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A simulation-based design method for arctic maritime transport systems

Martin Bergström

A simulation-based design method for arctic maritime transport systems

Thesis for the degree of Philosophiae Doctor

Trondheim, March 2017

Norwegian University of Science and Technology Faculty of Engineering Department of Marine Technology



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Abstract

This thesis proposes a method for the conceptual design of arctic maritime transport solutions integrating the goal/risk-based regulatory system of the recently enforced International Code for Ships Operating in Polar Waters (Polar Code) into a holistic design process considering operational and regulatory requirements, cost-efficiency, and design robustness. To enable full utilization of the goal/risk-based regulations of the Polar Code, the proposed method makes use of system thinking and discrete event simulation (DES) based Monte Carlo simulations. As demonstrated through a set of case studies, system thinking enables a holistic design process by making it possible to treat an arctic ship as a part of a wider arctic maritime transport system (AMTS) including for instance icebreakers, and facilitates the design process by making it possible to divide an AMTS into a set of subsystems that can be designed separately. DESbased Monte Carlo simulations, in turn, makes it possible to assess the operational performance of an AMTS considering a multitude of stochastic factors and various interaction and selfreinforcing effects, and to determine operational data relevant both for the design of various ship systems, and for the assessment of the cost-efficiency and robustness of competing AMTS designs. To enable a time and resource efficient design process, the study analyses the level of model fidelity that is required to capture relevant behaviours of an AMTS. Also, sensitivity analyses are carried out to gain understanding of potential design uncertainties and how they can be mitigated. The method is limited to parametric design, i.e., to the determination of a set of design variables representing criteria to be considered for instance in the design of the hull shape, hull structure, and propulsion system.

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Nomenclature

Abbreviations

AC	Canadian Arctic Class
AIRSS	Arctic ice regime shipping system
ALARP	As low as reasonably practicable
AMTS	Arctic maritime transport system
ASPPR	Arctic shipping pollution prevention regulations
BHP	Break horsepower
CAC	Canadian Arctic Category
CONOPS	Concepts of operations
CSR	Common structural rules for oil tankers and bulk carriers
DES	Discrete-event simulation
ENVP	Environmental protection
FPS	Fuel price scenario
FR	Functional requirements
FSA	Formal safety assessment
FSIC	Finnish-Swedish ice class
FYI	First-year ice
GBD	Goal-based design
IACS	International association of classification societies
IB	Icebreaker
ICAP	Implied cost of averting a fatality
IMO	International maritime organization
IS	Ice condition
LNG	Liquefied natural gas
MARPOL	International convention for the prevention of pollution from ships
MDO	Marine diesel oil
MYI	Multi-year ice
NSR	Northern sea route
OPS	Operations
PBD	Prescriptive-based design
PC	Polar Class
Polar Code	International code for ships operating in polar waters
PSC	Port state control
RBD	Risk-based design
RO	Recognized organization
RS	Russian maritime register of shipping
RQ	Research question
SAR	Search and rescue
SOLAS	International convention for the safety of the life at sea
STCW	International convention on standards of training, certification and
	watchkeeping for seafarers
SYI	Second-year ice
UI	Unified interpretations of international conventions and codes
UN	United Nations
UNCLOS	United Nations convention on the laws of the seas
UR	Unified requirements
USD	United States Dollar

Symbols

Ice ridge slope angle
Average ice ridge slope angle
Mean value
Ice ridge density
Variance
Impact area
Ice condition specific coefficient
The consequences of a risk event
Ice coverage
Ice condition specific coefficient
Ice condition specific impact frequency
Equivalent ice thickness
Ice ridge keel draft
Average ice ridge keel draft
Ice ridge sail height
The likelihood of a risk event
Minimum required performance
Performance of a design
Maximum acceptable risk
Risk associated with a design
Level ice thickness
Average annual distance travelled in ice
100-year extreme ice load

1. Introduction

Driven by climate change, an increased extraction of natural resources in the Arctic, and technological advances, the demand for arctic shipping is expected to increase in the years ahead. The motivation for this research stems from the resulting interest in new and improved methods for the design of arctic maritime transport solutions.

1.1. Research objectives

On January 1, 2017, the IMO enforced a new regulatory framework referred to as the Polar Code, aiming to ensure safe and sustainable arctic maritime operations. To this end, the Polar Code introduces a goal/risk-based regulatory system that, instead of determining traditional design rules prescribing a specific solution, determines design requirements in terms of functional requirements (FRs) prescribing a specific function. This gives designers increased freedom to find and apply new and innovative solutions, but consequently also more responsibility.

The hypothesis of the study is that the goal/risk-based regulations of the Polar Code could be integrated into a holistic goal/risk-based design method supporting the design of cost-efficient, safe, and environmentally friendly arctic ships¹. The objective of this work is to examine this hypothesis by developing a conceptual design method for arctic ships meeting the following criteria:

- Be compatible with the Polar Code, and enable full utilization of its goal/risk-based regulatory system.
- Enable a holistic design process considering operational and regulatory requirements, cost-efficiency, and robustness.
- Be time- and resource-efficient, while still being sufficiently accurate.

1.2. Research problems

The application of the goal/risk-based regulations of the Polar Code requires appropriate and relevant performance assessment tools, data, as well as agreed-on performance acceptance criteria. Thus, towards the objectives of the work, the status of these prerequisites must be clarified. This requires the identification of promising performance assessment tools, as well as of potential knowledge, data, and regulatory gaps limiting the applicability of the regulations.

To enable a holistic design process, it is necessary to determine an appropriate design framework that can consider both operational and regulatory requirements, and compare the cost-efficiency and robustness of competing design alternatives (e.g. an independently operating ship vs. an IB assisted ship). To this end, the framework must be able to consider a multitude of stochastic and uncertain factors (such as the ice conditions, fuel price, and icebreaker tariffs) as well as various interaction and self-reinforcing effects (e.g. effects of other ships on for waiting time for port berths, effect of ice conditions on IB waiting times). In addition, the framework must be able to consider possible effects of cargo storages or stocks, which in the case of industrial shipping, by providing a buffer against temporary shortage in transport capacity, could have a significant effect on the required payload capacity and speed of a ship.

¹ The term "arctic ship" is here defined as a ship designed for arctic-specific challenges (e.g. sea ice) and is thus not limited to ships designed for operation in the Arctic (geographic area).

The above listed challenges could potentially be managed by incorporating simulations and probabilistic methods such as the Monte Carlo method into the design process, and by extending the design boundaries beyond the individual ship, treating it as a part of a wider arctic maritime transport system (AMTS) that might include one or multiple arctic ships, IBs, as well as port-based resources. However, such measures are expected to be time and resource intensive, which is especially problematic in the conceptual design phase. Thus, their justification depends on whether they provide valuable new insights enabling better informed design decisions.

To keep the method as time- and resource-efficient as possible, it is necessary to find an appropriate level of model fidelity. An overly detailed and complex design model might not only result in a waste of design resources (e.g. time and money), but also in the risk of focusing on details of minor importance, rather than on those that matter. On the other hand, an overly simplified model might fail to capture relevant phenomena and behaviours of the system, and thereby fail to provide an adequate estimation of its performance.

Once developed, the design method is expected to be subject to design uncertainties due to various knowledge and data gaps. To manage those uncertainties, it is necessary to identify the most important sources of uncertainty, and to assess how those uncertainties might affect the outcome of the design process. Also, it is necessary to gain understanding of how various uncertainties can be mitigated.

1.3. Research questions

Based on the above outlined research problem, four research question (RQ) are formulated as follows:

RQ 1: To what degree are the goal/risk-based regulations of the Polar Code applicable on arctic ships considering the state-of-the-art of the required performance assessments tools, data, and regulations?

RQ 2: In the conceptual design of an arctic ship, is it justified to treat the ship as a part of an AMTS and to integrate Monte Carlo simulations into the design process, i.e., does it provide valuable new insights enabling better informed design decisions?

RQ 3: What level of model fidelity is appropriate for the conceptual design of arctic ships?

RQ 4: What are most significant design uncertainties in the conceptual design of arctic ships and how can they be mitigated?

1.4. Research scope and limitations

The work is limited to the development of a conceptual design method for arctic cargo ships. In accordance with Fig. 1, the work can be divided into two blocks: (1) the development of design procedures, and (2) the execution of case studies. The development of design procedures includes the determination of relevant terminology and concepts, the selection of appropriate performance assessment tools, the determination of appropriate system boundaries, and the determination of an appropriate level of model fidelity. These elements are carried out based on insights obtained from the case studies. Input for the design method include regulations, performance assessment tools, and data. All input is obtained from publically available sources. The study does not aim to modify, or to replace, any of the applied input.



Figure 1: Scope of work.

The design method is limited to parametric design, i.e., for the determination of performance criteria or characteristics that are to be considered in later design stages, for instance for the design of the hull shape, hull structure, and machinery. The method does not aim to enable a direct assessment of environmental, safety, or safety risks. However, it aims to produce data relevant for the assessment of such risks.

2. Background

2.1. Arctic shipping in general

The history of modern arctic shipping², i.e. shipping in ice infested waters, goes back to at least 1864 when the first Russian icebreaker (IB), the Pilot, was commissioned to extend the navigation season on the Gulf of Finland (GlobalSecurity.org, 2011). Over the years, the importance of arctic shipping has grown significantly, and nowadays it takes place on multiple sea areas including the northern parts of the Baltic Sea, along the northern coast of Russia, along the northeast cost of Canada, as well as on various lakes (e.g. the Great Lakes of North America, the Caspian Sea) and rivers (e.g. the Saint Lawrence river).

Based on the route, it is possible to define three categories of arctic shipping: (1) destination-arctic shipping consisting of shipping between arctic and non-arctic locations³, (2) intra-arctic shipping consisting of shipping between arctic locations, and (3) trans-arctic shipping consisting of shipping between non-arctic locations through arctic waters (Gunnarsson, 2013). Destination- and trans-arctic shipping, motivated by the need to serve ice-bound ports, are vital for many areas and communities. For instance, in winter all Finnish ports tend to be ice bound, making the nation's export and import dependent on efficient arctic shipping. The same applies for multiple communities along the northern cost of Russia, the northern costs of Canada, as well in the areas around the Great Lakes of North America. Trans-arctic shipping, on the other hand, is carried out to achieve a shorter transport distance and consist primarily of shipping along the Northern Sea Route (NSR) between Europe and East Asia.

The total volume of arctic shipping is best described in terms of the size of the global fleet of arctic ships and IBs. According to (LR, 2014), the total worldwide number of ships (500 GRT or greater) with some level of ice-strengthening is around 8,600, representing 15 % of the world fleet. However, according to the same source, only about 500 of these ship, or less than 1 % of the world fleet, are suited for operation in at least thin (≤ 0.7 m) first-year ice (FYI) conditions. According to (USCG, 2013), the total worldwide number of major IBs ($\geq 10,000$ BHP) is around 80, and the most significant icebreaker nations in terms of the number of active IBs are Russia (37), Sweden (7), Finland (7), Canada (6), and the USA (5).

The volume of arctic shipping is expected to grow in the years ahead. Growth is expected primarily from destination-arctic shipping, driven by the anticipated increase in the extraction of natural resources, such as oil and gas, in the Arctic (Østreng, et al., 2013). A significant growth could also come from an increase in trans-arctic shipping. For instance, (Bekkers, et al., 2015) estimates that, because of global warming and further technological improvements, up to two thirds of the traffic that currently goes through the Suez Canal, equalling approx. 7 % of the world trade, or 12,000 ships per year, will be re-routed to the NSR. However, other studies such as (Farré, et al., 2014) predicts that, due to unpredictability in terms of transit times, shallow fairways limiting the maximum feasible ship size, as well as due to an ever-increasing cost-efficiency of conventional shipping through the Suez Canal, the traffic along the NSR is likely to remain at its current volume of some tens of transits per annum. Naturally, politics also plays a role in the future development of arctic shipping. For instance, the development of destination-arctic shipping is dependent on permissions to extract oil and gas in the sensitive arctic environment (FNI and DNV, 2012). Likewise, the development of trans-arctic shipping depends on the development and maintenance of necessary services such as

² The term "arctic shipping" is here defined as shipping in ice infested waters and is thus not limited to shipping within the Arctic (geographic area).

³ The term "arctic location" is here defined as a location where arctic conditions (e.g. very low temperatures) occur and is thus not limited to locations within the Arctic (geographic area).

search and rescue (SAR), the development of rules and regulations, and the determination of transfer/IB tariffs (Staalesen, 2015).

Based on their ice-going capabilities, arctic cargo ships can be divided into two main groups: (1) icegoing ships, and (2) ice-strengthened ships (Riska, 2010). Icebreaking ships have an icebreaking bow that enables them to break ice independently, but significantly reduce their open water efficiency. Ice-strengthened ships, on the other hand, are generally fitted with a bulbous bow that makes them efficient in open water, but severely limits their icebreaking capability (Riska, 2010). Thus, icestrengthened ships are generally limited to operations in brash ice channels prepared by an IB. An IB is a ship that is specially built to assist other ships operating in ice. This means that IBs do not only need a sufficient icebreaking capability, but also a high level of manoeuvrability in ice, and the ability to engage in aggressive icebreaking operations involving frequent ice ramming (Riska, 2010).

2.2. Regulations concerning arctic ships

To ensure safe and efficient operations, arctic ships need to be specially designed and built to deal with a variety of arctic-specific challenges including ice loads, ice resistance, freezing temperatures, and difficult weather conditions. Towards this end, arctic ships are subject to a comprehensive regulatory system, the most important aspects of which are presented in the following.

2.2.1. Regulatory parties

The design and operation of ships is regulated by a mixture of international, national, and class specific rules and regulations, an overview of which is presented in Fig. 2. The main bodies of the regulatory framework are the United Nations Convention on the Laws of the Seas (UNCLOS), the International Maritime Organization (IMO), individual maritime states, recognized organizations (ROs), and the International Association of Classification Societies (IACS) (IACS, 2011).

UNCLOS defines the rights and responsibilities of nations in their use of the world's oceans, establishing guidelines for businesses, the environment, and the management of marine natural resources (UN, 1982). According to (IMO, 2012), UNCLOS can be described as a framework convention as many of its provisions can be implemented only through specific operative regulations in other international agreements. This is reflected in several provisions of UNCLOS requiring states to "conform to", or "to implement", relevant international rules and standards developed by the IMO (IMO, 2012).

The IMO is a United Nations (UN) agency responsible for the management of safety and environmental risks of ships (IMO, 2016a). "Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and universally implemented" (IMO, 2016a). The existing framework regulates all aspects of international shipping including ship design, construction, equipment, manning, operation and disposal (IMO, 2016a). To achieve its objectives, the IMO promotes the adoption of international conventions and guidelines. The most important IMO conventions include the International Convention for the Safety of the Life at Sea (SOLAS), the International Convention of Pollution from Ships (MARPOL), and the International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW) (IMO, 2016b).

