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SCENARIO BASED RISK MANAGEMENT FOR ARCTIC SHIPPING AND OPERATIONS

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ABSTRACT

Arctic oil and gas explorations and Arctic shipping must ensure the safety and protection of this sensitive environment in spite of the challenging operational conditions. However, current regulations and assessment methods do not predict the associated risk level reliably. In other words, ships transiting ice-covered waters are not designed according to physical measures, such as accurate limit states under ice loading, but according to economic and empirical design measures. Similarly, offshore installations should be designed according to the accurate limit states, but the actual ice loads are uncertain so this is not possible at present. Risk-based design methodologies using first principal methods offer a way to advance safe operations and transport of natural resources within and out of the Arctic Sea. This paper introduces a holistic treatment of the design relevant features and their identification to improve safe Arctic operations and transport. The focus is on design relevant Arctic aspects related to extreme and accidental ice events. The approach includes estimating ice loads, including extreme load events, assessing structural consequences of the loading events, assessing associated potential environmental consequences, and establishing a risk based design framework for managing risks.

INTRODUCTION

The increased activity in the Arctic involves hazards such as harsh environment, especially the ice cover and cold temperature, remoteness and lack of infrastructure, and lack of information about bathymetry. Ice cover is also highly variable in the Arctic. Variable and dynamic ice cover causes other hazards as well. Ships can get stuck in compressive (converging) ice cover and sustain extensive damage and drift aground with the ice motion. The remoteness of the Arctic areas means that in case of an accident, the search and rescue (SAR) capability is low. Also the fairways are not marked very extensively and especially the soundings taken for charting are relatively scarce – this brings additional hazards especially if an easier route through ice must be found. These Arctic hazards are compounded by the fact that rate of recovery of the Arctic nature is slow. The reduced SAR capability combined with the harsh climate also makes the human consequences more serious.

Consequently, Arctic shipping and operations must be safe to protect the sensitive Arctic environment. However, current regulations and assessment methods do not predict the associated risk level reliably. Consequently, ships transiting on ice-covered waters are not consistently designed according to physical measures, i.e. accurate limit states under ice loading, but according to economic and empirical design measures. Similarly, offshore installations should be designed according to the accurate limit states; however, the actual ice load is widely unknown. Hence, for safe operations and transport of the natural resources within and out of the Arctic Sea, risk-based design methodologies using first principal methods are required because empirical measures are not available and the tendency to minimize expenditure can lead to severe environmental catastrophes. The goal of this paper is to introduce the holistic treatment of the design relevant features and their identification to ensure safe Arctic operations and transport. Holistic risk analysis includes: definition of hazard scenarios, their occurrence probability and consequences, see Figure 1. Arctic sea transportation can be independent navigation or navigation with icebreaker assistance e.g. in level ice, ice floes and ridged ice with various amount of first year and multiyear ice features. In addition, the possibility of moving ice has to be included. Due to the changing effects of the world climate, also ice conditions on all ice-covered areas are changing.

The holistic treatment will be achieved through a consistent link between these elements and analysis of their effects on the conceptual design phase. Further, this holistic risk-based design methodology will take a step ahead by explicitly identifying the scenarios and how to evaluate their occurrence probabilities and consequences applying first principle methods. The novelty in this holistic risk-based approach is its focus on the design relevant actions occurring during the entire life-cycle of the ship or installation in question and not only on the initial service load conditions followed by a selection of required safety oriented assessments based on standard regulations.

