Journal of Polish Safety and Reliability Association
Summer Safety and Reliability Seminars, Volume 4, Number 1, 2013

Montewka Jakub

Goerlandt Floris

Kujala Pentti
Aalto University, Espoo, Finland

On a risk perspective for maritime domain

Keywords

maritime traffic, probabilistic modeling, risk analysis, risk management, decision making

Abstract

In the maritime domain, the risk is evaluated within the framework of Formal Safety Assessment (FS A), introduced by International Maritime Organization in 2002. Although the FSA has become internationally recognized and recommended method, the definition, which is adopted there, to describe the risk, seems to be too narrow to reflect properly the actual content of the FSA. Therefore this article discusses methodological requirements for the risk perspective, which is appropriate for risk management in the maritime domain with the special attention to maritime transportation systems (MTS). This perspective considers risk as a set encompassing the following: the set of plausible scenarios leading to an accident, the likelihoods of the unwanted events within the scenarios and the consequences of the events. These elements are conditional upon the available knowledge about the analyzed system, and understanding of the system behaviour, therefore these two are inherent parts of risk analysis, and need to be included in the risk description.

1. Introduction

In 2002 the International Maritime Organization (IMO) approved the guidelines for Formal Safety Assessment (FSA) as a method evaluating risk in the maritime domain. FSA has been described there as "*a rational and systematic process for assessing the risks associated with shipping activity and for evaluating the costs and benefits of IMO's options for reducing these risks*", see [13]. However, Psaraftis in his recent updated review about FSA - see [25] - expresses strong demand for scientific discussion in maritime domain about the fundamentals of the FSA namely concept of risk; moreover he claims a need for the development of knowledge-based risk models and the unification of terminologies used in risk analysis. These arguments are in line with the stand of Aven, who continuously calls for scientific discussion on understanding, expressing and communicating risk, see for example [3].

The basic philosophy of FSA is that it can be used as a tool to facilitate a transparent decision-making process. In addition, it provides a means of being proactive, enabling potential hazards to be considered before a serious accident occurs. However the description of the method can give an impression that the definition of the word "*risk*" does not fully reflect the way the risk is further explained and it seems that the risk components change depending on the context. In the context of risk analysis, presented in the FSA guidelines, *risk* is defined as a combination of the probability (P) and consequences (C) of a given action, see [12]. Whereas, in the context of Chapter 7, called "*Risk control options*" - [13], [12] - aiming to determine the areas needing control, the risk is decomposed and the uncertainty aspect of two risk components is added as an important element of the decision process. Moreover, for the identification of risk control measures, Chapter 7.2.2 suggests developing the causal chains of events leading to an accident, which means that the definition of risk includes an insight in certain scenarios leading to the undesired situations. Finally, Chapter 10 "*Presentation of FSA results*", stresses the need for the discussion about the assumptions, limitations and uncertainties of a risk model.

To make sure that all these relevant recommendations, which are located in different chapters of the guidelines, can be properly addressed at the appropriate stages of the risk analysis, a risk perspective, which foresees them needs to be adopted. This means, that such a perspective allows for the knowledge- and experience-based scenario building, thorough analysis of risk model uncertainty and model validation, see for example [29]–[30]. Otherwise, FSA being considered proactive, highly technical and complex method may be misused or even manipulated, yielding the results which may not fully reflect the relevant features of the analyzed system, for a discussion see for example [10], [16].

Therefore this paper serves the purpose of adding to the discussion asked for by Psaraftis and Aven, proposing the requirements for a risk perspective suitable for the maritime domain. The presented perspective enables risk-informed and knowledge-based decision making by reflecting the available knowledge and understanding of the analyzed system and mapping those into a model.

The remainder of this paper is organized as follows. The methodological requirements allowing risk description for a MTS are given in Chapter 2 and explained further in Chapter 3 along with some examples fro the field of maritime transportation. Concluding remarks are provided in Chapter 4.

2. Describing risk

The FSA defines risk as a combination of the probability (P) of an accident and its consequences (C), as follows:

$$R = (P, C) \tag{1}$$

As a risk measure the FSA proposes risk index (RI), which is defined more explicitly as a product of P and C:

$$RI = P \times C \tag{2}$$

The RI serves the purpose of being crude risk indicator used for ranking various hazards and selecting the most relevant, which are then analyzed in details. The same definition is often adopted among engineers to describe risks, but it easily leads to confusion, especially when comparing two situations A and B, where: A encompasses frequent events resulting in minor consequences - single or minor injuries and local equipment damage; B considers remote event of catastrophic consequence - multiple fatalities and total loss of a ship.

