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Review of Risk-Based Design for ice-class ships

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Abstract

The growing interest for Arctic and Antarctic shipping activities due to the decreasing ice cover will also increase the risks of accidents on these waters. The design of ships for ice has traditionally been based on the practical experience without a clear link to the physics of the ship-ice interaction. The rules are, however, getting more towards the goal based approach, which require good knowledge of all the various element important for design. Risk based ship design (RBSD) is also widely applied e.g. for the passengers ships. Therefore, the scope of this paper is the review of the knowledge necessary for RBSD for Arctic conditions. The main focus is on ice loads and ship structures. Accident prevention and environmental consequences of oil spills are also discussed, but more briefly. In risk analysis, there is a recent focus on the treatment of uncertainty, or conversely, the strength of knowledge underlying the risk quantification. In light of this, the review is performed with specific focus on the strength of evidence of the different fields of knowledge needed to perform RBSD in ice conditions. The results indicate that the risk based design for Arctic operations is challenging as the ice environment, together with all the possible ship-ice contact scenarios, are complicated to define properly, especially on proper probabilistic terms. The main challenges are still related how to describe the ship-ice interaction parameters such as ship-ice contact characteristics, pressure distributions, and load levels in all the various ice conditions. In addition, the possible environmental consequences of the accidents need further research. Finally, human factors need to be incorporated in risk analysis techniques.

Keywords

Risk-based ship design, uncertainty, strength of evidence, maritime safety, ice environment, ice load, structural limit states

1 Introduction

Activity in the Arctic occurs in remote regions where there is typically lack of infrastructure, sometimes insufficient basic information, such as bathymetry, and generally harsh environmental conditions, such as ice cover and low temperatures. Furthermore, the ice cover is highly variable

33 and dynamic, characteristics that are anticipated to increase in the future due to the effects of
34 climate change. These characteristics complicate Arctic operations. The remoteness of the Arctic
35 areas implies that in case of an accident, the search and rescue (SAR) capability is low. Fairways
36 are not marked very extensively and especially the soundings taken for charting are relatively
37 scarce. These Arctic conditions are compounded by the fact that the rate of recovery of the natural
38 environment in the Arctic nature is slow, i.e. the consequences of shipping accidents in the Arctic
39 are potentially very serious for the vulnerable ecosystem.

40 Conventional rule-based ship design follows a design spiral - a graphical representation that
41 captures the basic tenets of widely accepted ship design approaches (Evans 1959, Gale, 2003). This
42 design spiral consists of three main phases, namely, concept, preliminary and detail design. Safety
43 rules are often treated as design constraints in this design paradigm. Although rule or prescriptive-
44 based design approaches are easy to follow and implement, they may cause over-conservative
45 design problems and do not drive innovative changes for performance improvement (Yang et al.,
46 2013). Safety level is often uncertain or unknown in design rules and rules do not always reflect
47 experience. Therefore, a move towards a goal or performance-based approach to ship design would
48 be preferable over the conventional approaches. A risk-based design approach is one way forward
49 in this direction. This new design paradigm treats safety as a design objective rather than constraint
50 (Papanikolaou, 2009). This implies that a risk-based design can help to meet safety expectations in
51 cost-effective ways.

52 Risk assessment has for many years been considered to be a useful tool in many application areas
53 (Apostolakis, 2004), and has also been adopted as a basis for risk-based ship design (Papanikolaou,
54 2009; Pedersen, 2010). The underlying rationale of such a proactive approach to safe ship design is
55 in line with the philosophy adopted by the International Maritime Organization (IMO) to apply
56 goal-based (opposed to rule-based) ship design standards (MSC.1/Circ.1394/Rev.1, 2015). The
57 focus on risk-based approaches in international maritime regulatory decision-making is also clear
58 from the Formal Safety Assessment (FSA) framework adopted by the IMO (MSC-
59 MEPC.2/Circ.12/Rev.1, 2015) and the implementation of several research projects focusing on risk-
60 based design approaches for the maritime industry (Breinholt et al., 2012; Montewka et al., 2016;
61 Papanikolaou et al., 2013). For the marine industry risk assessment is nothing new. Classification
62 societies have published general guidelines on risk assessment and its applications to ship design
63 and operations (e.g., ABS, 2000; ABS, 2003). These guidelines have laid a reasonably good
64 knowledge basis for the adoption of the risk-based approach by the marine industry (Yang et al.,
65 2015a).

66 In general, a risk-based ship design approach helps to translate estimated risk values into design
67 parameters. To obtain such model, we need to answer four questions:

- 68 (1) How to identify the key hazards and associated parameters?
69 (2) How to measure risk consistently through a formalized procedure?
70 (3) How to integrate the risk assessment procedure into the design process?
71 (4) How to trade off among system performance, cost and risk reduction?
72

73 Bergström et al. (2016) have studied in detail the assessment of the applicability of goal- and risk-
74 based design on Arctic sea transport systems. The focus in the system level approach and how to

75 define a holistic design process considering operational and regulatory requirements, cost-
76 efficiency, and design robustness. The proposed method makes use of system thinking and discrete
77 event simulation based Monte Carlo simulations. (Bergström, 2017). Bergström et al. (2016) also
78 defined the difference between goal and risk based design, stating that goal based design approach
79 is for deterministic functional requirements for the performance parameters and risk based design
80 require probabilistic functional requirements. This means that in risk based design, the basic tools
81 developed as part of risk analysis framework will be applied and used in design e.g. to define the
82 target safety level or individual risks of the product under consideration. So risk analysis are needed
83 to determine probability of the various studied scenarios and their consequences and risk based
84 design aims to design the ships and other systems so that a proper risk level is achieved.

85 The scope of this paper is the review of the knowledge necessary for risk based ship design (RBSD)
86 for ice conditions, especially Arctic conditions. Following a scenario-based approach to quantitative
87 risk analysis, RBSD requires at minimum to cover the following topics: definition of hazard
88 scenarios, their occurrence probabilities, and consequences, see Figure 1. This is in line with the
89 well-known risk triplet “What can happen?”, “How likely is it that that will happen?” and “If it does
90 happen, what are the consequences” (Kaplan and Garrick, 1981). The minimum knowledge
91 requirements to apply RBSD for Arctic operations is an understanding of the behaviour of the sea ice
92 cover, ship-ice interaction and structural response, and the possible consequences of failures. The
93 paper includes both ship accidents and any local ship hull damages as possible scenarios, however,
94 the focus is on the local design of ship hull and related consequences such as local dents which have
95 been traditionally used a design scenarios for ice-strengthened ship hulls.

96 In risk analysis, there is a recent focus on the treatment of uncertainty, or conversely, the strength of
97 knowledge underlying the risk quantification (Flage et al., 2014). In maritime risk analysis
98 applications and FSA, uncertainties are often not elaborated on. As a step towards improving
99 current practices, the review is performed with specific focus on the strength of evidence of the
100 different fields of knowledge needed to perform RBSD in Arctic ice conditions. Such an evaluation
101 of uncertainties also serves as a research agenda, where priorities for reducing the uncertainties can
102 be set.