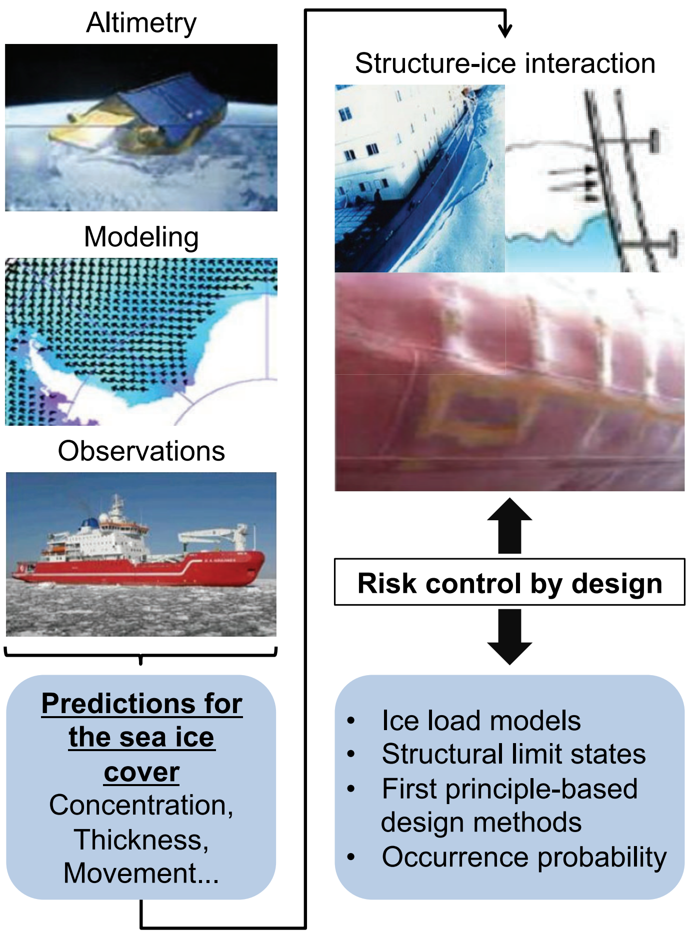

Figure 1. Scenario based risk management focusing on risk control by design using first principle methods

RISK-BASED DESIGN METHODS FOR ICE GOING SHIPS

During the last decades, great efforts have been put into human safety and the protection of the environment. Methods for both risk and reliability analysis are becoming very important as decision support in various engineering applications. Integration of these methods into the design process leads to risk-based design and Bainbridge et al. (2004) and Moan et al. (2006) place this into the context of ship design.

The development of structural reliability analysis in general started over 35 years ago as a new discipline in engineering, after a probabilistic theory linked reliability to rules. Standardized methods, guidelines, and related software tools nowadays support structural reliability analysis. The basis for the methods and terminology may be found in ISO 1998.

Risk-based approaches started in the early sixties in the maritime industry with the concept of probabilistic damage stability. However, it took more than a decade for the probabilistic concept to be introduced to the SOLAS regulations (SOLAS 74) as an alternative to the regulations on deterministic damage stability. Nowadays, the determination of damage stability is based on the probabilistic method, thanks to the intensive development of these rules over the last decade.

Reliability for ice-going vessels concerns the assessment of uncertainties related to ice-induced service loading, i.e. structural reliability analysis (see e.g. Kujala 1991a, Kaldasaun and Kujala 2011). The assessment of the risk in ice refers to the consequences of accidental ice-induced loading, i.e. risk-based methodology. Since about 1980, risk analysis has been mandatory within the offshore industry to identify risks, implement risk reducing measures, and to alert operators to the risks connected with their activities.

The goal of the risk-based framework is that all levels of analysis can be performed in a consistent way, by explicitly aiming at a common and transparent general criteria and methods of analysis. This approach is totally in line with Goal Based Standards (IMO 2004).

Risk-based approaches are already established quite well in the maritime industry and can be found for passenger ships, and some examples of cargo ships, e.g. MSC 76/INF.15, MSC 82/23/3. There is also a difference between risk assessment in the oil and gas industry and in the maritime industry. In the oil and gas industry each facility is assessed separately while in the maritime industry it primarily is done industry wide to establish rules and regulations. However, the design of ship for the operation in ice covered Arctic may suffer from limitations of the current rules and regulations concerning the ice-induced service loading. However, risk-based design and approval can then be used to identify the challenges and prove that the new solution is at least as safe as required using the newly gained knowledge on the uncertainties related to the ice-induced loading.

