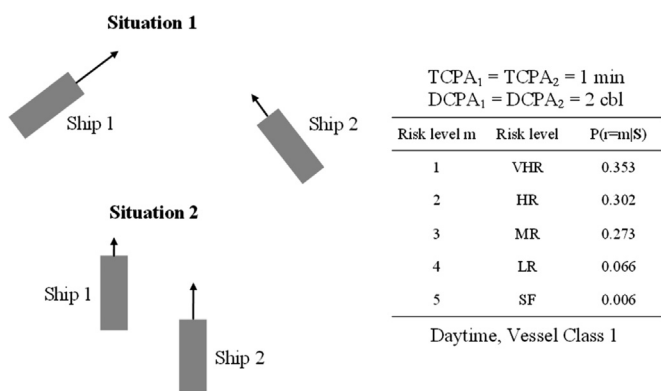


Fig. A4. Two situations with equal risk level according to M23.

encounter angle. Take for example the situations in Fig. A4, with equal TCPA and DCPA. According to the regression model, the risk level is most likely “Very high risk”, which means that collision is imminent, and that it cannot be avoided, see Fig. A3. For situation 1, this may be plausible. However, in situation 2, which is an overtaking encounter, this contradicts common navigational practice. It seems more plausible to rank this situation under “Low risk”, i.e. requiring safe navigational watch but not evasive action. This implies that the vessel conflict operator may not appropriately rank the detected encounters, leading to uncertainty in the shape of distributions  $p(C'_{max})$  and  $f(C'_{max})$ , and the calculated value for  $P_x(A)$ .

## Appendix B. Uncertainty assessment scheme

Flage and Aven [28] propose a method to assess uncertainties in a risk analysis application. A direct grading of the importance of

the uncertainty is performed through a judgment of an assessor of four criteria. A justification for the assessment of each criterion can be provided.

The knowledge is weak (uncertainty is high) if all of the following conditions are true:

- The assumptions made represent strong simplifications.
- Data are not available, or are unreliable.
- There is lack of agreement/consensus among experts.
- The phenomena involved are not well understood; models are non-existent or known/believed to give poor predictions.

The knowledge is strong (uncertainty is low) if all of the following conditions are met:

- The assumptions made are seen as very reasonable.
- Much reliable data are available.
- There is broad agreement/consensus among experts.
- The phenomena involved are well understood; the models used are known to give predictions with the required accuracy.

Cases between these two extremes are classified as involving medium knowledge (medium uncertainty).

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