103 The remainder of this paper is organised as follows. In Section 2, a brief background about the
104 treatment of uncertainty in risk analysis is provided. In addition, the methodology for assessing the
105 strength of evidence is outlined. In section 3, current approaches to ship hull design in Arctic
106 conditions are briefly reviewed and after that, in Section 4, first an overview of Arctic activities and
107 a history of ship accidents is described, and thereafter the various elements of a proper risk based
108 ship design approach, as illustrated in Figure 1, are reviewed and discussed. For the available data
109 and models, different quality characteristics are finally considered and judged, from which a rating
110 for their evidential strength is derived in Section 5.

111

112

113 *Figure 1. The minimum elements of holistic risk based design (Adapted from Kujala et al., 2015).*
 114 *The term holistic means here that the risk based design needs extensive knowledge on all the*
 115 *elements shown in this figure.*

116 2 Uncertainty in risk analysis: background, concept and method

117 2.1. Background

118 In the scientific risk research community, there is a recent focus on foundational issues, where
 119 concerted efforts are called for to strengthen the scientific basis for risk analysis applications and to
 120 improve current practices (Aven and Zio, 2014; Rae et al., 2014). One of the issues raised is the

121 appropriate characterization, representation and interpretation of uncertainty in risk analysis and
122 management (Flage et al., 2014). Whereas uncertainty treatment has been argued to be a validity
123 criterion for risk analysis (Aven and Heide, 2009) and is explicitly mentioned in IMO's FSA
124 guidelines (MSC-MEPC.2/Circ.12/Rev.1, 2015), current practices show that uncertainties are often
125 not considered in actual maritime risk analysis applications (Psaraftis, 2012). Yang et al. (2013)
126 highlight the need for practical frameworks for uncertainty treatment in FSA applications and goal-
127 based ship construction standards.

128 The treatment of uncertainty in risk analysis is an active area of research, and both the conceptual
129 understanding of its content and methods to characterize and represent it are seen as important
130 research topics for further strengthening the risk analysis discipline (Aven and Zio, 2014). As with
131 other terminology, different meanings are attributed to the uncertainty concept. Furthermore,
132 several methods for accounting for uncertainty in practical applications have been suggested. As
133 this linguistic ambiguity potentially complicates the discussion, the remainder of this section
134 formulates how uncertainty is understood in this paper (Section 2.2). Subsequently, the method
135 applied to characterize uncertainty in the literature review is introduced (Section 2.3).

136 2.2. The concepts of uncertainty and strength of evidence

137 In the most recent glossary of the Society of Risk Analysis, uncertainty is defined as "*for a person*
138 *or a group of persons, not knowing the true value of a quantity or the future consequences of an*
139 *activity*" and "*imperfect or incomplete information/knowledge about a hypothesis, a quantity, or*
140 *the occurrence of an event*" (SRA, 2015).

141 Various more precise definitions and classifications of the uncertainty concept are found in the
142 scientific literature. One often applied distinction is between aleatory and epistemic uncertainty
143 (Der Kiureghian and Ditlevsen, 2009). Uncertainties are classified as epistemic if they relate to the
144 limits of currently available knowledge, where a modeller foresees a possibility to reduce these by
145 gathering more data or by refining models. Uncertainties classified as aleatory relate to the inherent
146 variation in a considered population, where a modeller foresees no possibility to reduce these.

147 Murphy et al. (2011) make another distinction between endoxastic uncertainty and metadoxastic
148 uncertainty. Endoxastic uncertainty is inherent in the results of a model, and is generated by various
149 mechanisms in the model development and application: model inexactness, mistaken assumptions,
150 measurement error, statistical uncertainty, randomness in input variables, volitional uncertainty and
151 human error. Metadoxastic concerns the degree of confidence we should have in a model itself, in
152 relation to the choice between other models.

153 Levin (2005) makes a distinction not directly related to modelling, between outcome uncertainty
154 and evidence uncertainty. Outcome uncertainty is understood here as an assessor's cognitive
155 attitude, where different rival beliefs concerning an indeterminate outcome (at the time of
156 consideration) are simultaneously entertained. Evidence uncertainty concerns the lack of knowledge
157 about evidential elements, which stand in relation to the assessor's statement about indeterminate,
158 uncertain outcomes.

159 For the purposes of this paper, a concept closely linked to evidence uncertainty, namely the
160 strength-of-evidence, is applied. This strength of evidence has been put forward as an alternative
161 formulation to account for the deficiencies, limitations and/or unreliability of data, models,
162 judgments and assumptions underlying risk analysis applications (Flage et al., 2014). The rationale
163 is simple: if evidential, endoxastic or epistemic uncertainty is high, the strength of evidence
164 supporting the risk analysis is poor. Conversely, if uncertainty is low, the strength of evidence is
165 high. The primary reason for using this terminology is because it decreases linguistic ambiguity
166 concerning what one is uncertain about: the outcome of the model or analysis, or the underlying
167 evidence. See also Goerlandt and Reniers (2016a).

168 2.3. Method for assessing the strength of evidence

169 In risk analysis, there are two broad classes of methods for accounting for uncertainty (strength of
170 evidence) about the risk quantifications. Quantitative approaches apply different mathematical
171 theories to quantitatively bound the outcomes of the PRA, leading to a set of risk curves which
172 represent different levels of confidence about the outcomes (Paté-Cornell, 1996). Mathematical
173 theories for this include classical Bayesian statistics, imprecise (interval) probability, evidence
174 theory and possibility theory, see Helton and Johnson (2011) and Zio and Pedroni (2013).
175 Qualitative approaches do not attempt to quantify the uncertainty about the outcomes of the PRA,
176 but focus on providing direct insight in the strengths and weaknesses of the applied evidence, and
177 on the effects of uncertainties not considered in the PRA.

178 In the review of the literature in Section 4, the focus is not on a specific modelling approach, but
179 rather on the state of art in the main areas of knowledge related to risk based ship design for Arctic
180 transportation. As introduced above, the review is framed to consider for which knowledge areas
181 strong evidence is available and for which aspects the evidence currently is poor and would
182 especially benefit from more research, see also Figure 1. Correspondingly, quantitative approaches
183 for uncertainty treatment, which focus on specific applications, are not feasible for literature review
184 purposes. Hence, a qualitative method for assessing the strength of considered knowledge areas is
185 applied in Section 5.