Even though the products of P and C in both cases are the same - following the FSA guidelines the risk indices are the same, RI = 7 - these two situations differ substantially. The available information about A is most probably better than in the case of B, as A occurs frequent - is likely to occur once per month on one ship - and B occurs rare - likely to occur once per year in a fleet of 1000 ships, or likely to occur in the total life of several similar ship. This amount of information affects the amount of uncertainty associated with the descriptions of A and B. Also the measures to control the risks in these two situations might be different, as in the first case the focus might be given to the P, and in the second case C might be a subject to mitigation. Therefore, interpreting risk as a product of P and C, described as a single number or a single distribution, leads to the misconception that risk is a number and risk is divorced from the scenarios of concern. Applying this perspective, much of the relevant information needed for knowledge-based risk management is not properly reflected or even missing.

Thereby, the wider concept of risk should be applied, allowing systematic and hierarchical description of the risk and reasoning in the light of available knowledge about the analyzed system and possessed understanding of this system behavior.

Numerous definitions for risk have been proposed, for the recent and thorough review of the risk concepts see for example [10–12].

By studying the different risk definitions, regarding socio-technical systems, we found that many scientists perceive risk as a logic construct referring to the future events or situations resulting in an outcome, which is definable but uncertain, which puts at stake something, that humans value. Risk refers to the future but it is managed in the present, based on experience gained in the past. Therefore the knowledge and understanding of an analyzed system and the ability to predict/project system behavior in the future are inherent to risk.

An appropriate starting point to describe risk, which also fits in the maritime domain, has been introduced by [13], where risk is presented as a complete set of triplets:

$$R = (S_i, L_i, C_i)_i \tag{3}$$

Defined in this way, risk is not a number, nor a curve, nor a vector, as none of these mathematical concepts is big enough in general to capture the idea of risk. Kaplan and Garrick claim, that the set of triplets is always big enough, and if we start out with that, it always gets us on track, moreover it is easier to limit the analysis than to expand it with the factors which had not been anticipated in the beginning of risk analysis.

Triplet attempts to answer the following questions: what can go wrong in the system (Scenario - S), how likely is it that it goes wrong (Likelihood - *L*), and what are the consequences if the assumed scenario happens (Consequence - *C*)? However, describing the risk as a complete set of triplets is unattainable, simply because our knowledge on the system is never complete, therefore the system cannot be characterized exactly, see [8]. What we actually attempt to describe is an incomplete set of triplets, called "a set of answers". This set reflects the risk in a given system according to our best knowledge (*K*) about the system and our understanding (*N*) of its behavior; however certain triplets, yet existing, remain undiscovered and thus they cannot be captured. But, if our knowledge or understanding improves, new scenarios can be defined and added to the triplet, therefore the incompleteness of the risk set which is conditional upon *K* and *N* should be recognized. Due to this incompleteness, the notation of risk shifts from "a risk is equal to a set" to "a risk is described by a set", and the conditional dependency upon *K* and *N* is added, as follows:

$$r \sim (s_i, l_i, c_i) \,|\, (K, N), \tag{4}$$

$$\Delta \sim (K, N) \tag{5}$$

The parameter Δ is a set comprising of knowledge related uncertainties ($K = \{k_i\}$) which addresses the variables included in the model, meaning its quantitative part, and the understanding related uncertainties ($N = \{n_i\}$) which refer to the links between these variables, namely the qualitative part of the model.

In a more general way, following the formal requirements for a definition of risk given by [15], the description of risk can take the following form:

$$\boldsymbol{R} \sim (r; \Delta)\,, \tag{6}$$

By this notation we perceive the risk as a set of all *r* for which the existing Δ satisfies the formal definition of the risk. This means, that the outcomes of the analysis need to be definable, which is the case for maritime transportation systems, and there are basis for assigning the probabilities for *s*, *l* and *c*. The latter is not always the case, as some paths of the scenario - links between events - are better understood than another, or the knowledge about certain events is better than about another. This creates uncertainties with respect to variables (parameters) and links (structure), which can be reduced either by gaining *K* or improving *N*. As *K* and *N* are to different concepts, see for example, affecting the risk components in different manners, and require different treatment in order to be improved, we see the need for including them both into a risk perspective.