The enforcement of mandatory requirements of the IMO conventions depends upon the individual IMO member states, acting both as flag and port states. A flag state has the authority and responsibility to enforce regulations over ships registered under its flag. Since all ships must meet international requirements set by the IMO, flag states need to integrate their own statutory

requirements with the requirements set by IMO. "When a Government accepts an IMO Convention, it agrees to make it a part of its own national law and to enforce it just like any other law" (IMO, 2016c). Any IMO member has the authority to carry out so-called port state controls to ensure that the condition and equipment of ships visiting their ports comply with IMO standards (IMO, 2016d). In addition, an individual state can enforce its own rules on all ships operating on its territorial water, or within its exclusive economic zone (UN, 1982). For instance, because the NSR area is part of the exclusive economic zone of Russia, the country has the right to enforce its regulations on ships operating there (Østreng, et al., 2013).



Figure 2: Legislative framework of arctic ships.

Flag and port states can delegate statutory tasks such as the inspection and survey of ships, as well as the issuing of certificates to a RO. A RO is a classification society authorized by a flag state to carry out statutory tasks on its behalf. The extent of authorization differs from state to state. Some flag states delegate nearly all their duties to ROs, while others only delegate individual specific duties (BMWI, 2016).

A flag state can freely select its ROs providing they meet certain minimum standards, for instance regarding technical competence, set by the IMO (IMO, 2013). However, generally a ROs is one of the (currently) 12 member societies of the IACS. For instance, the Norwegian maritime authority recognizes the following societies: American Bureau of Shipping (ABS), Bureau Veritas (BV), DNV GL, Lloyds Register of Shipping (LR), RINA, and Nippon Kaiji Kyokai (ClassNK) (Sjøfartsdirektoratet, 2012).

In collaboration with its members, the IACS determines unified requirements that are to be integrated into the class requirements of each RO. Its main output includes the Unified Requirements (URs), the Common Structural Rules (CSR) for Oil Tankers and Bulk Carriers, as well as the Unified Interpretations (UIs) of international conventions and codes.

The development of regulations within the IMO might be influenced by external bodies such as the Arctic Council. The Arctic Council is an intergovernmental forum with eight member counties: Canada, Denmark, Finland, Iceland, Norway, Russian Federation, Sweden, and the USA (Arctic Council, 2016). Its objective is to promote cooperation towards a sustainable development and environmental protection in the Arctic (Arctic Council, 2016). Towards this end, the council might influence the decision-making within the IMO through its member working within the organisation.

2.2.2. Ice classes

In addition to rules and regulations for non-arctic ships (e.g. SOLAS and MARPOL), arctic ships are generally obliged to meet some ice class standard aiming to mitigate ice navigation specific risks. Currently there are several different sets of ice class standards locally enforced by classification societies and national maritime administrations. Thus, the specific rules and requirements that an arctic ship must follow depends on its route and the ports that its serves.

Existing ice class rules can be divided into two main regimes: (1) the Finnish-Swedish Ice Class (FSIC) rules for ships operating in light first-year ice (FYI) conditions, (2) and the IACS Polar Class rules for ships operating in more difficult ice conditions. The FSIC rules, which are determined by the maritime administrations of Finland and Sweden, specify in total five ice classes (Sjöfartsverket, 2016):

- IA Super, allowing operations in very difficult (> 1.0 m) FYI conditions.
- IA, allowing operation in difficult (0.5-1.0 m) FYI conditions.
- IB, allowing operation in moderate (0.3-0.5 m) FYI conditions.
- IC, allowing operation in light (0.15-0.3 m) FYI conditions
- II, allowing operation in very light (0.1-0.15 m) FYI conditions.

The rules are enforced in terms of port-specific traffic restrictions determining the minimum required ice class (and deadweight) for IB support with the aim to manage the risk of material damage due to ice loading, and to ensure safe and efficient shipping. The use of the FSIC rules is widespread because, in addition to being applied by the maritime administrations of Finland and Sweden, many classification societies have incorporated them into their own rules, which in turn are used by the maritime administrations of other nations, such as Estonia, to assign traffic restrictions (EMA, 2010).

To harmonize the various ice class standards, the IACS has determined a set of unified requirements for arctic ships, specifying in total seven ice classes referred to as Polar Class (PC) 1-7) (IACS, 2016a):

- PC 1, allowing year-round operation in all polar waters.
- PC 2, allowing year-round operation in moderate multi-year ice (MYI) conditions.
- PC 3, allowing year-round operation in second-year ice (SYI) that may include multiyear ice inclusions.
- PC 4, allowing year-round operation in thick (> 1.2 m) FYI that may include old ice inclusions.
- PC 5, allowing year-round operation in medium (0.7-1.2 m) FYI that may include old ice inclusions.

- PC 6, allowing summer/autumn operation in medium (0.7-1.2 m) FYI which may include old ice inclusions.
- PC 7, allowing summer/autumn operation in thin (0.3-0.7 m) FYI that may include old ice inclusions

The objective of the PC rules is to manage the risk of structural damage due to ice loading. Specifically, it can be assumed that the objective of the rules is to achieve an acceptable damage frequency, i.e., a specific minimum accepted return period of ice loads corresponding to the plastic limit load of a ship's hull structure. However, the minimum accepted return period has not been documented. Anyhow, it has been stated that the target return period is one year (Su, 2011). The PC rules co-exist with various nation and class specific ice class rules (e.g. the ice class rules of Russia and Canada). As described in the following, they are either enforced directly, or indirectly by equivalency.

Rules and regulations for ships operating along the NSR, and or serving Russian ports, are outlined in the Rules of Navigation on the Water Areas of the Northern Sea Route presented by (Mintrans, 2013). This document determines ice class criteria referring to the rules of the Russian Register of Shipping (RS) specifying in total 13 ice classes (RS, 2015):

- Ice1, Ice 2, and Ice 3, intended for navigation in freezing waters outside the Arctic.
- Arc4, Arc5, Arc6, Arc7, Arc8, and Arc9, intended for navigation in waters with the Arctic.
- Icebreaker6, Icebreaker7, Icebreaker8 and Icebreaker9, intended for ships acting as icebreakers.

The minimum required ice class is determined separately for various zones of the NSR based on the season and the prevailing ice conditions. A ship without a RS ice class is acceptable if it meets an ice class standard (e.g. an PC standard) that the Russian authorities consider at least equivalent to the minimum required RS ice class (RS, 2015).

In Canadian waters, ice class requirements are determined by the Arctic Shipping Pollution Prevention Regulations (ASPPR). The ASPPR divides Canadian waters into 16 so-called safety control zones, for each of which it determines fixed ice class-specific opening and closing dates (CCG, 2012). In individual cases, the determined opening and closing dates can be overruled by applying the Arctic Ice Regime Shipping System (AIRSS) determining ice class requirements based on the actual ice conditions (CCG, 2012). The ASPPR refers to multiple ice class standards including IACS Polar Class, Canadian Arctic Class (AC), Canadian Arctic Category (CAC) ship, as well as the Canadian ice classes for ice-strengthened ships Type A, Type B, Type C, and Type D that are all based on the FSIC rules (Transport Canada, 2009). However, Canadian authorities currently recommend that ships should be built in accordance with the international PC standards.

A general weakness of all the existing ice class rules is that they do not consider a ship's actual ice exposure, but determine ice class criteria simply based on the maximum ice conditions that a ship is expected to encounter. Thus, a ship that operates briefly in some specific ice conditions is assumed to require the same level of ice-strengthening as a ship that operates extensively in the same ice conditions. In addition, most of the ice class rules are semi-empirically determined and might therefore not be efficient when applied on ships and operations that differ from those based on which they were determined (Kim & Amdahl, 2015). Specifically, because the PC rules are semi-empirically determined based on data from relatively small ships, there is a significant level of uncertainty in terms of their applicability on larger ships (LR, 2014). It is assumed that this uncertainty is compensated for by design conservatism, resulting in unjustified investment and operating costs (LR, 2014).

2.2.3. The Polar Code

From January 1st, 2017, the International Code for Ships Operating in Polar Waters (Polar Code), is enforced on all ships operating in the Arctic or Antarctica as defined by the Polar Code. The Polar Code, which is presented by (IMO, 2015), is the first international regulatory framework specifically aimed at mitigating arctic shipping related risks that were previously mitigated solely by individual maritime administrations and ROs issuing ice class criteria. The specific objective of the Polar Code is to ensure the same level of safety for ships, persons and the environment in polar waters as in other waters (Kvålsvold, 2012). Towards this end, it supplements the SOLAS and MARPOL conventions to account for arctic specific safety hazards such as sea ice, icing, low temperatures, darkness, high latitude, remoteness, the lack of relevant crew experience, and difficult weather conditions. Safety and environmental risks related to these hazards are addressed in terms of regulations concerning the design, construction, equipment, operations, training, and pollution prevention. The Polar Code regulates thereby both active and passive risk prevention and mitigation measures, whereas ice class rules mainly concern construction and equipment, i.e., passive measures only.

A ship approved in accordance with the Polar Code will be issued a Polar Ship Certificate that classifies the ship as one of the following:

- Category A, for ships allowed to operate in at least medium thick first-year ice.
- Category B, for ships allowed to operate in at least thin first-year ice.
- Category C, for ships allowed to operate in ice conditions less severe than those included in Category A-B.

In addition to the ship category, the ice certificate determines detailed operational limits concerning for instance the minimum temperature and the worst ice conditions in which a ship can operate.

The Polar Code determines mandatory provisions in terms of goals, functional requirements FR(s), and regulations to meet the FR(s). The regulations are generally prescriptive, meaning that they prescribe the required means to achieve the FR, i.e., they prescribe a specific solution that is considered acceptable. However, the objective of the Polar Code is not to enforce a specific solution, but to ensure that the applied solution meets the FRs. Thus, in accordance with Fig. 3, a ship can be approved either as a prescriptive design, or as an equivalent design. A prescriptive design is a design that meet all the prescriptive regulations associated with the FR(s), whereas an equivalent design is a design that is approved in accordance with Regulation 4 of SOLAS Chapter XIV. This regulation, which is presented in (IMO, 2014), states that any solution may deviate from the prescriptive requirements determined by the Polar Code, if the alternative design meet the intent of the goal and functional requirements concerned and provide an equivalent level of safety as the prescriptive design. To prove equivalency, a design must to be analysed, evaluated, and approved in accordance with IMO guidelines.

Many of the prescriptive regulations of the Polar Code include references to the PC standards. For instance, for a Category A ship to meet FRs regarding structural strength, the scantlings of the ship must be determined in accordance with PC 1-5, whereas the scantlings of a Category B ship must be determined in accordance with PC 6-7. Alternative, the scantlings must be determined in accordance with a standard offering an equivalent level of safety in accordance with the above described principle of design equivalency.

Because the upcoming Polar Code is mandatory, all IMO member states, and consequently also all ROs, must integrate it into their own rules and regulations. This will contribute to a harmonization of the existing ice class rules. However, individual flag and port states will be free to add their own local requirements if they are not contradictory with the Polar Code. It should be noted that the Polar Code

is limited to ships operating in polar waters as defined by the IMO. Thus, it does not concern ships operating in other ice-infested waters, such as the Baltic Sea and the Great Lakes of North America.



Figure 3: Approval principle of the Polar Code.

2.2.4. Formal safety assessment

Formal Safety Assessment (FSA) is an approach for the determination of new or modified rules at IMO using risk analyses and cost benefit assessments. In accordance with (IMO, 2002), it consists of five steps:

- 1. Identification of hazards.
- 2. Assessment of risks, i.e., the assessment of the likelihood and consequences of the identified hazards.
- 3. Determination of risk control options, i.e., options for the management of the identified risks.
- 4. Assessment of the cost efficiency of proposed risk control options.
- 5. Recommendations for decision-making.

Risk acceptance criteria are determined in accordance with (IMO, 2000) in terms of the following:

- The maximum accepted individual risk (the annual risk of death or serious injury to which specific individuals are exposed)
- The maximum accepted societal risk (the risk of accidents involving large numbers of people)
- The Implied Cost of Averting a Fatality (ICAF) determining the maximum expenditure to avoid a statistical fatality in accordance with the principle of As Low As Reasonably Practicable (ALARP).

The FSA approach is useful because it enables a transparent decision-making process in which regulations are determined based on a systematic comparison of various risk control options. However, to date FSA has mainly been applied on bulk carriers (Papanikolaou, 2009). This is probably because the FSA process is highly technical and complex, taking approx. 1 year to complete (Papanikolaou, 2009).

2.3. General ship design methods

Existing ship design rules can be divided into two main categories: (1) prescriptive rules prescribing specific design solutions, and (2) goal-based rules prescribing design goals and FRs to meet the goals. Because the ship design process is strongly driven by the applied rules and regulations, the applied design method can be characterised based on the applied types of rules. Specifically, a design process

carried out following prescriptive rules can be referred to as Prescriptive-Based Design (PBD), whereas a design process carried out following goal-based rules can be referred to as Goal-Based Design (GBD). In the following, these two methods are discussed and compared in terms of strengths and weaknesses.

2.3.1. Prescriptive design

Because prescriptive rules specify many important design features, they limit the work of the designer, enabling a time and resource efficient design process. In addition, because prescriptive rules are generally clear-cut, it is easy for authorities to verify compliance. Thanks to these strengths, PBD has remained the standard ship design method for decades. However, PBD does have some fundamental weaknesses. First, because prescriptive rules predetermine important design features, they also act as design constraints limiting the feasible solution space, hindering design optimization and innovation (Papanikolaou, 2009). Second, the efficiency of the solution depends on the efficiency of the rules, which might be challenged for several reasons including the following:

- 1. Most of the rules are empirically or semi-empirically determined based on real-life experience. Thus, if the underlying data is insufficient, or if the data is determined based on ships and operations that differ from those of the ship being designed, the rules might not result in the desired performance (LR, 2014).
- 2. It is well known that the development of the rules has primarily been driven by disaster, i.e., that the rules have been determined or adjusted only following individual catastrophic events (Papanikolaou, 2009). In other words, the rules have failed to be proactive.
- 3. It appears most of rules have been determined without a systematic consideration of costefficiency and therefore it is possible that the same function could be obtained at lower cost by means other than those prescribed by the rules (Vassalos, et al., 2006).
- 4. Most of the rules have been determined without clear goals and objectives (Vassalos, et al., 2006). Thus, the actual safety level of a design built in accordance with the rules remains unknown. Also, because any design that meet the rule requirement is considered equally safe, the rules makes it difficult to award additional safety (Papanikolaou, 2009).
- 5. The rules often apply a one-fit-all approach, meaning that a specific set of rules is to be applied on a wide range of ships and operations. This is problematic for arctic ships that often represent innovative unique designs and case-specific operating conditions.