186 Different qualitative uncertainty assessment approaches have been proposed in the risk analysis
187 literature. Flage and Aven (2009) propose a crude uncertainty scoring method using the combined
188 quality of different evidence categories (data, models, judgments and assumptions), leading to a
189 ranking of low, medium or high uncertainty. A very similar approach is taken by Berner and Flage
190 (2016), where the focus shifts from uncertainty to the strength of evidence. Goerlandt and
191 Montewka (2015) propose an uncertainty rating method where the characteristics of the evidence
192 are more directly accounted for. Goerlandt and Reniers (2016a) discuss these crude qualitative
193 uncertainty assessment schemes, finding some ambiguities in the phrasing of the uncertainty rating
194 systems of Flage and Aven (2009) and Goerlandt and Montewka (2015). They suggest a method
195 where the ratings of the strength of evidence are kept separate, to more clearly show what type(s) of
196 evidence the different parts of the analysis are based on. Considering that the strength of evidence
197 assessment method by Goerlandt and Reniers (2016a) is the state of the art in risk analysis, see also
198 Zio (2016), it is applied as a methodological basis for the review in Section 4.

199 For data and models, different quality characteristics are considered and judged, from which a
 200 rating for their evidential strength is derived. These are shown in Table 1, where for conditions
 201 between strong and weak evidential characteristics, a ‘medium’ rating is applied.

202 *Table 1: Evidential characteristics and criteria for strength-of-evidence rating*
 203 *for data and model evidence types, Goerlandt and Reniers (2016a)*

Evidence type	Strong evidential characteristics	Weak evidential characteristics
Data		
Quality	Low number of errors High accuracy of recording High reliability of data source	High number of errors Low accuracy of recording Low reliability of data source
Amount	Much relevant data available	Little data available
Models		
Empirical validation	Many different experimental tests performed Existing experimental tests agree well with model output	No or little experimental confirmation available Existing experimental tests show large discrepancy with model output
Theoretical viability	Model expected to lead to good predictions	Model expected to lead to poor predictions

204

205 Using the characteristics of the data (quality and amount) and models (empirical validation and
 206 theoretical viability), a strength of evidence rating for these evidence types is determined as follows.
 207 First, it is decided based on the descriptions of strong and weak evidential characteristics, which
 208 categories apply for the quality, amount, empirical validation and theoretical viability. In
 209 applications, a justification for this rating should be provided, as the rating is a subjective judgment,
 210 the reasons for which needs to be traceable, see also Goerlandt and Montewka (2015). Then, the
 211 strength of evidence is determined as the average rating of the relevant characteristics of the data
 212 and models’ evidence categories, respectively.

213 3. Current approaches to ship hull design

214 Typically, ice class rules are based on the long-term experience of navigation in ice in various sea
 215 areas and the design scenarios used are not clearly specified. The most obvious definition of the
 216 design scenario is given for the IACS Unified Requirements for Polar Class Ships (IACS UR I.1-3),
 217 in which a glancing impact between ship and ice is used, see Figure 2. This is based on the original
 218 theory developed by Popov et al. (1967) and developed further by Daley (1999) assuming that the
 219 ship kinetic energy is spent in ice crushing when a ship hits an ice edge on a glancing impact. The
 220 scantling formulae are set with the use of plastic limit state equations for plating and frames (Daley
 221 et al. 2001, Kendrik 2015).

Figure 2. Design ice impact scenario IACS Unified Requirements for Polar Class Ships (Kendrik, 2015)

For other relevant Arctic ice class rules, such as Canadian ASPPR (Carter et al., 1992) and Russian rules (RMRS, 2010), the design scenarios are not so clearly illustrated. Both use so-called ice numerals to relate the prevailing ice conditions with the required ice class, which is based mainly on the long term experience of navigation in ice. For Finnish-Swedish ice class, the design scenario can be described as hitting the ice edge with level ice thickness of about 1.0 m for ice class IA Super and this decreases down to 0.4 m for ice lass IC, even though there is still remarkable uncertainty as to which ship-ice interaction scenario causes the highest loads (Riska et al., 2012).

The International Maritime Organization (IMO) has been developing a mandatory International Code of Safety for Ships Operating in Polar Waters (Polar Code). The Polar Code has been developed to supplement the existing IMO instruments in order to improve the safety of shipping and to mitigate harmful effects of shipping on the environment in the remote, vulnerable and potentially harsh polar waters. They came into force in January 2017. Even though the hull ice loading and scantling formulations are the same in Polar Code classes, the new guidance is planned to include an example of an acceptable methodology for assessing operational capabilities and limitations for ships operating in ice, the so called Polar Operational Limit Assessment Risk Indexing System (POLARIS). POLARIS provides a standard approach for the evaluation of risks to the ship and the ice conditions encountered or expected (ice regime). This system has been tested e.g. by Kujala et al. (2015, 2016) for Arctic and Antarctic waters, indicating that it is a good approach to determine the proper ice class once the ice conditions in the navigation area are known.

The proper safety level is not defined in the current ice-strengthening rules, but the latest standard for design for Arctic offshore structures (ISO 19906:2010) defines three exposure categories and related return periods for the probability of occurrence of these:

1. Ultimate limit state (ULS) for all exposure levels (EL's) requires extreme 100-year ice event with action factors dependent on the EL
2. Abnormal/accidental limit state (ALS) for 1,000-year ice events allowing some structural damage, but with no loss of life or harm to the environment
3. Serviceability (SLS) ensuring functionality under any 10-year ice event

252 These can be applied for ships as well, defining that the ultimate strength of the ship shell structures
253 has to be high enough to survive ice loads occurring with the annual probability of 10^{-2} . Accidental
254 limits states (like major deformation of shell structures but no leakage due cracks are allowed) can
255 take place with the annual probability of 10^{-4} . Serviceability limit state can mean, e.g., some
256 permanent deflection of the plating between frames due to the local ice load events that can occur
257 with the annual probability of 10^{-1} .

258 Another approach to optimise the design of structures and having the proper safety levels for
259 ultimate strength has been shown by Kujala and Ehlers (2014). It is shown that the amount of
260 allowable plastic deformations is not clearly defined in the present ice class rules. Nor is the critical
261 deformation limit that requires repair. It is possible to increase the scantlings until no plastic
262 deformations occur during the ship's lifetime. This will cause a high investment cost at the
263 construction phase, but no repair cost during the design life. Another possibility is to allow some
264 local plasticity requiring repair work at specified nominal frequencies during the ships' lifetime,
265 which causes smaller investments, but higher maintenance costs. The optimum between these two
266 extremes was described by Kujala and Ehlers (2014). This can be considered one way to determine
267 the cost-effective safety level.

268 4 Review of relevant fields of knowledge

269 4.1. Arctic shipping activities and accident statistics

270 The aim of this chapter is to give a good overview of the possible scenarios needed for RBSD based
271 on the accidents statistics. Historical data of the local dents caused by ice are the most important for
272 the future ice class rule development and application of risk based design. Unfortunately this data is
273 very limited and therefore it was considered appropriate to present an overview of accident data in
274 this chapter.