Scenario based risk management

The first task in scenario based risk management is to define the most relevant ice condition in compliance with the operation principles and scenarios for present and future Arctic activities. These tasks are concerned with the conceptual design from an operational perspective. Thereafter, first principle tools shall be used to evaluate the ice induced loads and their occurrence probabilities. Based on this the occurrence probabilities of various extreme and accidental limit states can be determined applying advanced structural analysis methodologies, i.e. first principal methods. The possible consequences of each limit state, including the environmental effects, shall be evaluated and based on this holistic risk based approach the conceptual design will be evaluated.

In order to develop such scenario based risk management methodology the Joint Center of Excellence for Arctic Shipping and Operations (CEARCTIC) has been funded by the Llyod's Register Foundation. The centre is coordinated by the Aalto University in Finland. To cover all the important elements in the holistic approach, expertise on design methods, ice environment, ship-ice interaction, and structural damage and consequence analysis is needed. CEARCTIC consists of four Universities: Aalto University in Finland (ice load assessment and modelling), Memorial University of Newfoundland in Canada (safety and risk modelling), Norwegian University of Science and Technology (structure-ice interaction modelling) and University of Helsinki in Finland (environmental effects and risk modelling). Figure 2 summarizes the scenario based risk management.

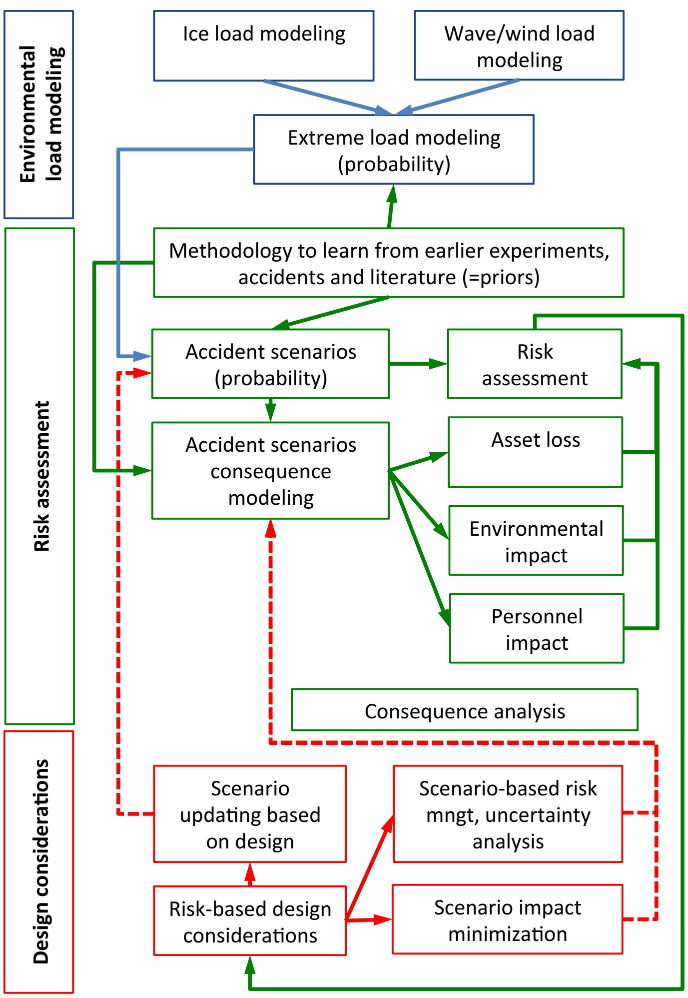

Figure 2. The basic elements and the process needed for risk-based design approach found in CEARCTIC