3. Systemized perspective

3.1 Knowledge and understanding

First, let us start with providing the definitions of knowledge and understanding, followed by Oxford Dictionaries and Merriam-Webster [22], [19]:

knowledge:

- facts, information, and skills acquired through experience or education; the theoretical or practical understanding of a subject; the range of one's information or understanding;
- the sum of what is known; the fact or condition of having information or of being learned; the fact or condition of being aware of something;
- true, justified belief; certain understanding, as opposed to opinion; cognition.

understanding:

- the ability to understand something; comprehension; a mental grasp;
- the power of abstract thought; intellect; the capacity to apprehend general relations of particulars;
- an individual's perception or judgment of a situation; the power to make experience intelligible by applying concepts and categories.

From these definitions we see that knowledge (*K*) is about facts or true, justified beliefs, which can be obtained by referring to the reliable sources. Knowledge focuses on believing a proposition, which could not easily have been false. Whereas understanding (*N*) is more than that, as it is about grasping explanatory connections and relations, thus it requires certain abilities, for the scientific discussion about the philosophical background supporting this conceptual difference the reader is referred to the recent works, for example [24], [9].

Putting it in the simplest terms — knowledge is facts; understanding is the real meaning of the facts. We might know something to be true, but we need understanding to realize why it is true and what is the impact of that truth.

If we know, that *B* is a reason for an event *A* (we know why *A*), we have basis for believing that *A* is because of *B*. But when we understand why *A* we additionally obtain a grasp on how *B* affects *A*. By getting this comprehension about *A* we are able to:

- develop an explanatory story about how *B* can cause or be a reason why *A*,
- infer about *B* knowing *A*,
- for some *A** and *B**, which are similar but not identical to *A* and *B*, draw the conclusion about *A** assuming *B**, and give the right explanation

for *B** assuming *A**.

Knowledge is factive whereas understanding can be non-factive, however to understand why *A*, the explanation must address the facts. In complex systems there are numerous causes of *A* which interacts in complicated manners therefore it is difficult to address all of the causes, which is a primary source of non-factivity. Secondary source is associated with the idealizations made when describing *A*. In non-factive cases we have some understanding of *A* without knowing all facts about *A*, which means that despite not possessing full knowledge about *A* we have an understanding of *A* which is enough for inference about *A*. This is the main reason for making a distinction between knowledge and understanding when describing risk. These two concepts different focuses, each of the concepts can be related to specific difficulties in the risk modeling, and it is considered useful to make the different difficulties explicit.

As an example we may think about a model estimating the probability of a collision between ships in the open sea. From the statistics we know the number of accidents (*N_a*) that have happened in the past, from Automatic Identification System we know the volume and composition of traffic (*V*), from the analysis we also know the long-term and short-term trends (*T*) for the number of accidents. These facts, which are observable and measurable, constitute our knowledge about the parameters of an analyzed system and provide a solid basis for variables, which can be used in a model of the analyzed system. However, the links between *V* and *N_a* are not clear, meaning that our understanding of the effect that *V* has on *N_a* is limited. The implication of the above is that despite of our knowledge of the crucial elements of the system (*V*, *N_a*, *T*), lack of our understanding of system behavior makes our inferences about the future behavior of the system rather unreliable, if it is based only on these variables.

By developing our knowledge about given system we are getting more confidence about variables used in a model of the system. By gaining understanding about the system we become familiar with the way the system operates, which at the end enables us to build the model reflecting the actual behavior of the system to the extend we are interested in, simply by putting the right variables in the right order. As the risk is about future events, the ability to grasp explanatory relations between elements in the modeled system is crucial, therefore understanding is inherent to risk.

3.2 Scenarios

A fundamental and most probably the most important stage of any risk analysis which in turn affects all the steps following the analysis is scenario identification, meaning the proper translation of *K* and *N* into a model. Intuitively, the importance of this step seems obvious, however it does not always receive due credits, see for example [25], [2], [26]. When describing risk the main focus is on understanding these scenarios, which ultimately lead to undesired events. Scenario identification is tantamount with discovering causality, which seems to be the natural way of understanding, analyzing and finally mitigating the hazardous situations, which produce risks. This mindset has been successfully adopted in nuclear power industry and process industry, moreover it is successfully pursued in the air transportation, see [1],[28]–[27]. In the recent years some researchers made attempts to follow this way to improve maritime safety as well, see for example [20], [17].