275 There is a long history of Arctic marine transport. For example, year-round navigation has been
276 maintained since 1978-79 in the ice-covered western regions of the Northern Sea Route (between
277 the port of Dudinka on the Yenisei River and Murmansk), see e.g. AMSA (2009). The Arctic today
278 is destinational, conducted for community re-supply, marine tourism and moving natural resources
279 out of the Arctic. Regions of high concentrations of Arctic marine activity occur along the coasts of
280 northwest Russia, and in the ice-free waters off Norway, Greenland, Iceland and in the U.S. Arctic.
281 Significant increases in cruise ships, a majority not purpose-built for Arctic waters, have been
282 observed in the summer season around Greenland within the past decade. Few years ago, there was
283 also a rapid increase in the number of voyages through the northern sea route (NSR), but the newest
284 numbers from the last year indicate a sharp decline (Grigoryev, 2016). Instead, the domestic cargo
285 turnover in the Russian area jumped 37% year on year to 5.3 million tons in 2015, supported by
286 accelerated work on the construction of the Yamal LNG plant and the nearby port of Sabetta.
287 Growing crude oil production from Gazprom Neft's onshore Novy Port and offshore Prirazlomnoye
288 oilfields in the Arctic also contributed to the 2015 traffic rise and is to play an increasing role in the
289 future (Grigoryev, 2016). This means that in the Russian waters, the cargo volumes will soon
290 surpass the historical highest value of the 7 million tons from 1987. On the Canadian side, there

291 have been mainly regular bulk shipping activities through ice, as well as occasional adventure
292 cruises, such as a recent transit through the Northwest Passage by *Crystal Serenity* in August 2016.

293 In the development of the Finnish-Swedish ice class rules for the Baltic Sea, damage statistics due
294 to the ship-ice interaction have played an important role. There are extensive data bases of detailed
295 damage cases starting from the early work of Johansson (1967) and continuing by Kujala (1991a)
296 and Hänninen (2004). They cover only ships navigating in the Baltic Sea, so this means only in first
297 ice with a maximum thickness of around 1.0 m.

298 Comprehensive statistics on accidents in the Arctic waters are presently not easy to find. However,
299 there have been several attempts to compile and analyze statistics on Arctic accidents. Each attempt
300 takes a slightly different approach than the other, making it more difficult to draw general
301 conclusions from them all. For instance, each study defines the Arctic geographic area in a slightly
302 different manner than the other. Some studies focus strictly on ship damage, while others include
303 personal injuries, and each takes a different approach to categorizing and explaining Arctic
304 accidents.

305 Kubat and Timco (2003) compiled and analyzed a database of ship damage in the Canadian Arctic
306 for the period between 1978 and 2002. They focused on Canadian waters north of 60°N latitude.
307 They analyzed 125 events that occurred during that time frame and concluded that the presence of
308 multi-year ice was a factor in 73% of the damaging events, with first-year ice being responsible for
309 the remaining damaging events. Also, the damage was more severe when multi-year ice was
310 present.

311 Marchenko's (2012) book on the Russian Arctic waters takes a different approach. She goes into
312 some detail regarding accidents in the Arctic seas bordering Russia. Her coverage spans accidents
313 since 1900 up until the early 1990s, when the volume of Arctic traffic in Russian waters dropped off
314 dramatically due to the collapse of the Soviet Union. However, most of the incidents described
315 (some in great detail) occurred before the 1980s, and while they are certainly informative, it is
316 unclear what lessons might be learned from some of these incidents given that many of them
317 predate the use of steel ships and diesel/electric/nuclear powered propulsion. Of the handful of the
318 more recent events described in this book, a common theme is the difficulty of dealing with ice and
319 the problems that navigation in ice presents – both with and without icebreaker assistance.

320 Kum and Sahin (2015) attempted to analyze accidents and incidents recorded by the Marine
321 Accident Investigation Branch (MAIB) that occurred north of 66° 33' between 1993 and 2011 using
322 root cause analysis techniques. Their study only examines 65 accidents, including 50 that were
323 characterized as 'Accident to person', meaning the other 15 were characterized as some form of
324 ship damage – making this a small dataset from which it is difficult to draw any conclusions
325 regarding potential damage to Arctic going ships, see Table 2.

326

327

328

329 *Table 2. Summary of accidents (Kum and Sahin, 2015)*

Contributor to accidents	# of Accidents	Percentage
Accident to person	50	76.9
Collisions and contacts	4	6.2
Grounding	4	6.2
Machinery failure	3	4.6
Flooding and foundering	2	3.1
Fires and explosions	2	3.1
Capsizing and listing	0	0.0
Total	65	100

330

331 Finally, as part of the Arctic Council’s Arctic Marine Shipping Assessment (AMSA) 2009 Report, a
332 database of a summary of the incidents and accidents occurring in the Arctic region between 1995-
333 2004 was developed from several other existing data sets. While this data set is one of the more
334 comprehensive available, it does not include any incidents that occurred in Russian waters. A lack
335 of recent data from Russia from any of the sources examined is regrettable. The AMSA covers
336 incidents in what is called the ‘circumpolar region’, which is not further defined – leaving a
337 question as to how loosely defined is AMSA’s definition of the Arctic geographic region. A
338 summary of results from AMSA can be found in Table 3 and Table 4, which break down the
339 accidents by vessel type and cause of damage, respectively.

340 While this summary is a good starting point, we believe that further analysis of the AMSA accident
341 database might provide some useful insight into the nature of Arctic accidents and how they might
342 be prevented. For instance, two prior studies cited the presence of ice as a major contributing factor
343 in Arctic accidents, but this is not a focus of the AMSA. AMSA does acknowledge that further
344 work is required and it cites the development of a consistent and accurate circumpolar database of
345 Arctic ship activity along with ship accidents and incidents to date as an area where further research
346 would be useful. Goerlandt et al. (2016b), have made a step in this direction by analyzing
347 wintertime accidents in the Northern Baltic based on AIS data together with ice and weather
348 information data from SMHI, aiming to provide qualitative insights in patterns and outlier cases in
349 the accidental conditions. It would probably be difficult to get the same level of detail for a similar
350 analysis for the Arctic, but it is a possible path for future research.

351 The challenge with all these damage databases for the Arctic waters is that they are not detailed
352 enough to evaluate the sequence of events causing the accidents, and therefore they cannot be easily
353 applied in the development of risk based design methodologies. In addition, the configuration of the
354 damage is typically not reported to the extent needed for proper analysis of, e.g., the load levels
355 required to cause the damage. This is an important gap as it means there is still considerable
356 uncertainty on the estimated maximum ice loads on the ship hull.