2.3.2. Goal-based design

In GBD, the rules determine the functions that a solution should provide to meet the design goal(s), but not how the functions are to be achieved. In accordance with (Papanikolaou, 2009), this provides many advantages including the following. First, by determining the design requirement in the function space in terms of a FR instead of the form space in terms of a prescriptive rule, the number of design constraints is reduced. Thus, the feasible design space is expanded, enabling new, innovative and cost-efficient solutions. Second, to achieve design approval, the actual safety and environmental risks of a design needs to be assessed, promoting a culture of responsibility and innovation among designers. Third, the application of FRs makes it possible to determine clear goals and to reward risk reducing measures beyond the minimum requirements.

A FR can be determined either in terms of a minimum required deterministic performance (e.g. the maximum acceptable evacuation time is 10 minutes), or in terms of a maximum acceptable level of risk (e.g. the maximum acceptable individual risk is 10⁻³). When designing for FRs determined in risk

terms, the design process can be referred to as Risk-Based Design (RBD), which thus can be considered sub-category of GBD.

Compliance with FRs is demonstrated by carrying out performance assessments. If the FR is determined in terms of a deterministic goal, the designer must demonstrate that the performance of the design (P_{Design}) is equal or higher than the minimum accepted performance $(P_{acceptable})$ in accordance with Eq. 1.

$$P_{Design} \ge P_{acceptable} \tag{1}$$

If, on the other hand, the FR is determined in risk terms, the designer must demonstrate that the risk associated with the design (R_{Design}) is equal or lower than the maximum acceptable risk ($R_{acceptable}$) in accordance with Eq. 2.

$$R_{Design} \le R_{acceptable} \tag{2}$$

 R_{Design} is generally defined as the product of the likelihood of an unwanted event times the associated consequences in accordance with Eq. 3.

$$Risk = \sum (L_i C_i) \tag{3}$$

, where L_i determines the likelihood of plausible risk events and C_i determines the related consequences (Papanikolaou, 2009). Thus, the level of risk can be managed to an acceptable level either by controlling the likelihood, and/or by controlling the consequences of an event by applying various risk mitigation options.

Weaknesses of GBD/RBD relates primarily to its practical application. First, because GBD/RBD enables a wider design space, and because performance assessment is necessary, it is likely to result in a more time- and resource-consuming design process than PBD, something that can be problematic especially in the pre-contractual phase (Papanikolaou, 2009). Second, because the design approval depends on performance assessments, uncertain/faulty performance assessment models, data and assumptions might result in bad design decisions (Jenkins, 2012). Third, to ensure that the performance of a ship remains acceptable over its whole life time, the ship must be maintained and operated as intended, and there can be no major changes in its operations or design without a reassessment of its performance (Jenkins, 2012). Fourth, because the authorities need to get access to relevant performance assessments, there might be issues related to transparency and intellectual property rights (Corrignan, 2013). Fifth, the comparison of performance assessments carried out by different ROs might be challenging (Corrignan, 2013).

2.4. Different types of performance assessment methods

The design of an arctic cargo ship is essentially about finding a solution that provides the required operational, safety, and environmental performance at lowest possible cost. Performance assessment is therefore central in the design process. In this study, different methods of performance assessment are divided into three categories: (1) empirical and semi-empirical methods, (2) experimental methods, and (3) theoretical methods. The characteristics of each of these methods are discussed in the following.

2.4.1. Empirical and semi-empirical performance assessment

Empirical performance assessment methods rely on full-scale operational data, and requires therefore access to empirical data originating from ships and operational conditions that are equivalent to those of the design task. If appropriate and sufficient data is available, empirical methods are generally reliable and the risk of significant assessment errors is limited. However, if the applied empirical data does not exactly relate to the design task, there is a risk of significant assessment errors, especially because the use of empirical methods does not encourage a deeper understanding of the various phenomenon affecting the performance of a design. Therefore, empirical methods are generally not well suited for the assessment of new types of designs or operations.

Semi-empirical performance assessment methods also rely on empirical data, but extend the range of applicability of the data by various means (e.g. mathematical interpolation). Consequently, they can be used for designs and operations that, to some degree, differ from those based on which the applied data was determined. However, because semi-empirical methods are generally not based on a complete understanding of all the underlying factors affecting the performance of a design, there is a risk of significant assessment errors.

In terms of risk assessment, the use of empirical data is generally problematic because it motivates the designer to assess risks solely based on previously materialized events. Thus, potentially serious, but still unmaterialized, risks might be overlooked (Papanikolaou, 2009). Also, because the volume of arctic shipping is relatively low, and because the technology development is fast, the accumulation of meaningful statistical data is difficult (LR, 2014).

2.4.2. Experimental performance assessment

Experimental performance assessment methods rely on scale model testing carried out in a controlled environment such as a laboratory. In the case of arctic ships, common types of scale model testing include ship model tests carried out in so-called ice tanks, various types of ice impact tests, and cavitation tunnel tests. To minimize scaling effects, the applied models, and consequently also the test equipment or facilities (e.g. ice tank), need to be relatively large (National Research Council, 1984). This contributes towards making scale model testing costly and time consuming, especially because after each test, a new model ice cover or sample must be prepared. On the upside, model testing is generally reliable.

2.4.3. Theoretical performance assessment

Theoretical performance assessment methods differ from empirical and experimental methods in that they rely on first-principle models, and do therefore not rely on design specific empirical or experimental data sets. Theoretical models require an in-depth understanding of all the phenomenon having a significant effect on the type of performance that is being assessed, and might therefore be costly and time-consuming to develop. However, once developed and validated, theoretical models generally enable fast and cost-efficient performance assessment of various design alternatives, enabling design innovation and optimization.

2.5. Design tools

Design tools that are relevant for the understanding of the thesis are presented in the following.

2.5.1. Equivalent ice thickness

An ice cover can be considered to consist of three main components: level ice, ice openings (open water), and ice ridges. Level ice is typically described in terms of thickness (t), whereas ice openings are described in terms of ice coverage (c), corresponding to the percentage of a sea area that is ice covered. The description of ice ridges is generally based on the simplified assumption that ice ridges have the shape of quadrangles formed by two isosceles triangles, one representing the ridge sail and the other representing the ridge keel. This simplification makes it possible to describe the size of an individual ridge in terms of its keel draft H_r , slope angle α , and the ridge sail height H_s in accordance with Fig. 4. Likewise, the size of prevailing ridges can be described in terms of average sail height H_{s_avg} , the average keel draft H_{r_avg} , and the average slope angle α_{avg} . The number of ridges in an area is often described in terms of the ridge density (ρ), corresponding to the number of ridges per km.

The overall ice conditions can be described in terms of the equivalent ice thickness (H_{eq}), which is generally defined as the average thickness of all ice features in an area. However, there is no agreed on exact definition of H_{eq} (Riska, 2010). Possible definitions include Eq. 4 determined by (Riska, 2010), and Eq. 5 determined by (Leppäranta, 1980).

$$H_{eq} = \left(c - 2\frac{1}{\tan\alpha_{avg}}\rho H_{r_{avg}}\right)t + \frac{1}{\tan\alpha_{avg}}\rho H_{r_{-}avg}^{2}$$
(4)
$$H_{eq} = tc + \frac{1}{\tan\alpha_{avg}}H_{r_{-}avg}^{2}\rho$$
(5)

Because the concept of H_{eq} is based on the principle of averaging, it fails to consider individual ice features such as individual large ridges that might stop a ship. Thus, as pointed out by (Valkonen & Riska, 2014), such individual ice features need to be considered separately. Other relevant ice condition related characteristics that are not included in the concept of H_{eq} include ice age (FYI, SYI, or MYI), ice temperature, and ice compression. These characteristics are important as they might significantly affect the ice load and resistance of a ship.



Figure 4: Ice ridge parameters.

2.5.2. Discrete-event simulation

Simulations, i.e., the imitation of the operation of real-world systems over time, are useful for the analysis and assessment of the behaviour of complex systems, i.e., systems composed of multiple components that may interact with each other resulting in non-linear behaviours (Banks, et al., 2014) (Rocha, 1999). Discrete-event simulation (DES) is a specific type of simulation in which the behaviour of a system is modelled as an ordered sequence of events, each of which takes place at a specific point of time and results in a change in the state of the system (Craig, 1996). Because no change occurs between events, DES enables fast simulations of extensive periods of time. Naturally,

the simulation of a system can be carried out at many different levels of fidelity, i.e., level of detail. To avoid unnecessary modelling costs and time, the level of fidelity should be no higher than what is required by the design task.

2.5.3. Ice load assessment

Due to the stochastic nature of both sea ice strength properties and the ship-ice interaction process, ship ice loading is known to be stochastic and can therefore only be estimated probabilistically (Kujala & Ehlers, 2013). For this purpose, (Jordaan, et al., 1993) propose a probabilistic ice load method, according to which the 100-year extreme ice load z that a ship is exposed to can be estimated in accordance with Eq. 6.

 $z = [4.6 + \ln(xf)]CA^{D}$ (6)

, where x = average annual distance travelled in ice [NM], f = ice condition specific impact frequency [impacts/NM], [C, D] = ice condition specific coefficients, and A = impact area [m^2]. Because the C and D values need to be determined empirically, the method can be considered semi-empirical. However, once the extreme load has been determined, it can be used as input for theoretical structural analyses (e.g. finite element method analyses) to determine the required level of ice strengthening. A weakness of the tool is that it only able to estimate the ice-loading related to the exposure to a single type of ice (e.g. thick FYI). In other words, it is not able to estimate the "cumulated" level of ice loading caused by the exposure to various types of ice. Another weakness of the tool is that its limited to the estimation of ice-loading affecting the bow section of a ship.

3. Summary of work

3.1. Overview of papers and declaration of authorship

The main body of the present thesis consists of three journal papers and one conference paper that are presented in the following.

Paper 1: Assessment of the applicability of goal- and risk- based design on arctic sea transport systems

This journal paper (published in *Ocean Engineering*, Vol. 128, pp. 183-198) contributes towards the objectives of the thesis by proposing a general framework for the conceptual design of arctic ships enabling full utilization of the goal- and risk-based regulatory system determined by the Polar Code. In accordance with Fig. 5, the framework, includes the definition of relevant terminology and concepts, a description of an appropriate design process, the selection of appropriate performance assessment tools. The paper addresses RQ 1 by assessing the framework's current range of applicability, considering various knowledge, data, and regulatory gaps.

I (the main author) developed the proposed framework, assessed its current range of applicability, and prepared the manuscript. The co-authors Stein Ove Erikstad and Sören Ehlers provided valuable comments, advice, and suggestions. Preliminary versions of the framework are presented and evaluated in the following conference papers:

- Bergström, M., Ehlers, S., Erikstad, S. O, Erceg, S., Bambulyak, A., 2014. *Development of an approach towards mission-based design of arctic maritime transport systems*. Proceedings of the 33th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2014), June 8-13, 2014, San Francisco, California, USA.
- Bergström, M., Erikstad, S. O. & Ehlers, S., 2015. *Applying risk-based design to arctic ships*. Proceedings of the ASME 34th International Conference on Ocean, Offshore and Arctic Engineering (OMAE 2015), May 31 June 5, 2015, St. John's, Newfoundland, Canada.



Figure 5: Contributions by Paper 1-3.

Paper 2: A simulation based probabilistic design method for arctic sea transport systems

This journal paper (published in *Journal of Marine Science and Application*, Vol. 15, pp. 349-369) addresses RQ 2 in accordance with Fig. 5 by presenting a case study based on which the merits of the general design framework proposed by Paper 1 are evaluated. I (the main author) carried out the case study, the related analyses, and prepared the manuscript. The co-authors Stein Ove Erikstad and Sören Ehlers provided valuable comments, advice, and suggestions.

Paper 3: An approach towards the design of robust arctic maritime transport systems

This conference paper (published as a chapter of the book *Maritime-Port Technology and Development*, p. 185-192, CRC Press, 2014) addresses RQ 2 in accordance with Fig. 5 by presenting a case study in which the merits of the design framework proposed in Paper 1 are evaluated. The paper differs from Paper 2 in terms of the way the proposed design framework is applied. I (the main author) carried out the case study, the related analyses, and prepared the manuscript. The co-authors Sören Ehlers and Stein Ove Erikstad provided valuable comments, advice, and suggestions.

Paper 4: The influence of model fidelity and uncertainties in the conceptual design of arctic maritime transport systems

This journal paper (accepted for publication in *Ship Technology Research - Schiffstechnik*), addresses RQ 3 and RQ 4 by presenting and analysing two case studies. In accordance with Fig. 5, RQ 3 is addressed by providing recommendations regarding the choice of model fidelity, and RQ 4 is addressed by providing insights into the effect of various design uncertainties, and how they can be mitigated. I (the main author) carried out the case study, the related analyses, and prepared the manuscript. The co-authors Stein Ove Erikstad and Sören Ehlers provided valuable comments, advice, and suggestions. The paper can be considered as a further development of the following conference paper:

- Bergström, M., Erikstad, S. O. & Ehlers, S., 2015. Assessment of the effect of uncertainties in design parameters on the design of arctic ships. Proceedings of the 12th International Maritime Design Conference (IMDC 2015), May 11-14, 2015, Tokyo, Japan.

3.2. Summary of paper 1: Assessment of the applicability of goal- and risk-based design on arctic sea transport systems

This paper presents a framework for holistic goal/risk-based conceptual design of arctic ships and maritime transport systems. The paper starts by defining relevant terminology as follows.

Risk is defined in accordance with Eq. 7 as a positive or negative effect of uncertainty on objectives.

$$Risk = \sum (L_i C_i) \tag{7}$$

, where L_i determines the likelihood of all plausible risk events and C_i determines the related consequences. Risks are managed by active and passive risk prevention and mitigation measures. Active measures consist of measures taken by the crew and are therefore achieved mainly by training and procedures. Passive measures, on the other hand, are achieved by hardware, i.e., by design and equipment. An AMTS is subject to various types of risks including the following:

- Operational risk: the risk of failure to meet the transport task. The opposite, i.e., the likelihood of meeting the transport task, is referred to as operational reliability. Thus, the sum of the operational risk and the operational reliability is always 100%.

- Safety risk: the risk of loss of life or injury.
- Environmental risk: the risk of environmental damage.
- Financial risk: the risk of financial loss or less-than-expected returns.



Figure 6: Overview of the proposed design process.