A scenario can be defined as a realization of a chain of events – see also [12] - triggered by an initiating event (*IE*). The *IE* may cause the system to move from its predefined safe and efficient trajectory (S_0) towards the set of trajectories (S_i), which are not as safe and effective as S_0, but it does not mean they are all unsafe. The system being on its trajectory S_i travels through various mid states (MS) at which transitions take place, redirecting the system towards the end states. The latter can be either an undesired event, like an accident, or safe operation of MTS, which means that the system may return at some point to S_0. A scenario encompasses various events (variables), which are linked with functions of varying complexity – from the simple Boolean logic to multivariable functions. Each scenario consists of two parts: qualitative and quantitative. The quantitative part reflects the content of the scenario, and is described by events, whereas the relations between the events are characterized by the scenario's structure, which refers to its qualitative part. This means, that each single scenario is developed based on our *K* and *N* about it.

For many complex systems, such as MTS, the levels of our *K* and *N* of the analyzed scenarios vary and usually are not equally spread over a scenario, as we know and understand more about given part of the scenario than about the others. This is especially important to realize when it comes to determining the risk control options (RCO) and defining the locations for these in a risk model. If we decide to place RCO somewhere along a path that is considered poorly understood, then their effect the real world may be completely different than anticipated in a model. By representing of *K* and *N* along a scenario:

- we define the weak paths of a scenario, which should be treat with caution, especially if the outcome of the scenario is sensitive to the changes along these paths;
- we decompose a scenario into smaller pieces, to avoid problematic links and focus on modeling events which are better understood;
- we demonstrate the effect of improper *K* and/or *N* on model's outcome.

A description of a scenario should shed some lights on the process of failure evolution, specifying the sets of associated *IEs*, *MSs* and *ESs*. There will be inevitably smaller or larger portion of the scenarios remaining uncovered, however the uncertainties associated with these scenarios may be smaller than their counterparts associated with the set of scenarios developed on assumptions not supported by available information. In the first case, the analysis is based on the observation of system behavior in the past, thus it is limited to the known events, which caused the MTS failure. However, if we manage to represent properly the available knowledge and grasp an understanding of a system experiencing those events, we can get a canvas for a predictive model determining the critical paths of the system leading to an accident in the future. Therefore, the uncertainty of this approach would be mostly associated with not observed *IEs*, *MSs*, *ESs* and links between those forming an unknown set of scenario paths. Whereas in the case, where the description of a system is not based on evidences nor is utilizing available information properly, the gap between a real system and its description becomes unidentifiable, and the risk moves toward ignorance, see [32].

3.3 Uncertainty

In this paper, we take a stand, that the uncertainty is a result of our limited knowledge and understanding of the modeled, which is in line with the commonly adopted claim that the uncertainty is a function of the available information on a given system in a given situation, see also [2], [31], [34], [18]. The lack of knowledge about the analyzed system leads to uncertainty in the model parameters, see [8], [36], but lack of understanding of the system behavior affects the hypotheses supporting the model structure, see for example [35]. Therefore it is relevant for a risk framework to communicate the background knowledge about the phenomena analyzed see, [13], [29], [4], likewise the level of system understanding as it allows structured analysis of uncertainties associated with a model of an analyzed system. Beside quantification of the uncertainties we determine their nature and distribute them across the model to determine the crucial areas of the model, where either *K* or *N* is limited.

The description of a scenario can be considered plausible and useful only to the extent it addresses the limitations in the available *K* and *N* and demonstrates their effect. There are numerous ways to address and express the model uncertainty depending on its type, see for example [21], [4], [14], [11]. The effect of uncertainties related to *K* can be evaluated for instance by considering the relevant variables as distributions and perform the analysis for a range of parameters that these distributions can take. The effect of understanding related uncertainties can take a form of alternative hypotheses testing, where set of models is developed, with the constant set of variables, but different, plausible hypotheses governing the links between variables, see for example [35].

In order to determine the effect of *K* and *N* on model outcome, the following steps should be taken, once the model structure(s) and content(s) is obtained:

1. Develop a set of models, where each model represents plausible and relevant combination of model parameters and model structures.
2. Perform the sensitivity analysis for each model (SA) to specify the variables, which are important for the model, as they variability affect the model outcome the most. The results of SA may be different for two models, which have the same quantitative parts (variables) but they differ in qualitative description (structure).
3. Perform the influence analysis (IA) for each model, determining the variables, which have the highest impact on the model outcome. IA allows crude judgment about the elements of the model, which are relevant for decision-making.
4. Perform the uncertainty analysis (UA) for each model for model's content.
5. Compare the results of SA and IA for every model for the variables they addressed, if there is disagreement between different versions of a model find the reason for them and list them.
6. Report the results of UA in the light of SA and IA.