Environmental load modelling

One of the main challenges for holistic risk modelling of Arctic operations is the lack of knowledge related to the evaluation of ice induced load levels and their occurrence probabilities. The difficulty in the prediction of ice loads arises from the stochastic nature of ice strength properties and ship-ice interaction process. As ice is formed in nature, numerous variables affect the mechanical and physical properties of ice. First principal tools capturing the physical process of ice crushing and breaking in a form suitable for design are needed. Ice induced loads and their frequencies are today primarily obtained based on empirical data, yet in view of navigation through ice-covered waters, ship traffic patterns and ice movements need to be investigated for a more direct approach. Full-scale measurements and damage statistics are important databases for model development and validation, as summarised e.g. by Riska and Kämäräinen (2012) for the Baltic Sea ice conditions. The statistical nature of ice-induced loads have been under active research, but still a sound link between the random character of ice-induced loads and prevailing ice conditions is missing see e.g. Kujala and Vuorio (1986), Kujala (1996), Jordaan et al. (1993), Hänninen (2002), Kujala et al. (2009), Suominen and Kujala (2010), Taylor et al. (2010) and Suominen (2011).

Risk assessment

Ideally, the risk-based design process seeks to identify the exact safety margin using the accurately assessed uncertainty related to the ice-induced load. As a result, there would be no need to speculate if the rule compliance suffices, since the safety level for the given environmental conditions is clearly identified. Thus the risk level for different designs must be quantified. In fact, risk shall be used to measure the safety performance. By having safety measurable, it is possible to effectively optimize the ship design by introducing risk minimization as a new objective along with standard objectives. In other words, one additional constraint enters the design optimization as follows:

$$R_{design} \leq R_{acceptable}$$

where R_{design} is the risk of the considered ship or system and $R_{acceptable}$ the acceptable risk. Furthermore, the trend is to apply the ALARP principle, which relates the acceptable probability of fatality, pollution and economic loss as a function of the magnitude of the consequences in view of the costs of reducing the risk. In order to assess the risk from accidental ice-induced loading, the consequences, i.e. the structural response and strength, needs to be obtained. Thereby, the related uncertainties can be assessed accurately. The state of the art review presented above for ice loading already identifies the need for accurate ice and structural interaction models. Furthermore, assessing the response to a vast number of possible accidental scenarios requires efficient computational methodologies to optimize the structural layout to minimize this risk.

In order to minimize the risk of a ship subjected to accidental ice-induced loading, conflicts are often faced. For example, being incapable to create a lightweight, safe and inexpensive ship might lead to conflicting objectives. Therefore multi-objective optimization is needed to foster proper treatment of the global objective to minimize the risk, i.e. maximize safety.

Concerning ship structures, multi-objective optimisation of ship structures can be found e.g. in Shi (1992) and Parsons and Singer (2000). Recently the use of Genetic Algorithms in multi-objective optimisation is quite popular (e.g. Okada and Neki 1992, Klanac et al. 2007). The papers by Soto and Diaz (1999) and Ignatovich and Diaz (2000) optimize structures for crashworthiness by changing material parameters based upon sensitivity information. Topology optimization in design under impact loading has been used e.g. by Soto (2001). These papers use heuristic schemes to update the design variables because they have difficulties to compute sensitivities. The latter shortcoming has been overcome by Ehlers (2010 and 2012) and may be applied for efficient computational risk-assessment.

The evaluation of the consequences of alternative accident scenarios has to cover the process from accident occurrence to its consequences, to ecosystem response and recovery.

CEARCTIC RESEARCH METHODOLOGY

In order to overcome the above-mentioned research and knowledge gaps CEARCTIC will employ at least 8 PhD candidates starting from the autumn of 2013 until 2018, with joint research amongst the four participating.

The following questions arises related to structural designs and concerning the estimation of environmental damages: How to integrate the evidence available from laboratories and field consistently and how to link their dependencies and information contents in a scientifically correct way? As a major methodological approach to answer these challenges, CEARCTIC will apply Bayesian hierarchical modelling tools (Gelman et al. 2004, Khakzad et al. 2012, Yang et al. 2012a). This will also ensure that the risk assessment and risk management (transfer of risk back to required designs) steps will be able to use all obtained information in the same way. CEARCTIC methods will be tested against real cases and data sets.