357

358

359

360 *Table 3. Accidents by vessel type (AMSA, 2009).*

Vessel Type	# of Accidents	Percentage
Bulk Carrier	37	12.6
Container Ship	8	2.7
Fishing Vessel	108	36.9
General Cargo Ship	72	24.6
Government Vessel	11	3.8
Oil/Gas Service & Supply	1	0.3
Passenger Ship	27	9.2
Pleasure Craft	0	0.0
Tanker Ship	12	4.1
Tug/Barge	15	5.1
Unknown	2	0.7
Total	293	100

361

362 *Table 4. Accidents by accident type (AMSA 2009)*

Primary Reason	# of Accidents	Percentage
Collision	22	7.5
Damage to Vessel	54	18.4
Fire/Explosion	25	8.5
Grounded	68	23.2
Machinery Damage/Failure	71	24.2
Sunk/Submerged	43	14.7
Miscellaneous	10	3.4
Total	293	100

363

364 4.2. Analysis of the most important elements in risk based ship design

365 The aim of this chapter is to critically review the state of art knowledge of the elements shown in
366 Figure 1, needed for evidence-based RBSD for Arctic shipping. Since the early work of Enkvist et
367 al. (1979), there has been a number of review papers of ship-ice interaction (e.g. Daley et al., 1990),
368 structural challenges (Kendrick et al., 2011) and Arctic regulations (Ghoneim, 2014). These and
369 some more recent research results are reviewed below, focusing mainly on the aspects related to the
370 risk based ship design for Arctic operations.

371 The evaluation of the failure probability of the ship hull is straight-forward once the long-term load
372 level is known. Typically, e.g. Gumbel 1 extreme value distribution can be fitted on the measured
373 ice load data to forecast the lifetime extreme loads on the ship. Then, by comparing these load
374 values with the ultimate strength of the frames using various ice classes to determine the scantlings,
375 the probability of reaching the planned limit state can be evaluated. This has been done e.g. by
376 Kujala (1991b) and Kaldasaun and Kujala (2011). As a result, a reliability index β is obtained by
377 defining a probability of failure for the shell structures of the ship. This approach is only possible
378 when full-scale long-term measurement data are available, and it is only valid for the specific ship
379 instrumented. The latest publications show how this approach can be used to validate the new Polar
380 Code risk based approach (Kujala et al., 2016) and how to determine the maximum safe ice
381 thickness for independent navigation and navigation with icebreaker assistance (Kujala et al., 2017)

382 The knowledge of the variation of the contact on the ship hull and its relation to the ice induced
383 loads in various ice conditions and operations is still too limited to form a good basis for risk based
384 design. Daley and Ferregut (1989) presented a model of structural risk for ice going ships, called
385 ASPEN (Arctic Shipping Probability Evaluation Network). The ASPEN model used a cell grid map
386 of the arctic, with ice statistics in each cell for each month. A user would specify a route in terms of
387 cells (and month). The model calculated the encounter-detection-avoidance-impact damage
388 probabilities using a set of probability algorithms. The program could evaluate the sensitivities of
389 aspects such as route selection, detection strategies, and structural capacity. Loughnane et al. (1995)
390 examined the risks for an Arctic oil tanker with a focus on oil spill risks and mitigation costs and
391 strategies. Buzuev and Fedyaikov (1997) examined the reliability and risk of shipping in ice along
392 the northern sea route (NSR) in Russia. The focus was more about transportation reliability than
393 structural risks, though both rely on similar models of ice conditions.

394 More recently, there have been studies related to the probabilistic analysis of the ship ramming
395 through an Arctic ice field (Ralph and Jordaan, 2013), analysis of the probability of a ship to get
396 stuck in ice (Montewka et al., 2015, Fu et al. 2016), and risk analysis of the winter navigation
397 system of Finland (Valdez et al., 2015, Goerlandt et al., 2016b).

398 4.2.1 Ice environment

399 The ice environment is difficult to define fully. When comparing the ice environment to open water,
400 in which typically only two parameters are needed, i.e., the wave height and period, it is far more
401 complex as ice can have various forms and typically at least the following parameters are needed to
402 describe it: level ice thickness, floe size, ice concentration, amount of rafted or ridged ice,
403 frequency and height of ridges, and amount of compression in the ice field. In addition, ice fields
404 are dynamic and changes in the ice cover characteristics can happen rapidly, e.g., due to winds and
405 currents. In addition, ice can be first, second or multiyear ice, which will have major impact on its
406 strength properties, as well as on its thickness. Sea ice thickness on various sea areas can be
407 estimated if the history of daily mean temperatures is known (see e.g. Kujala et al., 1994). In
408 addition, a lot of ice thickness data has been gathered for various areas, see e.g. Kendrik et al.
409 (2011).

410 With the rapidly developing satellite technology, remote sensing of ice cover is now possible for all
411 sea areas (see e.g. Kwok, 2010). Satellites are an efficient means to assess ice concentration and ice
412 movements, but still parameters like ice thickness cannot reliably be determined from this data. One
413 of the challenges is that the satellite resolution, as well as the scale of dynamic ice-ocean models, is
414 typically a few kilometres, even though the accuracy is constantly improving (see e.g. Bennetts et
415 al., 2013). However, the scale interesting for ice induced loads on ships is typically from 0.1 m to
416 100m, and the most important changes in the ice cover, such as floe break-ups, ridging and rafting,
417 take place as discrete events at this scale. The solid level ice thickness in various ice covers is the
418 most important parameter for evaluation of the possible ice induced loads. The most reliable
419 method to determine the solid ice thickness has been drilling a hole through the ice cover. Only
420 recently have some new approaches emerged. Lensu et al. (2015) summarise the various methods
421 that can be used to observe ice thickness onboard a vessel navigating in ice: visual observations,
422 electromagnetic (EM) sounding devices, and stereo camera systems. Visual observations have been

the traditional way to estimate ice thickness. EM is an efficient way to observe the total thickness of ice cover, although the solid ice thickness cannot be determined from this data. Stereo camera systems provide an approach to observe the solid ice thickness from the turning ice pieces (Suominen et al., 2013a). The comparison between these various methods indicate the visual observations give surprisingly accurate results, even though large variation can also occur, e.g., due to difficulties in separating the snow thickness from the actual ice thickness (Suominen et al., 2016). Recent advances in radar technology are enabling more informed tactical navigation through ice, which has potential for improved operations, including accident avoidance.

4.2.2 Ship-ice interaction

Ship-ice interaction has been under active research for at least the last 50 years. Russian scientists made the pioneering work as was summarised by Popov et al. (1967). A number of fundamental theoretical approaches were developed both to analyse the ship-ice contact and the possible highest loads occurring using the energy approach, i.e., assuming that the ship kinetic energy is spent in ice crushing and changes in the kinetic and potential energy of the vessel hitting the ice edge. There has been a lot research since to model the ship-ice contact as summarised e.g. by Enkvist et al., (1979), Daley et al., (1990), Jordaan (2001), and Kendrick et al., (2011). Typically, this research consists of laboratory measurements of ice failure, full-scale field tests of ice failure or full-scale measurements of ice induced pressure contact or local loads on board various ships. Still the knowledge of the variation of the contact on the ship hull and its relation to the ice induced loads in various ice conditions is limited. Three recent PhD theses give a good summary of the state of art in this field: 1) The variation of the structure-ice contact pressure based on laboratory measurement (Sopper, 2016) and 2) the variation of the local pressures on the ship hull based on full scale pressure measurements (Ralph, 2016) and uncertainty and variation in measured ice-induced loads on a ship hull (Suominen, 2018) All of these works indicated again how complicated the ship-ice contact process can be, and that reliable theoretical models to describe this process do not exist. Full-scale observations are still the best way to study these phenomena, but they are very expensive to conduct and the results are typically only valid for the studied ships and sea areas. Suominen et al. (2017a, 2017b) have systematically used the full scale data to analyse the statistics of ice induced loads with varying ship-ice interaction characteristics. A good summary of the available full-scale data is given e.g. by the ISSC (2015) committee report.