By applying this procedure we perform educated analysis of the uncertainties associated with a model, which are results of limited *K* about parameters included in a model and/or limited *N* of the relations between parameters. Moreover, the sensitive elements of the model are determined and the variables having the strongest impact on an outcome of a model are specified. The latter may be important for risk decision-making, when the effective measures to mitigate risk are sought. To run the above procedure efficiently appropriate modeling techniques need to be applied, allowing for quick reasoning and model updating in the light of new information, for example Bayesian Networks.

3.4 Risk control options

On the basis of proper scenario description, the RCO can be defined, with an am to break or redirect the chain of events leading to an undesired event. As the accident scenario can be divided into two phases: pre-accident and post-accident, different approaches of mitigating the risk can be studied, namely: reducing the probability of an accident, mitigating the consequences or both. In order to define general mitigating actions that RCO must perform in order to bring the outcome to a desired level, we carry out a crude analysis. This analysis informs us about the required changes in a given part of a model, which are needed to reach the desired level of outcome. Once this is done, and we manage to specify the areas of the modeled system, which we need to address, then the detailed investigation of these areas is carried out, which results in specific RCO. However, only the elements of the model, that have appropriate level of understanding and knowledge, can be seen as having a potential for decision-making.

For instance, if we consider a simplified risk model determining the environmental degradation due to an accidental oil outflow, as presented in *Figure 1*, we would like to know what are the best, effective and feasible options to control the risk. The available knowledge about model parameters is reflected by an intensity of variables (the darker the higher knowledge), and different types of arrows represent the understanding of relations between variables. Single arrow means low *N*, bold arrow means high *N* and double-stroke arrow stands for medium level of *N*. Now, let’s assume, that the results of our crude analysis suggest, that the most effective way to reduce the environmental pollution to an acceptable level is to reduce the oil spill size (*O_s*) or reduced the probability of an accident (*P_a*) or reduce the spread of an oil slick (*S_oil*). Moreover, we learn that *O_s* needs to reduce by 50% or *P_a* should be lowered by one order of magnitude or *S_oil* should go down by 10%. Then it is up to analyst or decision-makers to:

- specify whether the changes are attainable,
- specify the actions are needed to make the changes,
- prioritize them by their feasibility and the anticipate effectiveness.

The effectiveness of RCO can be quantified with reasonable accuracy if they address the technical part of the model, i.e. the improved crashworthiness of a ship structure, the improved oil spill response capacity. It is more complicated to evaluate the effectiveness of RCO, which address the socio-technical aspects of the modeled system, i.e. measures to reduce the probability of an accident by influencing the way in which a ship is navigated.

For example, if there is a need to reduce variable, which is not understood, for example *P_a* in *Figure 1*, additional studies, on the causes of accidents and the ways to mitigate them are needed. If our existing *N* and *K* does not allow for justified conclusions, though the selected RCO are feasible their effect on the outcome cannot be measured. A feasible and effective action might be to reduce the O_s, which means that the structure of a tanker needs to be improved, and the oil response capacity for the analyzed area should be modified. Moreover the effectiveness of these RCO seems very high, as once the structure is improved and in a case of collision it is going to absorb certain amount of energy according to a design - with high degree of confidence. Similar logic refers to oil spill response capacity, as if we decide to invest in purchasing an oil recovery ship, in a case of an accident she can react, unless the weather conditions do not permit.

The anticipated effectiveness of RCO is inherent with the understanding of a system we are modeling. Therefore there is not reason to force the existence of understanding of relations between variables, by modeling them, in the situations where there is no support for them. By creating superficial connection, and pretending that we understand, when we don’t, we drift from risk towards ignorance, see for example [15].

4. Conclusions

In this paper we present a risk perspective, which is suitable for risk analysis and decision making for maritime domain.