To enable a systematic and purposeful search for a good design, the paper suggests that the design process is carried out in accordance with the step-by-step process presented by Fig. 6. This process starts with the determination of the design context (e.g. transport task, operating conditions), followed by the determination of various possible concepts of operations (CONOPS). A CONOPS determines operational strategies for how to meet the design objectives. This includes the determination of (1) an ice mitigation strategy (IMS) describing how the AMTS will deal with sea ice (e.g. independent or assisted operation), (2) a strategy for how to compose the fleet (e.g. use of large or small vessels), (3) a strategy for how to balance the transport demand and capacity in varying operation conditions (e.g. reserve speed or reserve payload capacity).

Based on the design context, each CONOPS is developed into a preliminary AMTS design, which is subsequently divided into a hierarchy of subsystems. Specifically, in accordance with Table 1, an AMTS is to be divided into three main subsystems: (1) an operations (OPS) system carrying out the transport task, (2) a safety system managing safety risks, i.e., risks to humans, and (3) an environmental protection (ENVP) system managing environmental risks. Each of these main subsystems is subsequently divided into a set of sub-subsystems.

System level	OPS systems	Safety systems	ENVP systems
External systems	IB(s)	IB(s)	IB(s)
	Ports	SAR unit(s)	OSR unit(s)
		Emergency port(s)	
Fleet level systems	Fleet system		
Ship-level systems	Buoyancy system	Hull protection system	Accidental discharge prevention system
	Propulsion system	Flooding mitigation system	
	Cargo system	Fire protection system	
		Evacuation system	
		Propulsion and steering unit protection system	

Table 1: General system division of an AMTS

Because the fleet system, specified in terms of the number of ships as well as the payload capacity and h-v curve⁴ of each ship, determines requirements for most other systems, it should be designed first. Important performance measures of the fleet system include operational risk, operational reliability and robustness. The robustness is here defined as a measure of how sensitive the performance of an AMTS is to variations in the operating conditions. Thus, robustness and operational reliability are strongly connected.

For the determination of the operational reliability and robustness, the use of DES-based Monte Carlo simulations is recommended as it makes it possible to estimate the probabilistic performance of an AMTS considering a multitude of stochastic and uncertain performance factors.

Once the fleet variables have been determined, the ship-level OPS systems are determined considering criteria determined by the fleet system. For instance, if the fleet system determines that the ship(s) are to be able to operate independently in accordance with a specific h-v curve, the buoyancy system (hull shape) and the propulsion system (e.g. propulsion power) need to be determined accordingly. Naturally, to determine the propulsion power requirement of an arctic ship, it is first necessary to determine its ice resistance. Currently the ice resistance of a ship is typically estimated by model testing. To enable a more time- and cost-efficient design process, an appropriate theoretical ice resistance model is sought after.

With regards to the safety system, the design of the hull protection system is central as the applied level of ice-strengthening has a significant effect on both on the investment and operational costs of a ship. In order to make it possible to determine a ship's required level of ice-strengthening based on its actual ice exposure, the paper proposes the application of the probabilistic ice load method presented in section 2.5.3 using ice exposure data determined by the same DES-based Monte Carlo simulation applied for the design of the fleet system. However, the practical application of this method for GBD/RBD is currently complicated by the lack of agreed-on performance measures and criteria for the hull protection system. To fill this gap, the paper proposes the determination of a

 $^{^{4}}$ A *h*-*v* curve determines the speed of a ship as a function of the ice thickness.

maximum acceptable damage frequency determined based on the estimated return period of the ice loading corresponding to the maximum plastic limit load of a hull structure. To enable more accurate ice load estimates, the paper also recommends the determination of additional ice condition specific C and D coefficients needed for the application of the probabilistic ice load method.

Safety systems other than the hull protection system are to be designed as follows: the flooding mitigation system is to be designed based on IMO's goal-based probabilistic damage stability method, the fire and evacuation systems are to be designed either based on goal/risk-based methods developed for non-arctic ships, or using existing prescriptive rules, and the propulsion and steering unit protection system is to be designed based on prescriptive ice class rules. GBD/RBD of the propulsion and steering unit protection system is not possible both due to the lack of a sufficiently accurate ice-propeller model for the estimation of the level of ice loading acting on the system, and due to the lack of agreed-on performance measures and criteria. As acceptance criterion the paper proposes the determination of a maximum acceptable damage frequency.

Because there is no approach for the determination of the total safety risk of an AMTS, all the safety systems need to be designed and approved separately as described above. Obviously, this hinders a truly holistic design of the safety systems considering for instance the effect of IBs, other ships, SAR, and possible active measures.

Like for the safety system, there is no approach for the assessment of the total environmental risk of an AMTS. In addition, there no agreed-on environmental risk measures or criteria. Therefore, the design of the ENVP system is limited to the design of a ship-level accidental discharge prevention system, which is to be designed based on IMO's Probabilistic Oil Outflow Method. In accordance with this method, the performance of the accidental discharge prevention system is determined in terms of its so-called oil outflow performance, also referred to as pollution prevention index, which is not related to any specific environmental risk. As a first step towards a more risk-oriented design process of the ENVP system, the IMO needs to agree on a set of appropriate environmental risk measures and criteria.

Once each subsystem of each preliminary design (CONOPS) has been designed in accordance with all design criteria, a population of feasible competing AMTS designs is obtained. For the assessment and comparison of the cost-efficiency and robustness of the various AMTS designs, the application of operational data obtained by DES-based Monte Carlo simulation is proposed. For instance, the fuel consumption and costs can be estimated based on simulated data on the operating time in various ice condition (e.g. open water, brash ice, natural ice), whereas the costs for IB assistance can be estimated based on simulated data on the extent of IB assistance (e.g. number of assisted voyages and the assisted distance). Simulation data can also be employed to assess the robustness of a design to changes in the operating conditions.

To sum up, this paper proposes a design framework for holistic GBD/RBD of arctic ships and maritime transport systems. To enable a holistic and structured design process, the framework treats an arctic ship as a component of an AMTS. To assess the performance of an AMTS, and to determine operational data needed for the design of its various subsystems, the framework proposes the use of DES-based Monte Carlo simulations. As such, the framework enables full utilization of the goal/risk-based regulation of the Polar Code, and integrates those regulations into a holistic goal/risk-based design method. The proposes framework is already applicable for the determination of fleet parameters, ice loading, and for the comparison of the cost efficiency of competing designs. To extend the applicability of the framework, various knowledge, data, and regulatory gaps need to be addressed. Currently such gaps prevent GBD of both the hull protection system (no agreed-on performance criteria), and the propulsion and steering unit protection system (no performance assessment tool, no performance criteria). To enable full utilization of the principles of RBD, method

for the assessment of the total safety and environmental risks of arctic ships need to be determined. Currently, because such methods are not available, risk-based approaches can only be applied in the context of design equivalence, and the primary rules need to be either prescriptive or goal-based.

3.3. Summary of paper 2: A simulation-based probabilistic design method for arctic sea transport systems

This paper presents a case study through which the merits of the design framework proposed by Paper 1 are evaluated.

The case study deals with the conceptual design of an AMTS for the transport of liquefied natural gas (LNG) from the port of Sabetta (Russia) to the port of Zeebrugge (Belgium). The transport route, which is assumed fixed, is approximately 2,600 nautical miles (NM) crossing the North Sea, the Norwegian Sea, the Barents Sea, the Pechora Sea, and the South Kara Sea. Shallow waters along the route are assumed to limit the maximum vessel draught to 12 m, which in turn is assumed to limit the maximum feasible ship cargo capacity to 170,000 m³ LNG. LNG is assumed to be produced at a fixed rate of 100,000 m³/ day and stored in Sabetta until it is loaded onto a ship. Because the LNG storage is limited, it is necessary to maintain a sufficient transport capacity to avoid production stops caused by a lack of storage capacity. Because any production stop is assumed to results in a large economic loss, a high operational reliability is required. Specifically, the AMTS is to be able to meet the transport demand in the worst combination of operating conditions that is expected within a period of 100 years.

Sea ice is the most important environmental factors affecting maritime operations along the route. Other environmental factors, such as wind, waves, and sea currents are not considered as their impact is assumed small in comparison with that of sea ice. Using the Monte Carlo method, based on publically available ice data (e.g. month-specific average level ice thicknesses) and ice models determining the variability and dependencies of various ice features, stochastic sea ice conditions along the route are modelled for 100 separate operating years. As a simplification, the route is split up into three legs, along which the level ice thickness and concentration are assumed constant. Ice infested legs are further divided into approx. 50 NM long sub-legs, for which ice ridging characteristics (ridge size and density) are determined randomly resulting in locally varying H_{eq} values. Examples of ice scenarios/conditions determined in this manner are presented in Fig. 7.

Based on the determined design context, in total four CONOPS are determined:

- CONOPS 1: Use of independently operating ships with an ice-going capability of 2.1 m.
- CONOPS 2: Use of ships with an ice-going capability of 1.4 m. Use of IB assistance when the level ice thickness exceeds 1.2 m.
- CONOPS 3: Use of ships with an ice-going capability of 1.4 m. Use of IB assistance when the level ice thickness exceeds 0.5 m.
- CONOPS 4: Use of ships with an ice-going capability of 1.4 m. Use of IB assistance when the level ice thickness exceeds 0.5 m. Application of flexible contracting making it possible to deliver cargo to a more nearby destination (the port of Narvik) during years with exceptionally difficult ice conditions reducing the average speed along leg 3 below 5 kn.

The speed of the ships of each CONOSP are determined in terms of a h-v curves determined based on the ice-going capabilities of the ships. For CONOPS 2-4, separate h-v curves are determined for independent and assisted operation. Because all ships are assumed to be so-called double acting tankers (DAT), they are assumed to be able to penetrate large ridges at continuous speed (0.5 knots) without ramming.

Preliminary designs for all CONOPS are determined in accordance with Table 2. The estimated 100year worst round-trip times were determined based on the determined 100-year worst ice conditions, the h-v curves of the ships, the maximum expected port turn-around times, and the maximum expected waiting time for IB support (relevant for CONOPS 2-4). The effect of port-based storages is not considered at this stage.



Figure 7: Ice scenarios: (a) average H_{eq} values along the route in April for various ice scenarios, (b) an example of how H_{eq} might vary along the route (each bar represents 50 NM), (c) day-specific average H_{eq} along leg 3 (South Kara Sea) for various annual ice scenarios.

CONOPS	1	2	3	4
Estimated 100-year worst round trip time [days]	29.5	26.4	26.4	21.6
Number of vessels	18	16	16	13
Cargo capacity per vessel [m ³]	170,000	170,000	170,000	170,000
Transport capacity [1,000 m3 per day]	103.7	103.0	103.0	102.3

Table 2: Preliminary AMTS designs

Following the proposed design framework, each preliminary design is subsequently split into a hierarchy of subsystems in accordance with Table 1. In accordance with the proposed design process, the design of the subsystems begins with the design of the fleet system using DES-based Monte Carlo simulation. In the applied DES model, which is presented in Fig. 8, individual ships and cargo units are modelled as entities. Cargo units are loaded onto a ship by merging them with a ship entity. The number of cargo units that can be merged with a ship entity depends on the ship's cargo carrying capacity. Ship entities are created at the start of the simulation and circulate thereafter in a closed loop until the simulation stops. Cargo entities are produced at a fixed rate and leave the system once they have been transported to their destination, where they are split from the ship entity. During the simulation, the ship and cargo entities are stopped for various lengths of time corresponding to the duration of events such as completing a specific leg, visiting a port, and waiting for IB assistance.

Both the port of Sabetta and the port of Zeebrugge are assumed to have LNG terminals that can serve two ships at a time. If both berths are occupied, an incoming ship waits until a berth becomes available.



Figure 8: Overview of the applied DES model.

Based on the assumptions that the cargo capacity of the ships is limited to $170,000 \text{ m}^3$, and that the speed (*h-v* curves) of the ships is fixed, the fleet variables that are to be determined are limited to the required fleet size and the capacity of the port-based LNG storage in Sabetta. The port-based storage is of interest because, by acting as a buffer allowing temporary shortages in the transport capacity, it could have an impact on the required fleet size. This hypothesis is supported by the outcome of the simulation, presented in Fig. 9, indicating that the required fleet size is significantly affected by the capacity of the port-based storage. Due to a lack of relevant data, the paper was not able to assess the economically optimal ratio between the fleet size and the storage capacity of 800,000 m³ was selected for all CONOPS In accordance with Fig. 9, for this storage capacity the required fleet size for CONOPS 1-4 are 15, 14, 14 and 13 ships respectively. Thus, in comparison with the preliminary designs presented in Table 2, which were determined against a set of fixed values representing the worst expected combination of circumstances, the applied holistic simulation-based approach resulted in a significantly less conservative design.



Figure 9: Required fleet size vs. port-based cargo storage capacity.

In the applied DES model, IBs are modelled as resources that assist one vessel at a time. A ship in need of assistance waits until there is an available IB. However, the DES model is not able to model

the time it takes for an available IB to reach a ship in need of assistance. Therefore, this time is modelled in terms of an assumed triangular distribution. Anyhow, the total IB waiting time depends both on the number of assisting IBs and the randomly determined IB transit time. For the determination of the required fleet sizes presented in Fig. 9, the number of assisting IB was assumed to be 7. In accordance with Fig. 10, presenting examples of simulated IB waiting times and their dependency on the prevailing ice conditions, a reduction in the number of assisting IBs from seven to six would result in significantly longer waiting times during years with difficult ice conditions.



Figure 10: Example of simulated IB waiting times and their dependency on the prevailing ice conditions and the number of IBs.

The design of the hull protection system is carried out in accordance with the proposed design framework by using the probabilistic ice load method presented in section 2.5.3, and design case specific ice exposure data obtained by DES-based Monte Carlo simulations. Examples of simulated ice exposures are presented in Fig. 11. In accordance with the figure, the ice exposure is determined in terms of the average exposure to thin ($t \le 0.7$ m) natural or brash ice, medium ($0.7 < t \le 1.2$) natural or brash ice, and thick (t>1.2) natural or brash ice. Each individual bar presented in the figure represents a ship's exposure to the different types of ice during a specific year. The ice-loading related to the exposure to a specific type of ice (e.g. thick natural FYI) is determined based on the 100-year annual average ice exposure to the type of ice in question. Because the method is not able to calculate the cumulated ice loading caused by the exposure to whatever ice type resulting in the highest estimated ice loading. In this specific design case, the required level of ice-strengthening is
determined based on ice loading related to operation in thick FYI, which was found to be significantly higher than ice loading related to operation in thin and medium FYI.



Figure 11: Example of simulated ice exposures.