Because the icebreaking process is not well understood, a number of various approaches have also been developed to study the statistical nature of ice induced loads. Multiple studies have compared ice loads and ice pressures with the prevailing ice conditions using full scale data and varying statistical tools (see e.g. Glen and Blount 1984, St John et al. 1990, 1995, Kujala, 1994, Kotisalo and Kujala 1999, Frederking 2000; Hänninen et al. 2001; Leira et al. 2009; Matsuzawa et al. 2010; Kotilainen et al. 2017, 2018a, 2018b). Others have studied the maximum ice loads in time windows of certain length (e.g. Kujala et al. 2007), the highest local ice pressures (e.g. Jordaan et al. 1993) and the statistical distributions for the ice loads (e.g. Suominen and Kujala 2010; Suyuthi et al. 2012a, 2012b). Kotilainen et al. (2017) showed that if loads on one frame are studied as a function of ice and operational conditions (ship speed and ice thickness); a hierarchical Bayesian model can be used to predict the load distribution in different conditions.

464 A number of numerical models have also been developed during the last 40 years, using either
465 semi-empirical, discrete element, or finite-element approaches. The latest semi-empirical approach
466 is by Su et al. (2011). Ice breaking process is modelled and simulated using a semi-empirical
467 method to simulate crushing and breaking stages of breaking the level ice field. The contact is
468 assumed to be at the waterline, which is discretized into a closed polygon, and the edge of the ice is
469 discretized into a polyline in the simulation program. This approach is also used to study the
470 random nature of the contact along the ship hull causing high scatter on the ice load appearing on
471 the hull (Su et al. 2011). This approach seems to give a good estimate of the load levels on the hull,
472 but naturally due to the semi-empirical nature, the method relies on empirical results and it has been
473 shown in two recent master theses (Kuuliala 2015, Li 2016) that the approach is very sensitive to
474 the parameters used. Reliable modelling of the crushing and bending failures along the hull with
475 varying hull shapes needs further development.

476 The pure numerical models applying, e.g., finite elements approach have been shown to be still
477 unreliable, see e.g. Sazidy (2015), Lubbart and Loset (2001, 2015). Especially the failure process is
478 too complicated for the available material models so that the whole crushing and breaking process
479 cannot be numerically simulated and only limited validation with full-scale data is available.
480 Discrete element approaches are promising, but they are only useful so far for the relatively slowly
481 progressing ice failures such as ice ridging (see e.g. Paavilainen and Tuhkuri 2013, Polojärvi and
482 Tuhkuri 2013 and Ranta et al., 2015).

483 It can be summarised that the maximum pressure occurring locally when a ship hits massive, thick
484 ice can be reasonably well estimated (Ralph 2016, Ralph and Jordaan 2013), but still the relation of
485 the local pressures and local loads on ships with varying ice conditions are poorly understood (see
486 e.g. Suominen, 2013b, 2015a, 2015b). In addition, development of statistical models is important
487 as the pressure and load occurrence is strongly stochastic, but no good models exist to link the
488 stochastic properties to the prevailing ice conditions, even though there has been some progress in
489 that area (see e.g. Kotilainen et al., 2017, Kotilainen et al., 2018a, 2018 b).

490 4.2.3 Structural response

491 Kendrick et al. (2011) gives a good summary of the state of art related to the determination of the
492 structural limit states under ice loading. Basically, with current FE-modelling principles, limit states
493 such as first yield and ultimate strength due to extensive plasticity or local buckling are fairly
494 straight-forward to determine. The main research efforts today are devoted to applying the pressure
495 load on the FE-models. The practice for the design and analysis of ice-classed ship structures is to
496 assume stationary, uniform pressure loads. The credibility of this practice has been under
497 examination lately in several studies indicating that uniform and stationary loads might yield non-
498 conservative results compared with actual measured field data. Quinton et al. (2012) investigated
499 the effect of moving loads on ship structures and showed that moving loads may cause significantly
500 more structural damage than purely normal stationary loads. Furthermore, Erceg et al. (2014)
501 compared the response of a stiffened panel subjected to the rule-based pressure patch approach and
502 measured ice loads. Their findings suggest that the high degree of spatial and temporal variations
503 observed in ice load measurements, the so-called high pressure zones, can more easily lead to
504 permanent deformations in ship structures. Korgesaad et al. (2016) presented a 4D coupled pressure

method that allows imposing arbitrary time and location dependent pressure profiles on the structure. This is important considering the stochastic nature of ice induced loads. The approach is similar to the 4D pressure method developed by Quinton et al. (2012), but introduces the coupling whereby pressure values can depend on the nodal coordinates of a structure. This information sharing between the load and structure considerably enhances the possibilities of contactless loading methods, and thereby reduces the gap with simulations where ice failure is modelled explicitly as well. This has been applied to conduct systematic study of the effect of the used ice load characteristics on the response and especially on the failure of ice-strengthened structures (Korgesaad, 2018) showing how important it is to use realistic ice load patches to get reliable limit states for the structures.

Another important topic is how to determine the probability of cracks appearing on the structures with extensive deformation and e.g. what the effect of corrosion and fatigue on these might be, see e.g. (ISSC, 2015, Korgesaad 2018).

4.2.4 Environment consequence modelling

Consequence modelling is an indispensable part of risk assessment. The assessment of consequences of various Arctic shipping accident scenarios needs to cover the losses from asset damage to environmental and personnel impacts (Ehlers et al., 2014). Asset and personnel losses can be estimated given certain accident scenarios. However, there is a significant lack of knowledge of how accidental releases of contaminants might impact the Arctic environment (Afenyo et al., 2016a; Helle et al., 2011). In the near future, offshore operations in Arctic waters will be mostly related to oil and gas exploration and transportation (Borgerson, 2008). Therefore, future studies should focus on how to assess and model the environmental consequence of oil spills in Arctic waters. A standard ecological risk assessment framework can be adopted to quantify the potential environmental consequence (EPA, 1992). This framework consists of three main components: a) fate and transport modelling, b) exposure modelling, and c) dose-response modelling. Lack of oil spill and ecological background data is the main impediment in the implementation of this framework in the domain of oil spills in sea ice. A comprehensive oil spill database must be developed for a wide range of oil, ice types, and release scenarios. The information about species' distributions, level predator-prey dependencies, reproduction and migration patterns should be collected through potential sources, such as local residents in the Arctic and sub-Arctic regions. There are also significant uncertainties about each of the above three components of the framework.