The risk is about future events, but its description is based on experience gained in the past, which is a combination of our knowledge of the analyzed system and understanding of its behavior. Therefore knowledge and understanding are inherent parts of risk description, which in our opinion should be reflected by a notation of risk. Therefore, a risk perspective, which is proposed here, combines a well-founded Kaplanian triplet (scenario, likelihood and consequences), with knowledge and understanding of a modeled system. Despite distinction between knowledge and understanding is evident among philosophers, it has not received due credits among engineers yet. The importance of seeing these two concepts separately and its implication on the process of risk model development, uncertainty analysis and selection of risk measures has been demonstrated.

Although a risk perspective that is presented here is discussed in the narrow context of maritime transportation systems, it can be applied to any technical system. A concept introduced here leads to systematic and transparent risk analysis, where all requirements as specified by the IMO in the official guidelines for Formal Safety Assessment can be met.

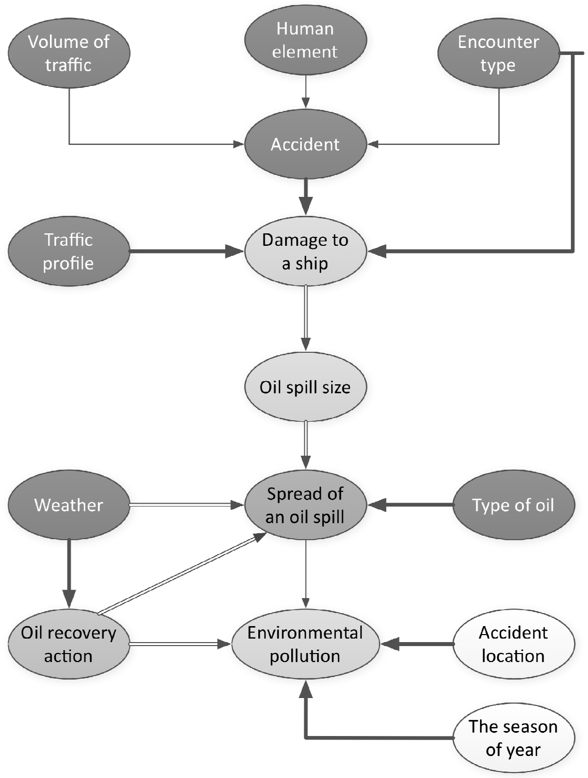

Figure 1 Simplified risk model for an accidental oil outflow

Acknowledgements

This study was conducted as a part of “Minimizing risks of maritime oil transport by holistic safety strategies” (MIMIC) project. The MIMIC project is funded by the European Union and the financing comes from the European Regional Development Fund, The Central Baltic INTERREG IV A Programme 2007-2013; the City of Kotka; Kotka-Hamina Regional Development Company (Cursor Oy); Centre for Economic Development, and Transport and the Environment of Southwest Finland (VARELY). Kaarle Ståhlberg,is greatly appreciated for the inspiring conversations.

References

[1] Ale, B.J.M., Bellamy, L.J., van der Boom, R., Cooper, J., Cooke, R.M., Goossens, L.H.J., Hale, A.R., Kurowicka, D., Morales, O., Roelen, A.L.C. & Spouge, J. Further development of a Causal model for Air Transport Safety (CATS): Building the mathematical heart. *Reliability Engineering & System Safety*, Vol. 94, No. 9, 1433–1441, Sep. 2009.

[2] Apostolakis, G.E. (1990). The Concept of Probability in Safety Assessments of Technological Systems. *Science*, Vol. 250, No. 4986, 1359–1364.

[3] Aven, T. (2012). Foundational issues in risk assessment and risk management. *Risk Analysis*, Vol. 32, No. 10, 1647–56.

[4] Aven, T. (2010). On how to define, understand and describe risk. *Reliability Engineering & System Safety*, Vol. 95, No. 6, 623–631.

[5] Aven, T. (2013). Practical implications of the new risk perspectives. Reliability Engineering & System Safety.

[6] Aven, T. (2012). The risk concept—historical and recent development trends. Reliability Engineering & System Safety, Vol. 99, No. 0, 33–44.

[7] Aven, T. & Heide, B. (2009). Reliability and validity of risk analysis. Reliability Engineering & System Safety, Vol. 94, No. 11, 1862–1868.

[8] Aven, T. & Zio, E. (2011). Some considerations on the treatment of uncertainties in risk assessment for practical decision making. *Reliability Engineering & System Safety*, Vol. 96, No. 1, 64–74.

[9] Baumberger, C. (2011). Understanding and its Relation to Knowledge, 16–18.