Based on the simulated ice exposure, the estimated 100-year maximum ice loading of the ships is calculated in accordance with the probabilistic ice-load method as a function of the design area as shown in Fig. 12. Because there are no agreed-on performance measures or criteria for the hull protection system, the calculated ice loading is used to determine whether PC 4, i.e., the ice class standard required by the Polar Code for operation in thick (> 1.2 m) FYI, provides a sufficient level of ice-strengthening. To this end, the calculated extreme ice loads are compared against polar class specific design loads as shown in Fig. 12. Assuming that the design area of interest is typically within the range 0.6–1 m², we find that the calculated extreme loads are below the design load of PC 3. This indicates that the prescribed PC 4 standard is appropriate for all the ships.

In accordance with the proposed design framework, once a population of feasible AMTS designs representing various CONOPS have been determined, they are to be compared in terms of cost-efficiency and robustness. The cost assessment is carried out based on three types of costs: time

charter costs rate (including capital, crew, and maintenance costs), fuel costs, and costs for IB assistance.



Figure 12: Calculated 100-year extreme ice loading.

Time charter costs are calculated as the product of the number of ships, the daily time charter rate per ship, and the simulated total operating time (all time except off-time due to dry-docking). The daily time charter rate of the CONOPS 1 ships is assumed to be USD 130,000, whereas the daily time charter rate of the CONOPS 2-4 ships, due to their lower ice-going capability, is assumed to be 5 % lower at USD 123,500.

Fuel costs are calculated based on the simulated total number of operating hours at various operating modes (operation in open water, independent operation in ice, and assisted operation in ice), the estimated power requirement at each operating mode, and the assumed specific fuel consumption. The power requirement of the CONOPS 1 ships is assumed to be 45,000 kW in open water and 65,000 kW during independent operation in ice. The power requirement of the CONOPS 2-4 ships is assumed to be 43,000 kW both when operating in open water and in ice, with or without IB assistance. The specific fuel consumption of all ships is assumed to be 170 g/kWh. All ships are assumed to operate on marine diesel oil (MDO), for which four future price scenarios are determined in accordance with Fig. 13.



Figure 13: Applied fuel price scenarios.

IB costs are calculated based on the simulated number of assisted voyages and an assumed IB tariff of 1.5-3-0 USD/GT per assisted voyage.

Based on the above, the annual average costs per transported cubic meter of LNG, as a measure of cost-efficiency, as well as the variance of the annual average costs, as a measure of design robustness, are calculated for the various CONOPS and fuel price scenarios. The outcome of the performance assessment, which is presented in Fig. 14, indicate that CONOPS 4 is the most cost-efficient at an average transport cost of USD 23 /m³. However, CONOPS 4 is not directly comparable with the other CONOPS because it transports a part of the cargo (around 0.5 %) the port of Narvik instead of the port of Zeebrugge. Among directly comparable CONOPS 1-3, the results indicate that CONOPS 3 is both the most cost-efficient at USD 24 /m³ and the most robust at a variance of 14. CONOPS 1, on the other hand, appear to be both the lest cost-efficient at USD 26 /m³ and the least robust at a variance of 20. Thus, for this specific case, the use of IB assistance appear to favour both cost-efficiency and robustness.

To sum up, this paper demonstrates that the proposed design framework enables the following:

- Assessment of the probabilistic transport capacity of an AMTS considering a multitude of stochastic parameters (e.g. parameters dependent on seasonal and inter-annual variations in the ice conditions), as well as various interaction and self-reinforcing (e.g. the waiting time for IBs increases as the ice-conditions get worse) effects.
- The determination of various types of operational data, relevant both for the design of various ship systems, and for a holistic performance assessment of competing AMTS designs.
- The consideration of port-based cargo storages, which in the presented case study was found to have a significant effect on the required fleet parameters.

Based on the above, in response to RQ 2, it can be concluded that the proposed design framework, applying system thinking and DES-based Monte Carlo simulations, provides valuable information enabling better informed design decisions.



Figure 14: Example of performance assessment.

3.4. Summary of paper 3: An approach towards the design of robust arctic maritime transport systems

This paper presents a case study in which elements of the design framework proposed by Paper 1 are applied to compare the cost-efficiency of various ice mitigation strategies for various future ice scenarios.

The case study deals with the design of an AMTS for the transport of LNG from Sabetta (Russia) to Narvik (Norway). The route is approx. 1489 NM in distance crossing the Western Kara Sea, the Pechora Sea, and the Barents Sea. The operational criterion is to provide an annual transport capacity of 3.65×10^7 m³ LNG, corresponding to the assumed annual LNG production in Sabetta.

In search for a cost-efficient and robust design, three CONOPS representing three ice mitigation strategies (IMS) are determined as follows:

- CONOPS 1: Use of PC 7 classed ships that can operate independently in up to 0.7 m thick ice. Use of icebreaker assistance when the ice thickness exceeds 0.7 m.
- CONOPS 2: Use of PC 5 classed ships that can operate independently in up to 1.2 m thick ice. Use of icebreaker assistance when the ice thickness exceeds 1.2 m.
- CONOPS 3: Use of PC 4 classed ships that can operate independently in up to 1.7 m thick ice. Use of icebreaker assistance when the ice thickness exceeds 1.7 m.

Based on the assumed prevailing ice conditions along the route, four different ice scenarios, including one scenario with statistically increasing ice conditions (IS 1), two scenarios with statistically decreasing ice conditions (IS 2-3), and one scenario with statistically unchanged ice conditions (IS 4), are determined in accordance with Fig. 15.



Figure 15: Average ice thickness for the distance Kara Strait- Sabetta for ice scenario 1-4.

The operational performance of the various CONOPS are assessed using a similar DES-based Monte Carlo simulation approach as the one applied for the case study of Paper 2. Assuming that the h-v curves of the ships are fixed, the determination of the fleet variables is limited to the determination of the fleet size and the cargo carrying capacity of each ship. Significant simplifications include the following: (1) convoy speed, i.e., speed with IB assistance, is assumed to be 8 knots on average regardless of the ice conditions, (2) IB waiting times are determined solely based on an assumed distribution, i.e., the number of IBs is not considered, (3) port-based storages are not considered, (4) local ice features such as ice ridging are not considered.

Based on the outcome from the DES-based Monte Carlo simulation, the required fleet size and ship capacity for CONOPS 1-3 are determined for IS 1-4 in accordance with Table 3. To maintain a sufficient transport capacity in IS 1, a fleet of 6 vessels, each with a capacity of 172,000 m³, is required for all designs. For IS 2-4, ships with a somewhat smaller capacity are sufficient. To avoid the risk of insufficient transport capacity, all CONOPS are designed for IS 1.

	CONOPS	Required number of ships	Required capacity per ship [m3]	Capacity utilization with 172,000 m3 per ship
IS 1	1-3	6	172,000	100%
IS 2	1-2	6	170,000	99%
	3	6	160,000	93%
IS 3	1	6	165,000	96%
	2	6	163,000	95%
	3	6	150,000	87%
IS 4	1-2	6	171,000	99%
	3	6	163,000	95%

Table 3: Fleet utilization for various AMTS designs and ice scenarios

The cost-efficiency of the various CONOPS are determined in terms of the Net Present Cost (NPC) calculated based on (1) costs for icebreaker assistance, (2) investment cost, and (3) fuel costs. As a simplification, only IMS-specific costs were considered. For instance, in terms of investment costs, only costs related to an ice class higher than PC 7, i.e., the ice class of CONOPS 1, are considered. Likewise, in terms of fuel costs, only fuel costs related to a higher ice class and additional independent ice-going capability relative to CONOPS 1 are considered. Other costs are assumed to be the same for all CONOPS and thus not relevant for determining which CONOPS is the most cost-efficient.

All costs are calculated using operational data obtained by DES-based Monte Carlo simulations including the following:

- The total sailing time with IB assistance, based on which the IB costs are calculated (in contrary to the case study of Paper 2, IB costs are here calculated based on an assumed daily tariff for IB support).
- The total operating time in open water and in ice, based on which the fuel consumption and costs are calculated.

In accordance with the outcome from the cost assessment presented in Table 4, CONOPS 1 is the most cost-efficient for all ice scenarios. These findings clearly indicate that, for the analysed design case, it is more cost-efficient to use vessels with a relatively low ice-going capability utilizing a significant amount of IB assistance, than to use vessels with a high ice-going capability minimizing the need for IB assistance. Especially in the case of IS 2-3, CONOPS 3 performed poorly while the utilization of its vessel's ice-going capabilities is limited to the start of the analysed 10-year period, and thus only results in additional capital costs and operating costs towards the end of the period.

CONOPS 1	Ice scenario IB support [days] Fuel cons.[t]	1 5647 0	2 4233	3 3065 0	4 4734 0		
	NPC [USD]	4.E+08	3.E+08	2.E+08	3.E+08	Average:	3.0E+08
CONOPS 2	Ice scenario IB support [days]	1 2385	2 979	3 227	4 1453		
	Fuel cons.[t] NPC [USD]	380000 5.E+08	380000 4.E+08	331000 4.E+08	383000 4.E+08	Average:	4.3E+08
CONOPS 3	Ice scenario IB support [days]	1 227	2 0	3 0	4 8		
	Fuel cons.[t] NPC [USD]	940000 9.E+08	633000 7.E+08	390000 6.E+08	757000 8.E+08	Average:	7.5E+08

Table 4: Average costs for various ice scenarios for various CONOPS

To sum up, in response to RQ 2, this paper demonstrates a further example of how the proposed design framework applying system thinking and DES-based Monte Carlo simulations can provide valuable information enabling better informed design decisions. The presented case study differs from the case study of Paper 2 in that it, instead of simulating the performance of an AMTS for a number of random operating years, simulates the performance of an AMTS for multi-year periods representing various long-term ice development trends. Also, the cost efficiency of various AMTS designs is quantified in terms of NPC instead of in terms of the average transport costs.

3.5. Summary of paper 4: The influence of model fidelity and uncertainties in the conceptual design of arctic maritime transport systems

The objective of this paper is threefold: (1) the determination of the required level of model fidelity, (2) the identification and assessment of the effects of model uncertainties, and (3) the analysis of various methods of design uncertainty mitigation. The study is centred around two case studies: (1) Case A dealing with the design of an AMTS for year-round operation on the Arctic, and (2) Case B dealing with the design of an AMTS for year-round operation on the Baltic Sea.

The paper concludes that the required model fidelity to estimate the transport capacity of an AMTS is case specific. Generally, Case A appear to require a higher model fidelity than Case B. Specifically, in Case A it appears necessary to consider individual ridges in terms of their shape and size as well as their distance to adjacent ridges. In addition, it appears necessary to consider day-specific ice conditions. In Case B, on the other hand, it appears sufficient to consider average ice ridging characteristics and month-specific ice conditions. These findings are significant, because whether to consider individual ridges, and whether to consider day-specific ice conditions, have a significant effect of the required modelling effort and simulation time. With regards to the required model fidelity for the assessment of ice-loading, because ice loads are assumed to be logarithmic and dependent only on the average distance travelled in various ice conditions, the required model fidelity is independent of the case and lower or equal to what is required for the estimation of the operational performance.

By reviewing publically available sources looking for conflicting information, the study identified a range of possible uncertainties that can be divided into three categories: (1) uncertainties in parameters describing the prevailing operating conditions, (2) uncertainty in applied design tools and assumptions, and (3) uncertainty caused by potential long term trends (e.g. climate change). With regards to the estimated 100-year maximum transit time, the paper concludes that Case A is generally

more sensitive towards possible uncertainties than Case B. The 100-year maximum transit time of Case A proved to be the most sensitive towards possible uncertainties in the assumed H_r/H_s -ratio (37 %⁵), the definition of H_{eq} (31 %⁵), the assumed month and leg-specific average level ice thickness (28 %⁵), and the assumed month-and leg-specific average ice coverage (20 %⁵), the average ridge density (13 %⁵), the average slope angle (10 %⁵). The 100-year maximum transit time of Case B, on the other hand, proved to be the most sensitive towards variations in the modelling of the IB waiting time (9 %⁵) and the definition of H_{eq} (6 %⁵). With regards to the estimated ice loading, both cases appear robust towards uncertainties, with the exception for possible uncertainties in the empirically determined area and ice conditions specific C and D coefficients required for the application of the probabilistic ice load tool presented in section 1.5.3.



Figure 16: Variations in H_{ea} vs. relative variations in ship speed.

The paper suggests that the reason for the differences in the sensitivity to uncertainties with respect to the estimated maximum transit time is that, due to more difficult ice conditions, the ship of Case B generally operate at a lower range of their h-v curves than the ships of Case A. Consequently, as demonstrated in Fig. 16, any variation in the estimated ice conditions results in a larger relative change in ship speed and transit time.

The paper concludes that in both case studies, it is feasible to mitigate the consequences of uncertainties affecting the estimated operational performance, i.e., the estimated transit time, either by reserve ship payload capacity, or by reserve ship speed. However, in Case A, based on the assumption that any increase in payload capacity requires an increase in fleet size, it appears to be more advantageous to mitigate uncertainty by reserve ship speed. This is demonstrated in Fig. 17, accordance to which mitigation by reserve payload capacity would require an increase in the fleet size by 1-2 vessels, whereas mitigation by reserve ship speed requires an increase in ship speed in 2.1 m ice thickness by 5-12 %. With regards to the mitigation of uncertainty in terms of the estimated maximum ice loading, the paper does not propose any specific solution, but emphasises the need for additional area- and ice-condition-specific *C* and *D* values to reduce uncertainty in the applied values.

To sum up, in response to RQ 3 and RQ 4, the required model fidelity for the conceptual design of an AMTS, and the sensitivity to possible design uncertainties, are case specific as they depend on the ice conditions and the ice-going capability of the ship(s) in question. Because the sensitivity to uncertainties is high for ships operating at the limit of their ice-going capability, the proposed method is best suited for ships operating with some level of margin with regards to their ice-going capability (e.g. so that their speed generally does not drop below approx. 3 knots). For the assessment of the level of ice-loading that arctic ships are exposed to, i.e. for the determination of the required level of ice-strengthening, the required model fidelity is equal or lower to that required for the assessment of the operational performance, and the outcome is mainly sensitive to variations in the applied ice

⁵ Percentage deviation between the values obtained using the least and the most conservative parameter definition.

conditions specific C and D values. In addition to addressing RQ 3-4, by applying the proposed design framework for the design of an AMTS for operation on the Baltic Sea, the paper provides, a further example of how the framework can be applied to enable better informed design decisions.



Figure 17: Example of a comparison of various design risk mitigation strategies.