The weathering and transport of oil in sea ice is different from that in open water. For example, the spreading and dissolution can be substantially reduced in cold and icy conditions. Afenyo et al. (2016a) have pointed out knowledge gaps in our understanding of the weathering and transport processes: there is no existing algorithm that is applicable to model these two processes. A few attempts have been made to develop a fate and transport model that is capable of predicting multi-media concentrations of the spilled contaminants in ice-infested waters (Afenyo et al., 2016b; Yang et al., 2015b). These studies have proved the usefulness of a fugacity-based approach in this area. They have also proposed that the existing open water algorithms may be tuned to make them

suitable for ice-infested water by using experimental data. Therefore, more experiments, such as the study by Gjølsteen and Løset (2004), need to be conducted to explore the feasibility of this approach. Encapsulation and release processes have never been considered. However, they have a potential to affect significantly the transport of pollutants in sea ice. The extent of drifting ice has increased because sea ice has become thinner due to the rapid rate of ice melt. This means pollutants could be transported faster and through longer distances from the source of release. Encapsulation and subsequent release takes oil from one location in the marine environment and could potentially release it back elsewhere. The mechanism of these processes need to be investigated to establish a predictive model that can be integrated with other process algorithms to form a comprehensive fate and transport model for oil spill in sea ice.

The exposure modelling for Arctic mammals, fish, and birds requires general biological knowledge, such as species distribution, migration patterns, and predator-prey dependencies. However, such information can be scarce or totally missing. Additionally, ice, making the Arctic environment different from temperate one, could affect the exposure period of toxic contaminants to ice dwelling organisms (Lee et al., 2011). For example, multi-year ice, which is less porous than first-year ice, would release water-soluble chemicals at a lower rate. This results in a longer exposure period. Future work is needed to adapt existing exposure models by incorporating ice as an important element.

Dose-response relationships help to translate the outcomes of fate and transport and exposure modelling into biological effects. There is lack of research on how to obtain the dose-response relationship for the species of concern in the Arctic. Other measurement endpoints, such as no observed effects level (NOEL), are also missing for the determination of the species sensitivity to the exposure of spilled oil. Nevalainen et al. (2016) have recently developed a quantitative risk assessment approach based on the Arctic food web on functional group levels. The use of functional group increases the amount of information available for impact assessment. The European Chemicals Legislation, Registration, Evaluation and Authorization of Chemicals (REACH) has recommended in-silico ecotoxicological methods (a combination of computation and experimental methods) to be utilized to generate missing toxicity data. The National Academy of Science has proposed a shift from whole organism toxicology to a pathway perturbation based paradigm for toxicity testing (Krewski et al., 2014). Toxicokinetic (TK) and toxicodynamic (TD) approaches could be better suited in the Arctic scenario than statistical methods such as quantitative structure-activity relationships (QSAR). TK approaches deal with the uptake, distribution, biotransformation and depuration of the chemical, while TD models link the exposed concentration to damage and survival in the organisms. TK models when combined with the TD models, can predict the toxic effects to the organisms (Heine et al., 2015). As they are mechanism-based models, they can be applied to a wide range of chemicals and also for extrapolation between different species and chemicals.

4.2.5 Human factors

Human factors have been getting a lot of attention lately at the IMO – the highest level of maritime regulation - as an important element of risk analysis. The new Polar Code is also putting a lot of emphasis on the training of the crew to mitigate risks of Arctic operations. It is well known that

588 human factors continue to be a leading contributor to accidents in all domains (Rothblum, 2000;
589 Shappell & Wiegmann, 2004). To understand this we must understand the role that humans play in
590 the entire operation.

591 Operators make adjustments to work to accommodate the dynamic and variable conditions that they
592 are presented with daily (Hollnagel, 2012). When considering the complex nature of shipping, with
593 its combination of complex technologies, organizational structures, regulatory regimes, economic
594 stakes, harsh environments and social pressures – foresight of the possible outcomes of the various
595 actions can be limited. Well-intended actions may have adverse outcomes due the complex
596 interdependencies. This makes it difficult to predict outcomes within traditional risk frameworks. It
597 is clear that the understanding of the human factor is in a transitional phase in terms of safety and
598 risk. This means that there will be high uncertainties associated with the human factor in many
599 industries, including for Arctic shipping. The recent state-of-the-art review for the society of risk
600 analysts states that for areas of high uncertainty, surprises and the unexpected, traditional
601 approaches to risk may not be appropriate (Aven et al., 2015).

602 How to include the human element in the design phase is a challenging topic, due to the very
603 limited data and models especially for Arctic conditions. It can be useful to adopt a few strategies
604 from human factors design. This is based on trying to eliminate so-called “bad fits” between
605 humans and technology from designs. Firstly, when considering the design of a technical element,
606 one should also consider the human, organizational or societal need that this technology is being
607 designed to fulfil. For example, when designing a hull shape for navigating ice-covered waters, the
608 technical need would be that the hull be capable of withstanding the design ice load cases. The
609 human/organizational needs that should be fulfilled by this technical improvement is that the
610 captain can navigate through ice more easily and the organization should see fuel savings (and
611 lower loads on structure). Because we have also considered the human need associated with this
612 design element, we would be more likely to consider how the operators (humans) would be able to
613 achieve this need. More formally, this approach can be incorporated into designs by using the
614 human-tech ladder (Vicente, 2004). This approach focuses on eliminating bad fits between humans
615 and technology. The first step of the ladder is to ensure there is affinity of the design with human
616 physiology. The second step is to assess the design’s affinity with human psychology. Similarly,
617 the remaining 3 steps of the ladder involve the assessment of the design’s affinity with humans at
618 the team level, organizational level and societal or political level, respectively. By paying attention
619 to these elements throughout the design process, more functional designs can be achieved. This can
620 then improve human performance, especially under time and production pressures.

621 5 Discussion

622 Risk based design for Arctic operations requires knowledge of a number of parameters, which
623 include a number of challenges. Using the approach defined by Table 1 and the characteristics of
624 the data (quality and amount) and models (empirical validation and theoretical viability), a strength
625 of evidence rating for the various factors described in section 4 is presented in Table 5.

Accident statistics are important, e.g., for the specification of the extreme events that can take place when navigating in Arctic waters. The quality and quantity of the accident statistics data are low as described in section 4.1. The main reason for this is that the databases do not specify enough detail about the causes and consequences of the accidents. The situation can be only slowly improved as accidental events in ice covered waters are rare. Similarly, there is a lack of suitable accident models, but this can be improved by constructing theoretical models of the possible sequence of events that cause accidents. They can, however, only be validated through expert opinions as not much empirical data exists.