[10] Devanney, J. (2013). *Formal Safety Assessment in Wonderland.* Center for Tankship Excellence, USA

[11] Flage, R. & Aven, T. (2009). On treatment of uncertainty in system planning. *Reliability Engineering & System Safety*, Vol. 94, No. 4, 884–890.

[12] IMO, Guidelines for formal safety assessment (FSA) for use in the imo rule-making process. 2002.

[13] IMO, Formal Safety Assessment, Outcome of MSC 90. Draft revised FSA guidelines and draft HEAP guidelines.” IMO, Aug-2012.

[14] Kaplan, S. (1997). The Words of Risk Analysis. *Risk Analysis*, Vol. 17, No. 4, 407–417.

[15] Kaplan, S. & Garrick, B.J. (1981). On The Quantitative Definition of Risk. *Risk Analysis*, Vol. 1, No. 1, 11–27.

[16] Kontovas, C.A. & Psaraftis, H.N. (2009). Formal Safety Assessment: A Critical Review. *Marine Technology*, Vol. 46, No. 1, 45–59.

[17] Kristiansen, S. (2010) A BBN approach for analysis of maritime accident scenarios.

[18] Levin, R. (2006). Adequacy Conditions for Reporting Uncertainty in Chemical Risk Assessments. *Human and Ecological Risk Assessment: An International Journal*, Vol. 12, No. 5, 834–855.

[19] M.-W. Dictionaries, Knowledge - Definition and More from the Free Merriam-Webster Dictionary. Available: http://www.merriam-webster.com/dictionary/knowledge.

[20] Mullai, A. & Paulsson, U. (2011). A grounded theory model for analysis of marine accidents. *Accident Analysis & Prevention*, Vol. 43, No. 4, 1590–1603.

[21] Nilsen, T. & Aven, T. (2003). Models and model uncertainty in the context of risk analysis. *Reliability Engineering & System Safety*, Vol. 79, No. 3, 309–317.

[22] O. Dictionaries, Knowledge. Oxford University Press, Apr-2010.

[23] Paté-Cornell, M.E. (1996). Uncertainties in risk analysis: Six levels of treatment. *Reliability Engineering & System Safety*, Vol. 54, No. 2–3, 95–111.

[24] Pritchard, D. (2009). Knowledge, Understanding and Epistemic Value. *Royal Institute of Philosophy Supplements*, Vol. 64, 19–43.

[25] Psaraftis, H. N. (2012). Formal Safety Assessment: an updated review. Journal of Marine Science and Technology, Vol. 17, No. 3, 390–402.

[26] Rae, A., McDermid, J. & Rob, A. (2012). The Science and Superstition of Quantitative Risk Assessment.

[27] Roelen, L.C. (2008). Causal risk models of air transport: comparison of user needs and model capabilities. IOS Press, 2008.

[28] Roelen, A.L.C., Lin, P.H. & Hale, A.R. (2011). Accident models and organisational factors in air transport: The need for multi-method models. *Safety Science*, Vol. 49, No. 1, 5–10.

[29] Rosqvist, T. & Tuominen, R. (2004). Qualification of Formal Safety Assessment: an exploratory study. *Safety Science*, Vol. 42, No. 2, 99–120.

[30] Rosqvist, T. (2010). On the validation of risk analysis - A commentary. *Reliability Engineering & System Safety*, Vol. 95, No. 11, 1261–1265.

[31] Rowe, W.D. (1994). Understanding Uncertainty. *Risk Analysis*, Vol. 14, No. 5, 743–750.

[32] Stirling, A. & Gee, D. (2002). Science, precaution, and practice. *Public Health Reports*, Vol. 117, No. 6, 521–533.

[33] Veland, H. & Aven, T. (2013). Risk communication in the light of different risk perspectives. *Reliability Engineering & System Safety*, Vol. 110, No. 0, 34–40.

[34] Winkler, R.L. (1996). Uncertainty in probabilistic risk assessment. *Reliability Engineering & System Safety*, Vol. 54, No. 2–3, 127–132.

[35] Zio, E. & Aven, T. (2012). Industrial disasters: Extreme events, extremely rare. Some reflections on the treatment of uncertainties in the assessment of the associated risks. *Process Safety and Environmental Protection*, Sep. 2012.

[36] Zio, E. & Apostolakis, G.E. (1996). Two methods for the structured assessment of model uncertainty by experts in performance assessments of radioactive waste repositories. *Reliability Engineering & System Safety*, Vol. 54, No. 2–3, 225–241.