Ship design relevant actions and predictive accident modelling

CEARCTIC concentrates on the identification of the Arctic ship design relevant actions and their uncertainty occurring during the ship's life cycle. These actions include service and accidental ice, iceberg and general collision loads. Consideration is given not only to the initial service load conditions followed by a selection of required safety oriented assessments based on standard regulations, but also to the explicit assessment of the consequences of relevant actions and to the evaluation and prediction of ice induced load levels and their occurrence probabilities in the Arctic operations. Full-scale measurements and damage statistics in the Baltic Sea and Arctic waters are used to validate the developed first principle approaches for evaluation of ice induced loads (Muhonen 1992, Kujala 1991b, Kujala 1994, Kujala 1995, Kotisalo and Kujala 1999, Kaldasaun and Kujala 2011, Riska and Kämäräinen 2012). The statistical nature of ice induced loads and pressures have also been studied in model scale to get deeper understanding of the physical processes (Kujala and Arughadhoss 2012).

Predictive accident modelling is an important research area that comprises the following activities: i) Identification of marine accident causes: this subtask will include detailed study of the causes related to weather, marine systems, navigational errors, and human factors. ii) Development of accident causation model: this subtask will include linking causes in a logical sequence and defining their dependency and condition of occurrence. iii) Implementing a probabilistic approach to accident causation: this subtask will include defining probabilities and dependency of causes. iv) Accident analysis: this activity will involve probability analysis of accident causation and estimation of accident probability in given conditions. v) Probability updating (Ferdous et al. 2012a and 2012b): this activity will investigate methods of updating predictive accident probability in light of new information, such as changing weather conditions, routes, or impact of safety measures. Accident models will help to develop and apply reliable accidental safety assessment procedures (Ehlers 2009 and 2010) for sub-zero, i.e. Arctic, temperatures (Ehlers and Østby 2012). In conclusion, the risk-based design of ships sailing in ice-infested waters will become possible because the uncertainties related to the service, accidental actions and the ship operations will be assessed. The knowledge gained in these topics will be closely connected to the development of a multi-level modelling approach for ship structural and systems optimization.

Structure-ice interaction modelling

This multi-level modelling approach focuses on the global and local ice and structural behaviour under Arctic conditions considering accidental events and thereby contributes to the risk assessment of Arctic ships. The ice and ship impact simulations for the holistic risk-based design for Arctic vessels includes phenomena that span length scales from the microscopic material behaviour and heterogeneity of ice and steel, initiation and propagation of fractures on multiple length scales, to overall response of ice and ship hulls to loads resulting from their interaction, see Figure 3. Therefore, CEARCTIC develops a multi-scale and hierarchical computational framework that can integrate the developed ice mechanics and steel material and physical understanding of the key phenomena in such a way that the overall uncertainty in the estimates that form the basis for the risk-based design of ships is minimized. Latest developments include detailed studies of the ice failure process using numerical simulations, see von Bock und Polach et al. (2013) and von Bock und Polach and

Ehlers (2013). This first principle based simulations are carried out for model scale ice including experimental validation. Tomac et al. (2013) carried out a promising full ship model in ice simulation using the developed model. New testing approaches have been developed to measure the local ice induced pressure and loads on the ship model (Suominen and Kujala 2012). By first principle methods the relationship between ice conditions and ice-induced loads can be established. Concerning full-scale simulations, Aalto's extensive full-scale database will be used. As a result of the developed computational methodology, probabilistic models or optimization for risk-minimization with large numbers of independent sampling and searches can be performed. Further, this computational solution environment will form the basis for the holistic risk-based design methodology.