The knowledge of the ice environment is described in section 4.2.1 and the characteristics of the ice cover are well specified with a number of high quality data and good theoretical models. The main research needs on this topic are related to the gathering of more detailed data of the existence and characteristics of ice ridges, ice floe sizes, ice concentration and ice movements for various sea areas.

Table 5. Evidential characteristics of the reviewed factors affecting risk based design for Arctic operations

	Data	Justification		Models	Justification	
		Quality	Amount		Emperical validation	Theoretical viability
Accident statistics	L	Typically the accident scenario and detail consequences are not known	There is a fair amount of data but it is not detailed enough to draw reliable conclusions of the sequence of events	L	The accident models for Arctic operations are rare	No theoretical viability analysed
Ice environment	M-H	The challenge for the quality is that the level ice thickness can not be accurately measured by satellites	The amount of data is satisfactory	M	A number of empirical validations have been conducted for definition of the ice environment	The modelling of ice environment have seen a number of good theoretical viability analysis
Ship-ice interaction	H	The quality of the ship-ice interaction data has big scatter but there is enough good quality data	A fair amount of data based on the laboratory and full scale observations exist	L-M	Still, only in few cases the ship-ice interaction models have been validated with the most important empirical evidence: full scale	High amount of theoretical, especially numerical models have been established to study the viability
Structural response	H	A number of high quality data of structural response exists	A large data base of structural response exists	M-H	There is a number of empirical validation, the challenge is that it is mainly	Theoretical viability is well studied, only the crack initiation and propagation is

					done in laboratory scale	not known in detailed enough
Effect on environment	L	The quality of the data related to the ecological effects is poor	The amount of the data related to the ecological effects is poor	L	Not much empirical validation exist	Not much theoretical viability studies exist
Human factor	L	The human factors have not been studied in Arctic environment	No data available	L-M	In general good human factor models with empirical evidence available even though not applied for the Arctic environment	No studies for theoretical viability in the Arctic environment exists

641

642 The main challenges are related to the ship-ice interaction, even though a number of full-scale and
643 laboratory scale data sets exist as summarised in section 4.2.2. No reliable theoretical models have
644 been published which can be used to evaluate the contact characteristics between ship and ice, as
645 well as to evaluate the load level on various ice conditions. The clear stochastic nature of the ice-
646 induced loads needs further research in varying ice conditions. Most reliable models are developed
647 for the cases when ships are ramming heavy ice, but for other conditions the models need
648 improvements. These other conditions can include: ice concentration is less than 100%, ice floe
649 sizes vary and ice cover appearance changes dynamically due to the moving ice. A good design
650 basis can be that the possible extreme events are evaluated first and the load level on these
651 occasions are evaluated and compared with the available full-scale data.

652 The best situation is with the structural response analysis because limit states such as first yield and
653 ultimate strength due to the extensive plasticity or local buckling are fairly straight-forward to
654 determine with current FE-modelling principles as described in section 4.2.3. The main research
655 efforts today are devoted to how to apply the pressure load on the FE-models, but here the level of
656 knowledge both for the data and models can be considered to be high.

657 Effects on the environment of the possible accidents in the Arctic are still poorly understood, so the
658 level of knowledge concerning both the data and models is low, see section 4.2.4. There is a high
659 need to conduct more research related to the oil in ice and the environmental consequences of
660 possible accidental events.

661 Human factors play an important role in managing risks, especially at the operational level as
662 illustrated in section 4.2.5. The techniques that have traditionally been used in risk-based design
663 have treated the human factor as a source of error. If we redefine the role humans play in risk-based
664 assessments, the human factor can be a source of resilience, thus helping to manage risks.
665 Currently, the knowledge base for managing the human factor is low, especially for designers in the
666 Arctic shipping domain. There are methods that can be used to increase what we know by
667 incorporating systemic approaches, and promoting designers and operators to share information and
668 to unify their approaches to shipping. Three methods that can help designers increase their
669 knowledge and achieve more functional designs are the Human-tech approach, the Functional

670 Resonance Analysis Method (FRAM) and the Systems-Theoretic Accident Model and Processes
671 (STAMP) (Hollnagel, 2012; Leveson, 2004; Vicente, 2004).

672 Finally, the proper safety level is touched upon. Section 4 shows that it is fairly straight-forward to
673 design the shell structures using either ultimate or accidental limit states with the proper probability
674 level of their occurrence. The main challenge here is how the long term ice loads are evaluated with
675 the proper probability level of occurrence. The broader challenge is how to conduct proper risk
676 analysis and risk assessment including all the possible scenarios that can cause accidents and harm
677 to the people and environment. The main issue here is how to use the RBSD framework, i.e., how
678 the risk analysis links with risk assessment and risk management. On open water, the use of
679 ALARP and individual risk criteria are well established including mainly "costs to avert a fatality"
680 as the main criteria. There is a need to study what is a good risk-cost effectiveness criterion for
681 Arctic operations. This paper aimed to summarise the main elements needed for proper RBSD and
682 the authors are convinced that all the elements discussed in this paper are needed to base the future
683 ship design on specified safety or risk level targets. This is the way forward to obtain the best cost
684 benefits for the future ships and maritime products used on these waters.

685 6 Conclusions

686 In this paper, the minimum requirements to apply risk based ship design for Arctic operations is
687 discussed covering the most important topics such as behaviour of sea cover, ship-ice interaction
688 and structural response together with the effect of possible accidents on the environment. In risk
689 analysis, there is a recent focus on the treatment of uncertainty, or conversely, the strength of
690 knowledge underlying the risk quantification. As a step towards improving current practices for risk
691 based design, the review is performed with specific focus on the strength of evidence of the
692 different fields of knowledge needed to perform RBSD in ice conditions.

693 The results indicate that the risk based design for Arctic operations is challenging as the ice
694 environment together with all the possible ship-ice contact scenarios are complicated to define
695 properly. Accident data is very limited, making it difficult to determine the extreme events for these
696 operations. Ice coverage is well defined overall, but still more data on a number of details are
697 needed, such as ice concentration, floe sizes, and the appearance of dynamic ice fields. The main
698 challenges are related how to describe the ship-ice interaction parameters such as ship-ice contact
699 characteristics, pressure distributions and load levels in the varying ice conditions, which all have
700 clear stochastic nature. The best situation is with the structural response analysis as with current
701 FE-modelling principles limit states such as first yield and ultimate strength due to the extensive
702 plasticity or local buckling are straightforward to determine. The potential effects of accidents on
703 the environment are not studied in required detail, even though these consequences have a major
704 role in the assessment of the proper risk level to be used for design. Human factors are important
705 and a good approach is to consider the human needs early in the design. If the human element is
706 considered at the end of the design, then it may be too late to make appropriate changes and the
707 humans will be forced to adapt to the design rather than the design adapting to the humans.

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