4. Discussion

4.1. Original contributions

This thesis presents an original proposal for how to apply the goal/risk-based regulations of the Polar Code, and for how to integrate those regulations into a holistic design process. This includes the determination of appropriate design procedures, proposal of appropriate design tools, approaches, and data sources, and examples of how they should be applied. Naturally, the method does not have to be applied exactly as proposed by the author. Instead, it should be considered as a way of thinking. As such, it should be applicable and relevant for a large variety of design tasks.

Because the operating conditions and operations of an AMTS are very complex, model simplifications are necessary, both to make the method time-efficient, and to make it transparent and comprehensible for the all concerned stakeholders. To help designers to find an appropriate level of model fidelity, the thesis presents a systematic assessment of the required level of model fidelity for the conceptual design of arctic ships. The author is not aware of any other similar assessment.

Design uncertainties are inevitable when designing an AMTS. However, they can nevertheless be understood and managed. To this end, the thesis provides an original overview of various possible sources of design uncertainties as well as a sensitivity analysis with regards to how they could affect the estimated transport capacity and ice loading of arctic ships.

4.2. Limitations

The method appears mainly suited for the design of arctic ships operating along a single, or a set of, fixed ice-infested routes. In particular, the method appears suitable for the design of ships for industrial shipping where the ship is an integrated part of a wider industry operation and the shipping risk is taken by the cargo owner. However, elements of the method, especially the possibility to determine operational data, are relevant for the design of any ship operating in ice-infested waters. The method does not appear relevant for the design of ships operating in ice-free arctic waters such as along the northern cost of Norway, where other than sea ice related challenges are dominating.

Limitations and weaknesses of the method include the following:

- The method is not able to consider the effect of actions taken by the crew to avoid areas with particularly difficult ice conditions, potentially reducing both a ship's transit time and its ice loading. Naturally, the exclusion of such measures results in increased design conservatism.
- The proposed design process does not apply (and does not appear well-suited for), any mathematical optimization algorithm. Due to complexity of an AMTS and its many nonlinear behaviours, the author does also not advocate a more mathematical optimization model. For the design of separate ship systems, on the other hand, optimization is justified.
- The design model is not well suited to deal with ship's getting stuck in ice. Based on the available ice models, data, as well as an assumed ridge penetration capability of a ship, the applied model is able to estimate the probability of a ship getting stopped by a large ridge. However, once a ship has got stopped, the model is not able to estimate the time it takes until the ship can continue its voyage (e.g. the time it takes for the ship to repeatedly ram a ridge until it gets through, or to wait for IB assistance).
- The design model is not able to simulate the time it takes for an available IB to reach a ship in need of IB assistance. Modelling of that time would require an in-depth understanding and

detailed modelling of how IBs operate (e.g. how they determine what ship is to be assisted first considering a multitude of factors, such as the location and route of other IBs and ships).

- When a ship rams an ice ridge exceeding its ridge penetration capability, the ship will get stopped. However, the ship will always penetrate a part of the ridge by its inertia, reducing the distance that it needs to cover by ice milling (in the case of double acting ships). Because the model is not able to simulate the distance a ship penetrates into a ridge on its first ram, the ship is assumed to have to penetrate the whole ridge by ice milling. This adds to the conservatism of the estimated transit time.
 - The design model is not able to consider the effect of ice movements (e.g. caused by sea currents or wind) resulting in compressive ice, and or in the closing or dislocation of ice channels.

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5. Conclusions and recommendations for future work

5.1. Concluding remarks

This thesis proposes a method for the conceptual design of arctic ships. In order to be compatible with the Polar Code, and to enable a full utilization of its goal/risk-based regulatory system, the method makes use of system thinking and the technique of DES. With regards to the application of the Polar Code, system thinking provides two main benefits. First, it makes it both possible to treat an arctic ship as a part of a wider AMTS. In the pursuit of meeting FR determined by the Polar Code, this makes it possible to extend the boundaries of the design process beyond the individual ship and to for instance consider the effect of IBs. Second, it makes it possible to apply GBD/RBD where feasible and justified, and to use PBD where not. The use of DES, in turn, supports the application of the Polar Code by making it possible to replace missing empirical operational data, needed for the design of various ship-level systems, with simulated data.

In response to RQ 1, the study concludes that application of the goal/risk-based regulations of the Polar Code is limited by a number of knowledge, data, and regulatory gaps. First, there is no method for the assessment of the total safety and environmental risks of an AMTS, preventing a truly holistic design approach considering for instance IBs, SAR resources, and oil spill response resources. The lack of such methods means that it is necessary to approve each system individually. This in turn means that the primary regulations need to be either prescriptive or goal-based, and that RBD can only be applied in accordance with the principle of safety equivalency. Second, in case of the hull protection system (ship structure), the application of GBD is challenged by the lack of agreed-on performance measures and criteria. To fill this regulatory gap, the study proposes the determination of a maximum acceptable damage frequency determined in terms of the minimum accepted return period of ice loads corresponding to the plastic limit load of a ship's structure. Third, in the case of the propulsion machinery and steering unit protection system, the application of GBD/RBD is not feasible both due to the lack of a sufficiently accurate and detailed performance assessment method, and due to the lack of agreed-on performance measures and criteria. As acceptance criteria, as for the hull protection system, the study proposes the determination of a maximum acceptable damage frequency.

The use of system thinking and DES-based Monte Carlo simulations do not only support the application of the Polar Code, but also a holistic design approach considering operational requirements, as well as cost-efficiency and robustness. In terms of operational performance, system thinking in combination with DES makes it possible to estimate the operational performance of an AMTS considering IBs, other ships, and port-based storage. For instance, as demonstrated by case studies, the consideration of port-based storages might have a significant effect on the required fleet parameters to meet the transport task. In addition to estimating the operational performance of an AMTS, the use of DES makes it possible to determine various operational data relevant for the assessment of the cost-efficiency and robustness, supporting the search for a cost-efficient and robust solution. For instance, as demonstrated by case studies, despite high IB tariffs, the use of IB assisted ships might provide a higher total cost-efficiency than the use of independently operating ships. Based on the above, in response to RQ 2, the study concludes that it is justified to treat the ship as a part of an AMTS, and to integrate DES-based Monte Carlo simulations into the design process.

Because the method is to be used in the conceptual design phase, it is important that it is time- and resource-efficient, while still being sufficiently accurate. To this end, it is necessary to determine an appropriate level of model fidelity. In response to RQ 3, the study concludes that the required level

of model fidelity for the determination of operational performance is case specific, depending on the operating conditions and the ice-going capability of a ship. Generally, the closer a ship operate to its maximum ice-going capability, the higher model fidelity is required. With regard to the estimation of ice loading, the required model fidelity is independent of the design case and lower or equal to what is required for the estimation of the operational performance.

The outcome of the proposed design method is inevitably affected by some degree of design uncertainty caused by knowledge and data gaps. Both uncertainties affecting the estimated operational performance, and uncertainties affecting the estimated ice loads were analysed. In response to RQ 4, the study concludes the following. First, the effect of uncertainties affecting the operational performance is case specific, depending both on the operating conditions and the icegoing capability of a ship. Generally, the closer a ship operate its maximum ice-going capability, the higher the influence of uncertainties. This is because, for a ship operating at the lower end of its h-vcurve, uncertainties have a larger relative effect on its speed. Significant sources of uncertainties affecting the operational performance include the estimated ridge draft, the definition of H_{eq} , the definition of the (average) level ice thickness, as well as the modelling of IB waiting times. Second, with regards to uncertainties affecting the estimated level of ice-loading, the study concludes that the most significant sources of uncertainty are the assumed ice-conditions specific coefficient, i.e., the C and D values needed for the application of the probabilistic ice load tool presented in section 2.5.3. As demonstrated by the case studies, uncertainties affecting the operational performance can be efficiently mitigated by reserve ship payload capacity, by reserve ship speed, or by reserve port-based storage capacity. For the mitigation of uncertainties affecting the estimated level of ice-loading, the paper does not propose any specific measures, but emphasizes the need for more empirical ice load data based on which to determine C and D values for additional types of ice conditions.

5.2. Recommendations for future work

To advance the design of the hull protection system (ship structure), the following is recommended:

- Determination of relevant performance measures and criteria.
- Determination of additional *C* and *D* coefficients, both for additional sea area (e.g. the Baltic Sea) and for additional operating modes (e.g. operation with IB assistance).
- A further development of the probabilistic ice load tool to allowing it to estimate the "cumulated" ice loading based on operations in different ice conditions. The current version of the tool is limited to the estimation of the maximum ice loading related to the exposure to a single ice condition.
- A further development of the probabilistic ice load tool to make it able to, in addition to estimating the ice-loading acting on the bow area, estimate ice-loading acting on additional parts of the hull (e.g. the aft sides).
- Measures to increase the general understanding of the ship-ice interaction process towards a theoretical ship hull ice load model.

To advance the design of the propulsion and steering unit protection system, the following is recommended:

- Development of a sufficiently detailed ice-propeller model.
- Determination of relevant performance measure and criteria.
- Determination of full-scale propeller ice loads measurements for the validation of future icepropeller models.

To advance the modelling of a ships transit through ice, the following is recommended:

- Clarification of the determination of H_{eq} .
- Determination of additional ice data, for instance on how ice ridging characteristic develops throughout an ice season.
- Determination of a method for the consideration of the effect of compressive ice on a ships transit time.
- Measures to increase the general understanding of the ship-ice interaction process to enable a theoretical ship ice resistance model.
- Measures to increase knowledge and data related to the modelling of IB waiting times.
- Development of an approach for the estimation of the influence of active measures (e.g. the avoidance of areas with difficult ice conditions) on a ship's transit time. To be able to consider such measures, without having to significantly increase the model fidelity, the potential to increase ship speed by active measures could perhaps be considered in the determination of H_{eq} . For instance, if a low ice coverage allows the ship to steer away from ice floes, the potential for speed gains by active measures would be higher where the ice coverage is low.

To support the search for a cost-efficient design, an interdisciplinary effort to establish approximate relationships between a ship's level of ice strengthening, fuel costs, hull shape, and investment costs is recommended. This would for instance enable a more systematic comparison of the merits of various ice mitigation strategies and operational risk mitigation measures.

For an enhanced environmental protection, relevant environmental risk performance measures and criteria need to be agreed on. In addition, a method for relating the IMO's oil pollution index to some general environmental risk measure would be useful as it would enable the application of the principle of design equivalency on the ENVP system.

Many of the above recommendations for further work contributes towards a holistic safety and environmental risk assessment of arctic maritime operations, which should be a long-term goal for the arctic maritime industry. The author believes that, to make the assessment of the safety and environmental risks of arctic ships feasible in terms of time and resource expenditure, simplified risk models, calculating the risk based on a limited set of case specific variables (e.g. a set of design parameters plus a ship's simulated exposure to various operating conditions and areas) are needed. Established safety assessment methods such as the safety case-based approach applied within the UK offshore industry do, due to their complexity and high time and resource expenditure, not appear well-suited for the design of an individual AMTS or arctic ship.

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Appendix A: Papers

Paper 1

Bergström, M. Erikstad, S.O., & Ehlers, S., (2016). Assessment of the applicability of goal- and riskbased design on arctic sea transport systems. *Ocean Engineering*, Vol. 128, pp. 183-198.

Paper 2

Bergström, M. Erikstad, S.O., & Ehlers, S., (2016). A simulation-based probabilistic design method for arctic sea transport systems. *Journal of Marine Science and Application*, Vol. 15, pp. 349-369.

Paper 3

Bergström, M., Ehlers, S., & Erikstad, S.O., (2014). An approach towards the design of robust arctic maritime transport systems. *Maritime-Port Technology and Development*, p. 185-192, CRC Press.

Paper 4

Bergström, M. Erikstad, S.O., & Ehlers, S., (2017). The influence of model fidelity and uncertainties in the conceptual design of arctic maritime transport systems. Accepted for publication in *Ship Technology Research – Schiffstechnik*.

Paper 1

Bergström, M. Erikstad, S.O., & Ehlers, S., (2016). Assessment of the applicability of goal- and riskbased design on arctic sea transport systems. *Ocean Engineering*, Vol. 128, pp. 183-198. Ocean Engineering 128 (2016) 183-198

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Assessment of the applicability of goal- and risk-based design on Arctic sea transport systems



OCEAN

Martin Bergström^{a,*}, Stein Ove Erikstad^a, Sören Ehlers^b

^a Norwegian University of Science and Technology, Department of Marine Technology, 7491 Trondheim, Norway
 ^b Technical University of Hamburg, Department of Ship Structural Design and Analysis, D-21073 Hamburg, Germany

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ABSTRACT

This paper proposes a framework for holistic goal- and risk-based design (GBD/RBD) of arctic maritime transport systems (AMTS). In order to best utilize the principles of GBD/RBD, the framework treats an AMTS as a hierarchy of subsystems. Each subsystem performs a specific function and can be designed separately. As a result, it possible to apply GBD/RBD where appropriate and feasible, and to use other methods where not. In addition, the applied system thinking makes it possible to extend the boundaries of the design process beyond the individual ship, making it possible to consider the performance of an AMTS as a whole. In order to assess the stochastic performance of an AMTS, and to produce the operational data required for the design of its individual ships, the framework integrates simulations and probabilistic assessments into the design process. To further extend the applicability of the framework, a number of knowledge gaps (e.g. an incomplete understanding of the ship-ice interaction), data gaps (e.g. a lack of performance), and regulatory gaps (e.g. a lack of performance measures and criteria for some ship functions) need to be addressed.

1. Introduction

Shipping in Arctic waters requires Arctic cargo ships, i.e. ships that are designed and built to withstand Arctic specific hazards such as sea ice and extreme weather conditions. An individual Arctic cargo ship can be considered a component of an Arctic Maritime Transport System (AMTS) that might include multiple Arctic cargo ships, icebreakers (IBs), and port based-based facilities such as cargo storages. An AMTS can be used for various types of operations including intra-arctic shipping (operation between Arctic ports), destination-arctic shipping (operation between Arctic and non-arctic ports), and trans-arctic shipping (operation between non-arctic ports through Arctic waters). In the case of intra- and destination-arctic shipping, it might form a vital transport line for the Arctic location that it serves. In the case of trans-arctic shipping, it might provide significant savings in terms of transport costs and time.

Traditionally, safety and environmental risks of Arctic ships are managed by empirically determined prescriptive rules, which often in great detail define the required means of achieving safety objectives (RINA, 2010). This approach, which in the following is referred to as prescriptive design (PD), has remained the standard for risk management of ships thanks to its many strengths such as quick and straightforward application and monitoring of compliance. However, the approach does have a number of fundamental weaknesses including the following. First, due to the short history of artic shipping, in particular with large ships, there is a lack of relevant empirical data based on which to determine rules to mitigate Arctic specific hazards such as ice loads (LR, 2015). Second, the prescriptive rules might act as design constraints hampering innovation and design optimization (Papanikolaou, 2009). Third, the rules generally do not relate to any specific level of risk, i.e., the level of risk associated with a design designed in accordance with the rules remains unknown (Papanikolaou, 2009).