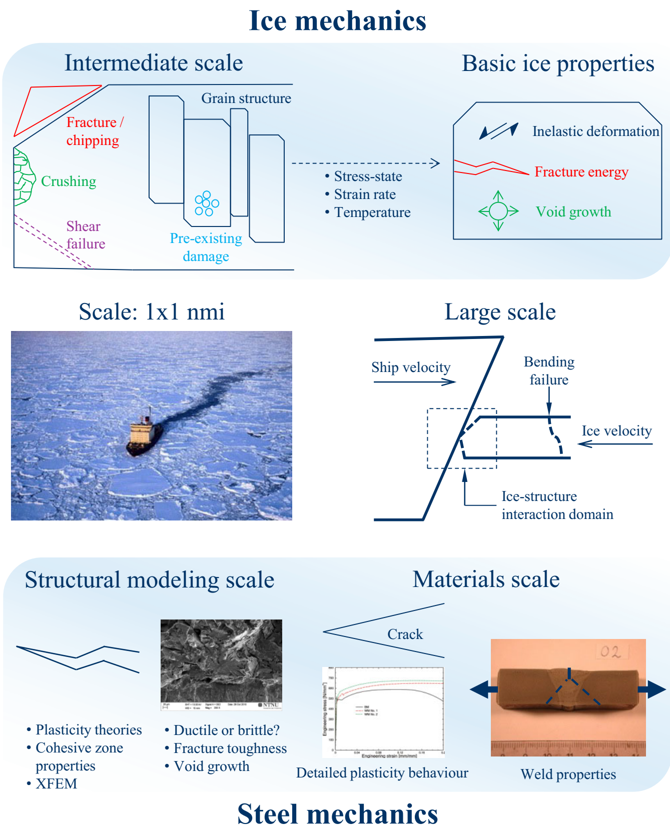

Figure 3. Multi-scale ship-ice-interaction process

Environmental consequences modelling

As a result of the above developed computational solution environment, direct consequences of alternative accidents can be evaluated. These include the area specific probabilities of, for example, the ice induced spills and the conditional probability distribution of the spill size for each accident type. There is significant uncertainty in terms of how the release of contaminants might impact the Arctic environment. The evaluation of the consequences of alternative accident scenarios covers the process from accident occurrence to its consequences, to ecosystem response and recovery. Each step in this chain is complex, which creates uncertainties in model predictions (Klemola et al. 2009, Helle et al. 2011). The first step is to decide on a representative set of possible accidents, consequences and ecosystem compartments that are relevant. As most of the near future operations in the Arctic are related to oil and gas exploration and transportation we will concentrate on accidents leading to oil spills. CEARCTIC will develop a model for consequence assessment in the Arctic environment. The model will use a fugacity approach along with uncertainty modelling. Important steps involved in this task are: i) Dispersion/transportation and contaminant partition modelling in different media. ii) Exposure modelling: this step will study how contaminants might be exposed/available to different ecological entities. iii) Ecosystem response modelling: this subtask will attempt to assess impact caused by contaminant release. iv) Uncertainty analysis: this task will consider variability and imprecision in the knowledge and attempt to qualify uncertainty in assessed consequences.

The ecosystem response is studied using example species whose living habitat spans from surface water, coastal regions and ice edges. Such species are, for example, seals, polar bears, and some bird species. The rationale for this choice is that modelling the oil drift, animal behaviour and ecotoxicological impacts in deep water layers are practically infeasible under current knowledge. Modelling the surface area close to the coast and close to ice edges is already a step forward from current state-of-the-art methods (Nazir et al. 2008). The modelling will especially focus on species that are both sensitive to oil and which have a high conservation status. Here we refer to the index approach by Ihaksi et al. (2011) and the software approach by Kokkonen et al. (2010), which make use of ecological and threatened species knowledge in focusing oil combating actions. The approach of Ihaksi et al. (2011) takes into account the likely exposure of the whole population and mortality due to spill, recovery potential and the relative effectiveness of alternative combatting options in helping the population, or transferring the impact from surface, ice edge and coastal species to underwater species living in deeper layers (use of chemicals to disperse the oil; Nazir et al. 2008, Helle et al. 2011).