Faced with the above listed weaknesses of PD, the Arctic shipbuilding industry is leaning towards Goal-Based Design (GBD). GBD is a general term for design methods determining design requirements in the function space in terms of functional requirements (FRs). FRs determine the level of functional performance that the system should provide to meet the objectives (e.g. safety objectives), but not the means by which that performance is to be achieved (IMO, 2006a). This gives the designer the freedom to apply any solution that provides the required function, supporting innovative designs and design optimization (Papanikolaou, 2009). In addition, because the designer is free to apply first-principle methods to demonstrate that a design meets a specific FR, GBD reduces or eliminates the dependency on empirical data. Furthermore, by applying a sub-class of GBD known as Risk-

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^{*} Corresponding author. E-mail address: martin.bergstrom@ntnu.no (M. Bergström).

Based Design (RBD), in which FRs are determined in terms of the maximum acceptable level of risk, it becomes possible to quantify the acceptable level of risk, and to apply risk assessments to demonstrate that risk criteria have been met. On the downside, GBD/RBD might result in a time consuming and costly design process as the designer has to carry out performance assessments to demonstrate compliance with FRs. Another weakness of GBD/RBD is the risk of bad design decisions caused by faulty or inaccurate performance assessments models.

General prerequisites for GBD/RBD include a regulatory system that enables goal- and risk-based approval as well as the ability to demonstrate through performance assessments that all the relevant FRs have been met. The performance of a design is assessed by either empirical or theoretical performance assessment methods. By empirical performance assessment methods, we mean methods that are based on design specific experience and whose applicability therefore is limited to designs of a specific size range and type. By theoretical performance assessment methods, we mean methods that are independent of design specific experience, and that therefore are applicable on any types of design. Empirical assessment of performance measures requires a significant amount of relevant experimental data, i.e. operational experience of ships whose design and operational conditions are similar to the design and operational condition of the system that is being designed. Theoretical assessment, on the other hand, requires relevant input data and knowledge based on which relevant performance assessment models can be determined.

In the anticipation of the upcoming Polar Code, which is fundamentally goal-based, the topic of GBD/RBD has been under active discussion. However, what we are missing from the discussion are practical aspects on how this new design and regulatory approach is to be applied in practise. For instance, it appears like GBD/RBD is discussed solely in connection with the mitigation of safety and environmental risks. However, in order to be able to utilize the full potential of GBD/RBD when designing an AMTS, we think it is, if not necessary, at least motivated, to integrate the method into a holistic design process also considering operational aspects. In addition to the matter of application, we are missing a practical discussion regarding the prerequisites for GBD/RBD. For instance, we think it is necessary to discuss and specify what relevant well-proven performance assessment methods and data are available and what are missing.

In the present paper we aim to contribute to the discussion by addressing the above presented topics summarized in the following questions: 1. How to best utilize the principles of GBD/RBD when designing an AMTS? 2. What potential knowledge, data, and regulatory gaps need to be addressed to increase the applicability of GBD/RBD?

The first research question is addressed by determining a design process model that allows the full utilization of the principles of GBD/ RBD, and by looking into how each step of that design process could be carried out. The second research question is addressed in parallel with the first by identifying, for each design step, the required, available, and missing performance assessment tools, methods, and data.

The paper is organized as follows. First, we define and discuss the applied terminology. Second, we provide a brief overview of the current application of goal- and risk- based approaches in shipbuilding and other industries. Third, we determine a process model for the application of GBD/RBD on AMTSs. Forth, following the outlined process model, we analyse the availability of relevant design methods, data and regulations. Fifth, we discuss the outcome of the study and draw conclusions.

2. Terminology

2.1. Prescriptive vs. goal- and risk based rules

It could be argued that all mandatory rules and regulations are prescriptive. Anyhow, in the present paper we choose, in accordance with established practise applied by Papanikolaou (2009), BIMCO (2014), and IACS (2011) among others, to differentiate between prescriptive rules and goal-and risk-based rules. We use the term 'prescriptive rules' as name for the specific types of rules that prescribe a specific solution to meet the objective (e.g. the minimum required plate thickness to achieve the safety objective). Alternative names for prescriptive rules include deterministic rules (i.e. rules that require a specific solution assumed to provide a specific deterministic performance), and specification rules (i.e. rules that specify the required solution).

We use the term goal-based rule as name for rules determining the required function and performance to meet the objective in terms of a deterministic FR (e.g. in order to meet safety objectives, the maximum evacuation time is 10 min), whereas we use the term risk-based rule as name for rules determining the required function and performance to meet the objective in terms of a probabilistic FR (e.g. the maximum accepted individual risk is 10^{-3}). Alternative names for goal- and risk-based rules include performance-based rules and probabilistic rules, respectively.

2.2. The concept of risk

We define risk in accordance with Eq. (1) as a positive or negative effect of uncertainty on objectives (ISO, 2009).

$$Risk = \sum (L_i C_i)$$
(1)

where L_i determines the likelihood of all plausible risk events and C_i determines the related consequences. A risk event is the occurrence or change of a particular set of circumstances resulting in a specific consequence (ISO, 2009). The likelihood is the chance of a risk event happening, which can be quantified either qualitatively or quantitatively (mathematically) based on historical data, theoretical forecasts, risk models (e.g. fault trees, event trees, Monte Carlo simulations), or expert opinion (ISO, 2009).

Risks are managed by active and or passive risk prevention and mitigation measures. Active measures consist of measures taken by the crew and are therefore achieved mainly by training and procedures. Passive measures, on the other hand, are achieved by hardware, i.e., by design and equipment.

An AMTS is subject to a variety of different types of risk that we classify as follows:

- 1. *Operational risk*: the risk of failure to meet the transport task. The opposite, i.e., the probability of meeting the transport task is referred to as operational reliability. The sum of the operational risk and the operational reliability is thereby 100%.
- Safety risk: the risk of loss of life or injury. IMO (2000) further divide safety risks into individual risk, which is the likelihood of death or serious injury to an individual person, and societal risk, which is the likelihood of death or serious injury to a large number of people.
- 3. Environmental risk: the risk of environmental damage.
- 4. Financial risk: the risk of financial loss or less-than-expected returns.

It should be pointed out that the quantification of risk in accordance with Eq. (1) requires the quantification of both the likelihood and the consequence(s) of a risk event. However, there are risk events whose likelihood or consequence is difficult to quantify. Because of this, it is sometimes necessary to measure risk just by its likelihood or by its consequences.

3. Overview of the current application of goal- and riskbased approaches in shipbuilding and other industries

3.1. Introduction

The application of goal-and risk based design approaches is wellestablished in numerous industries including nuclear, aerospace, offshore, and the maritime (Papanikolaou, 2009). With regards to the objectives of the present study, it is motivated to examine some of these applications. In specific, we choose to examine the application within the UK offshore industry, the Norwegian offshore industry, and the international maritime industry. The UK offshore industry is of interest because it has given rise to several widely used concepts including the safety case and the principle of as As Low As Reasonably Applicable (ALARP). The Norwegian offshore industry, on the other hand, is interesting because of its "self-regulatory" approach. Naturally, current applications within the maritime industry are also of interest.

3.2. UK offshore industry

Safety and environmental risks in the UK offshore industry are regulated by the Health and Safety Executive (HSE). The regulatory system is based on so-called 'safety cases', an approach that originates in the UK but which is nowadays applied in multiple countries to regulate risks associated with offshore activities (Bureau Veritas, 2016). In short, the objective of a safety case is to ensure an adequate level of safety for a particular installation (HSE, 2006a). In order to achieve this objective, the safety case approach is based on the principle that those who create the risk must also manage it (Bureau Veritas, ,2016).

Because the safety case is mandatory, operators cannot start or, after a major modification, continue their operations without an approved safety case (Bureau Veritas, 2016). Once approved, a safety case must be reviewed at least every 5 years (HSE, 2006c). For a safety case to be accepted, it must include a detailed description of the installation itself as well as of its operation and operational environment. Based on this description, the safety case must identify and assess related risks, and describe how these are controlled (e.g. in terms of emergency procedures and systems) (HSE, 2006b).

The main purpose of the risk assessment is to identify and rank the risks so that they can be adequately managed (Bureau Veritas, 2016). In accordance with HSE (2006b), there are three levels of risk assessment: 1. Qualitative, 2. Semi-qualitative, 3. Quantified. Quantitative assessments are mainly to be used to assess risks that potentially need to be reduced, whereas qualitative and semi-qualitative assessments are appropriate for screening for hazards that need to analysed in greater detail, i.e. to find the hazards that needs to be assessed quantitatively (HSE, 2006b).

Naturally, when accessing risks, the estimation of frequencies of risk events is central. In the UK offshore industry, frequencies are either determined in accordance with standardised numbers, which are usually based on generic data, or in the case of uncertainty, based on conservative assumptions (HSE, 2006b). If the use of conservative assumptions complicates the approval, a reduction in conservatism can be accepted on the condition that it can be demonstrated by a quantitative assessment that the level of risk is acceptable (HSE, 2006b).

Detailed requirements and risk acceptance criteria for various types of risks are set by related regulations (e.g. The offshore installations (prevention of fire and explosion, emergency response) regulations 1995, Offshore Installations and Wells (Design and Construction, etc.) Regulations 1996) (HSE, 2006b). Many of the requirements within these regulations are qualified by phrases such as so far as it is reasonably practicable (SFAIRP) or as low as reasonably practical (ALARP). In accordance with the ALARP, risks are quantified as broadly acceptable, tolerable, and unacceptable (HSE, 2006b). Any tolerable risks, including all risk levels between broadly acceptable and unacceptable, must be reduced until the effort to achieve a further reduction is deemed to be "grossly disproportionate" to the benefits gained (HSE, 2006b). In accordance with HSE (2006b), this means in practise that measures that saves a life over the lifetime of an installation costing less than £1,000,000 should be implemented, while measures that costs more than £1,000,000 are not justified (HSE, 2006a). Determining whether risks have been reduced in accordance with ALARP involves thereby an assessment of the risk to be avoided, and an assessment of the sacrifice (costs) involved in taking measures to avoid that risk, and a comparison of the two (HSE, 2006b). When applying a "standardized" solution, ALARP status can be achieved simply by demonstrating that "good practise" is applied (HSE, 2006a). Generally, good practise equals an established well-proved solution. Any new solution that deviates from "good practise" can be accepted if it can be demonstrated that the risks related to the new solution are no greater than those related to "good practise" (HSE, 2006b).

3.2.1. Norwegian offshore industry

Safety and environmental risks within the Norwegian offshore industry are regulated by the Petroleum Safety Authority (PSA). Key regulations include the health, safety and the environment (HSE) regulations as well as the working environment regulations (PSA, 2016a), determining a combination of prescriptive and goal-based rules. What is notable in the Norwegian system is that the authority does not approve any specific solution, meaning that the responsibly for meeting the rules rests with the operator itself (PSA, 2016a). However, the authority does act on situations that are considered unacceptable (PSA, 2016b). The motivation for this approach, which by Papanikolaou (2009) is referred to as self-regulatory, is to avoid a situation where the operator transfers his responsibility in terms of risk management to the authority (PSA, 2016b). Instead of approval, compliance is achieved through a combination of audits, verifications, investigations, meetings, and surveys by the PSA (Morgan et al., 2010).

The regulations by the PSA determine both prescriptive and goalbased rules. However, according to PSA (2016b), the use of prescriptive rules is decreasing because they have been found to work against the aim of the self-regulatory system, i.e. to prevent operators from transferring responsibility to the authority. According to Morgan et al. (2010), an increase in the use of goal-based rules has resulted in a more cooperative relationship between operators and the authorities, resulting in improved safety and environmental protection.

In contrary to the UK system, the Norwegian regulatory system does not apply safety cases. However, the extent of the information to be provided to the regulator is similar to that required for a safety case (Morgan et al., 2010). Neither does the Norwegian system apply the concept of ALARP. However, there is an equivalent concept expressed in section 11 of the HSE regulations: "In reducing the risk, the responsible party shall choose the technical, operational or organisational solutions that, according to an individual and overall evaluation of the potential harm and present and future use, offer the best results, provided the costs are not significantly disproportionate to the risk reduction achieved" (PSA, 2016a).

Following the principle of self-regulation, operators are obliged to determine their own acceptance criteria for various types of risks including safety risks, the risk of loss of main safety functions, environmental risks, and the risk of damage to third party (Morgan et al., 2010). Like in the British system, qualitative and quantitative risk assessments are being used decide on risk reducing measures. In accordance with Vinnem (2014), the application of qualitative risk assessment has, despite some persistent scepticism, increased over the last decade largely due to an improved database of empirical data, which plays a central part in the assessment of the frequencies and consequences of potential hazardous events, as well as due to better computer model (e.g. for the calculation of structural loads and responses).

3.2.2. Maritime industry

Safety and environmental risks of ships are regulated by a mixture of international and national regulations that are enforced by individual flag and port states. The international rules are determined by international conventions issued by the International Maritime Organization (IMO), the most important of which are the International Convention for the Safety of Life at Sea (SOLAS), and the International Convention for the Prevention of Pollution from Ships (MARPOL). Individual flag or port states are obliged to make these rules a part of their own national law and enforce then as such (IMO, 2014c). The regulations include prescriptive as well as goal- and risk-based rules. Goal-based regulations include the concepts of probabilistic damage stability and probabilistic oil outflow performance. Risk-based approaches include the concepts of formal safety assessment, design equivalence, and ALARP (Papanikolaou, 2009). A detailed overview of how these concepts can be applied on non-arctic ships is provided by Papanikolaou (2009). It should be pointed out that currently no risk-based approach is the primary approach, i.e., any risk-based approach is an alternative to a corresponding prescriptive or goal-based approach.

4. Design process

4.1. Background

Based on the above analysis of the regulatory systems applied in the UK and the Norwegian offshore industries, we are convinced that neither is appropriate for the design and approval of an AMTS.

The safety case based approach applied in the UK offshore industry requires that a safety case is prepared and approved separately for each individual offshore installation. For an offshore installation, the significant cost and use of time related to this practise is acceptable in relation to the size of the investment and the length of its expected life time. However, applied on ships, the costs and time consumption related to the preparation of a safety case for individual maritime operations would be proportionally higher, and probably unacceptable, not in the least because the shipping industry is characterized by a high competition and low profit margins. In addition, because ships, in contrary to offshore installations, are not stationary and might engage in various types of operations, we assume that the application of the principle of ALARP on ships is more challenging, in particular considering the general lack of understanding of Arctic specific hazards such as ice loads and icing.