The modelling of species' response to oil will be conducted utilizing a hierarchical modelling framework to combine all available knowledge. The aim is to build a methodology by which the learning from expert knowledge (Lecklin et al. 2011, Ferdous et al. 2011, 2012a) from earlier oil spills and from laboratory experiments would be as effective as possible in order to accurately predict the possible responses in future scenarios. This is a very important methodology to be used for species that are threatened and therefore cannot be used in laboratory tests, but which likely have similar ecotoxicological sensitivities as such species that can be used in laboratory. The hierarchical Bayesian inference offers a state of the art solution to such learning from all such knowledge. CEARCTIC aims to provide a methodological framework where the learning from earlier accidents is effective, providing as good as possible predictions for planning the activities and assessing the risks. These predictions will further be improved by combining them with the existing ecological models that will be converted from deterministic to probabilistic representation (Vanhatalo et al., 2013, Nazir et al. 2008, Ferdous et al. 2012a and b).

Risk assessment and risk based decision making

Finally, risk assessment and risk-based decision making will be carried out as a result of the following five steps: i) data collection and analysis from different sources, ii) engineering failure analysis considering external factors and also utilizing data collected in earlier steps, iii) consequence analysis using appropriate financial and ecological models applicable to sensitive environments, iv) risk analysis using the outcome of last two steps, and v) integrating assessed risk into a decision-making framework. CEARCTIC extends the evaluation of the consequences of alternative accidents into risk assessment and decision making tools. International conventions define some limits for impacts of human activity in Arctic areas. Thus, a methodology by which decisions concerning alternative structural designs can be measured against these limits will be built. Such a methodology will provide a probabilistic decision-making framework to support the decision, i.e. how much additional safety is needed due to the sensitivity of the environment to control the risks and what is the most cost effective way to reach the accepted risk level. CEARCTIC will assess the risk as a design consideration comprising the following activities: i) Probabilistic risk assessment: here, results of the predictive accident model will be multiplied with consequences. As consequences are assessed in three domains (asset, environment, and personnel) they all will have different units. An important challenge of this subtask will be to bring all consequences to a common domain so that they can be combined with probability to estimate risk. ii) Risk as a design parameter: this subtask will investigate how to use estimated risk as a design criterion. The challenge of this activity will be translating risk into design criteria and subsequently into design parameters (such as shell thickness or hull design). iii) Effectiveness of design: in this subtask recommended changes as per risk criteria will be assessed for economical and technical feasibility. This activity will help to assess whether a design is economically and technically feasible.

Finally, a methodology will be developed for alternative decisions (the alternative structural designs) to possible probabilistic risk. This challenge will be tackled with Bayesian networks (Kuikka et al. 1999, Varis and Kuikka 1999, Barton et al. 2012, Khakzad et al. 2012), which provide an efficient and theoretically sound framework for describing the causal structures in the problem at hand by using conditional probability tables (Jensen 2001, Khakzad et al. 2012). Such models have been used for example, in analysing oil spill risks and eutrophication management measures in the Baltic (Helle et al. 2011).

CONCLUSIONS

CEARCTIC will address the challenges related to the design of Arctic ships and structures through the development of a scenario based risk management methodology for Arctic shipping and operations. The main expected outcomes are:

- Probabilistic framework for extreme load events in Arctic operations
- Probabilistic predictive accident model with an updating mechanism considering accidental load events and their probabilities
- Numerical model for ship-ice interaction
- Numerical model for ice-induced damages on ships and optimized scantlings
- Model for ecosystem response after oil spill
- Probabilistic framework for species whose living habitat spans surface water, coastal regions and ice edges
- Risk assessment and decision making tools
- Risk-based design methodology with models to assess economical and technical feasibility for Arctic operations

The results of this Joint Center of Excellence for Arctic Shipping and Operations will continuously be provided through ceArctic.com

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