The self-regulatory system applied within the Norwegian offshore industry requires a continuous trusting cooperation between the all the operator(s) and the authority. Due to the relatively large number of Arctic ships and ship operators, the application of such a system does not appear feasible. In addition, because Arctic shipping is generally international, a self-regulatory system would require the operator to earn the thrust and compliance of multiple authorities. Furthermore, if the ownership of a ship changes, each new owner would be required to establish a close relationship with the authorities.

With regards to the goal-and risk-based maritime regulations, including those determined by the Polar Code, we are lacking a framework within which to apply these approaches to address the Arctic specific challenges (e.g. ice loading) related to the design of an AMTS. In view of the above mentioned issues, it does not appear feasible to quantify the total operational and environmental risks of an Arctic ship with an accuracy that would be sufficient for ALARP. Therefore, we think that the use of risk-based approaches is primarily limited to the application of the principle of safety equivalence, i.e. to demonstrate that an alternative design is at least as safe as a 'standard' design determined in accordance with the relevant goal-based or prescriptive rules. Consequently, we propose a hybrid approach allowing the application of a combination of different types of rules.

In order to enable such a hybrid approach, we propose the

application of the principles of system-based ship design presented by Levander (2009). In accordance with this approach, an AMTS can be treated as a hierarchy of subsystems, where each subsystem performs a specific subtask that is integrated into the total mission of the AMTS. As the various subsystems can be designed one by one, it becomes possible to choose what type of rules and design methods to apply on each individual subsystem. Another advantage of a system-based approach is that it allows, as advocated by Hagen and Grimstad (2010), the designer to move from a ship perspective to a transport system perspective. In other words, it allows the designer to apply a holistic design approach in which an individual Arctic ship is considered as a subsystem of a wider transport system including for instance IBs and ports, enabling the optimization of the performance of the transport system as a whole.

In the following we outline the main features of the design process model, starting by determining the applied system terms. The reader should note that this chapter is limited to presentation of the design process. Challenges related to the design of the individual subsystems are dealt with in Chapter 5.

4.2. System terms

In accordance with the principles of system-based design, we divide an AMTS into a hierarchy of subsystems, where each subsystem serves a specific function that is designed to meet the overall objectives of the AMTS. Each system is defined in terms of a set of design variables that are precise characteristics of the system, controlled and determined by the designer. Any factor affecting the performance of the system that is controllable by the designer can be turned into a variable. However, for an efficient design process, it is necessary to limit the number of design variables to the most important ones considering the objectives of the design process.

Generally, a subsystem has one primary objective (e.g. to meet safety requirements) and one secondary financial objective (e.g. to minimize costs) that are determined either quantitatively or qualitatively. A system's performance is estimated by a performance prediction model. In accordance with Fig. 1, any performance prediction model is subject to some degree of internal uncertainty, e.g. due to simplifications or due to incomplete or faulty assumptions. The conditions under which a system operates are defined in terms of design parameters of which there are four main types: environmental (e.g. ice conditions), operational (e.g. waiting time for IB support), technical (e.g. steel properties), and financial (e.g. IB tariffs). As shown in Fig. 1, the design parameters might be subject to external uncertainties due to natural variability and uncertain future events. Like in the case of the design variables, it is necessary to limit the number of considered design parameters to the most important ones with respect to objectives of the design process. The boundaries of the design space are determined by design constraints. In accordance with Fig. 1, design constrains consist of either physical limit values (bounds) determined in the form space, or of mandatory FRs determined in the function space. Various types of constraints include operational constraints determined by the transport task (e.g. maximum feasible ship size), technical constraints determined by the limits of technical feasibility (e.g. maximum feasible ship size), and regulatory constraints determined by rules and regulations.

The adequacy of a design is evaluated by comparing its estimated performance with performance criteria consisting of quantitative performance goals or requirements (IMO, 2006a). In accordance with Fig. 1, the performance criterion $P_{criterion}$ depends both on the required performance $P_{required}$ and the desired performance $P_{desired}$. The required performance $P_{required}$ is determined based on mandatory FRs, whereas the desired performance with Fig. 1, mandatory FRs are either determined based on rules and requirements, or based on the system objectives. Conditional FRs, on the other hand, are determined solely based on the



Fig. 1. Relationship between various subsystem factors.

system objectives (e.g. to minimize costs). FRs are determined either quantitatively (e.g. the evacuation time must be maximum 10 min), or qualitatively (e.g. ships shall have sufficient stability in intact conditions when subject to ice accretion). Thus, a performance criterion is either determined directly based on the FR, or based on a qualitative expression of its intent.

Conditional FRs should be met as long as there is there is no conflict between them and the mandatory FRs. Thus, mathematically $P_{criterion}$ is determined in accordance with Eq. (2), where it is assumed that the performance is viewed as positive by the regulators.

$$P_{criterion} = max \{P_{desired}, P_{required}\}$$
 (2)

In the case $P_{criterion}$ equals $P_{desired}$, the criterion is a goal, whereas in the case $P_{criterion}$ equals $P_{required}$, the criterion is an absolute requirement. A system whose performance deviates from a goal might still be feasible. If the goal is exceeded, there might be a reward, if the goal is not achieved, there will be a penalty. An absolute requirement, on the other hand, must be met to make the design feasible. However, some "absolute" performance requirements determined by mandatory FRs can be treated as goals; the rules might allow for a compensation of possible deviations from the criteria by for instance increasing the performance of another system or by adjusting the operational limits of the ship (IMO, 2014a).

For some systems, it is neither necessary nor motivated to determine specific performance criteria. In such cases, the design variables are determined directly based on the system objective(s) (e.g. to minimize the fuel consumption).

4.3. Design process context

In accordance with Fig. 2, the design process starts by determining the context of the design process. This includes the determination of the value proposition, mission, and operating conditions of the transport system. The value proposition should provide a description of the desired characteristics of the AMTS in terms of for instance reliability, cost-efficiency, environmental friendliness, and safety. The mission describes the transport task in terms of the loading and unloading ports, type of cargo, and transport demand. The operating conditions are determined in terms of a rough description of the environmental conditions (e.g. ice conditions) along the route and the rules and regulations to follow.

4.4. Concepts of operations

Once the design context has been determined, the design process proceeds in accordance with Fig. 2 by determining various Concepts of Operations (CONOPS) describing how the AMTS will operate to achieve its objectives. Thus, each CONOPS needs to determine how to deal with various issues including the following:

- 1. How to deal with sea ice? Bergström et al. (2014) propose various Ice Mitigation Strategies (IMS) including the following:
- 1. Use of ships with a high ice-going capability that are able to operate independently year-round.
- Use of ships with a medium ice-going capability that make use of IB assistance during periods of difficult ice conditions.
- Use of ships with a low ice-going capability. Avoidance of difficult ice conditions by limiting the operation to periods and areas with little or no ice.
- 1. How to compose the fleet? Possible Fleet Composition Strategies (FCS) include:
- Use of multiple small or medium-sized ships to mitigate operational risks.
- 2. Use of a minimum number of large ships for maximum transport efficiency.
- How to balance the transport demand and capacity in varying operation conditions? Erikstad and Ehlers (2014) propose various Transport Capacity Adjustment Strategies (TCAS) including variants of the following:
- 1. Varying the utilization of the cargo capacity of the ships.
- 2. Varying the speed of the ships.
- 3. Varying the number of ships in operation.
- 4. Varying the utilization of the capacity of port-based storage facilities.
- 5. Backhauling during periods with overcapacity.
- 6. A combination of the above listed strategies.

Each CONOPS is developed into a preliminary conceptual design determined in terms of the number of ships as well as the cargo capacity, speed, type of propulsion system, and operational profile of each ship. The speed is determined in terms of an h-v curve that determines the speed of a ship as a function of the ice thickness. The type of propulsion system is determined in terms of the type and number of propulsion units (e.g. single or twin straight shaft propellers, single or multiple azimuth thrusters) and the type of power plant (e.g. LNG or MGO, the number of engines, type of power transmission). The operational profile determines how a ship makes use of IB support. Specifically, it determines the maximum ice thickness in which the ship



Fig. 2. Design process model for AMTSs.

operates independently. That thickness does not have to correspond to the ice-going capability of the ship because IB assistance can be used as a mean to maintain a higher speed in ice conditions in which the ship would be able to operate independently.

4.5. Determination of feasible AMTS designs

4.5.1. System division

In accordance with Fig. 2, in order to facilitate the design process, each preliminary conceptual design is broken down into a hierarchy of interlinked subsystems each of which serves a specific function.

An AMTS can be considered consisting of three main subsystems:

- An operations (OPS) system that carries out the primary function, i.e., the transport of cargo. It consists of a fleet cargo ships, as well as of ship-based systems such as buoyancy systems (ship hulls), cargo systems, and propulsion systems. In addition, it generally includes ports and IBs.
- 2. A safety system that controls safety risks. It consists of a number of ship-based safety systems including systems for hull protection, flooding mitigation, fire protection, icing protection, and evacuation. These systems might be supported by external resources such as IBs, search and rescue (SAR), and emergency ports.
- 3. An environmental protection (ENVP) system that control environmental risks. It consists primarily of a ship-based accidental discharge prevention system that might me supported by external resources such as IBs and Oil Spill Response (OSR) resources.

In accordance with this system division, an AMTS has a single OPS system that might include multiple cargo ships, each of which has its individual safety and ENVP system. The function of the OPS system is thereby not necessary dependent on an individual ship, because it might be able to meet its transport task even thou an individual ship would be out of service. For an acceptable safety and ENVP performance, on the other hand, it is essential that the performance of the safety and ENVP systems of each individual ship is sufficient.

An IB generally consists of a ship that is specially designed and built for icebreaking. However, basically any ice-going ship can provide IB assistance for another ship (IMO, 2014a). Likewise, SAR and OSR resources might consist of dedicated SAR and OSR units (e.g. SAR ships and helicopters), or of any other type of ship that is specially equipped and trained for such duties. Consequently, the designer might be able to influence the availability of such resources.

The above described system division is presented in Table 1. It should be pointed out that all the systems are required for successful operations. Thus, whether a specific system is classified as OPS, safety, or ENVP is of minor importance. The classification mainly indicates on which basis the system requirements are determined: the OPS systems are designed considering requirements set by the transport task, the safety systems are designed considering safety regulations, and the ENVP system is designed considering ENVP regulations.

4.5.2. Subsystem design

In accordance with Fig. 2, each subsystem is designed either based on design criteria, or based on a combination of design criteria and a design objective.

In the case of a system for which it is justified to specify performance criteria, the design is carried out in accordance with the following. First, the design criteria are determined based on financial and operational assessments considering both mandatory and conditional FRs. Second, a preliminary design is determined in terms of a preliminary set of design variables. Third, the performance of the preliminary design is assessed. Forth, the estimated performance is compared with the design criteria. Fifth, if the criteria are not met, the

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Table 1

General system division of an AMTS.

System level	OPS systems	Safety systems	ENVP systems
External systems	IB(s)	IB(s)	IB(s)
	Ports	SAR unit(s) Emergency port(s)	OSR unit(s)
Fleet level systems	Fleet of cargo vessels		
Ship-level systems	Buoyancy system Propulsion system Cargo system	Hull protection system Flooding mitigation system Icing protection system Evacuation system Propulsion and steering unit protection system	Accidental discharge prevention system

design variables are adjusted and the performance of the updated design is subsequently assessed. The process is repeated until a system design that meets the criteria has been found. Because the design meets the criteria determined based on financial, operational, and regulatory considerations, it represents the "best possible" design.

For some systems it might be neither necessary nor justified to determine performance criteria. For instance, when designing the hull shape, it might not be justified to determine a criterion for the resistance level. Instead, the design process should be carried out directly based on the system objective, e.g. to minimize the average hull resistance. In such cases, the design is carried out in accordance with the following. First, a number of feasible competing design alternatives, i.e., designs that meet all mandatory performance criteria, are determined. Second, a probabilistic performance assessment is carried out to compare the performances of the competing design alternatives with respect to the design objective. Third, the best performing design alternative is selected. If that design is deemed satisfying, it is selected as the final design. Otherwise a new population of alternative designs is created based on the best design of the first generation. The process is repeated until a satisfying design has been obtained.

Various subsystems are designed one by one. However, because the systems need to be integrated into the total mission of the AMTS, each subsystem needs to be designed taking possible requirements and limitations set by other systems into account. Thus, it is necessary to design the systems in a specific sequence. However, when designing an arbitrary system B, it might turn out that the performance requested by an interlinked system A cannot be achieved. In that case, the design of system A needs to be adjusted in accordance with the performance limit set by system B. Thus, the process is necessarily iterative.

Because there is a general lack of experience of Arctic shipping, the performance of an AMTS needs to be determined using theoretical performance assessment methods. Factors affecting the fidelity of theoretical performance assessments include the quantity and quality of the input data, as well as the accuracy of the applied performance assessment models. In general, the aim should be to obtain a high level of fidelity. However, a highly detailed model might hamper the search for a good solution by diverting the attention to design details of minor importance. In addition, it might result in unnecessary design costs. Thus, simplifications are necessary and justified.

Input data for a theoretical assessment consist of design parameters and constraints. The determination of design constraint is generally straightforward because they have precise and often given values. The determination of design parameters, one the other hand, might be more challenging. Parameters that are subject to uncertainty are to be determined in terms of value distributions reflecting the level of uncertainty. Thus, the type of distribution to be used is case specific. For most types of parameters, a Gaussian distribution is appropriate. The determination of a Gaussian distribution requires the determination of both the mean and the standard deviation of the parameter value. However, for many parameters, only a minimum amount of information is available. In such cases, in order to avoid having to fill out missing data, we think it is preferable to apply a distribution requiring a minimum amount of input data such as a triangular or a uniform distribution.

It should be pointed out that whether a specific system characteristic acts as a design variable, parameter, or constraint is often case specific. Turning exogenous factors into endogenous factors can turn constraints and parameters into design variables and vice versa. However, naturally there are also parameters and constraints that cannot possibly be controlled by the designer and therefore also not be turned into variables.

4.6. Assessment of the total safety and ENV risks (complete RBD only)

When carrying out a complete RBD in accordance with the principle of ALARP, once all the safety related sub-systems have been designed, the total safety and ENV risks of the design must to be assessed. The design is modified until it meets the related acceptance criteria, i.e., until it is feasible. Because the objective is to obtain an acceptable total risk level, the risk level can be managed by both passive and or active risk prevention and mitigation measures. However, in accordance with Section 4.1, we do not think it is feasible to seeks approval for an AMTS based on its total estimated safety and environmental risks.

4.7. Determination of a population of feasible designs

The procedure described in Section 4.5.2 is repeated for all subsystems of each design concepts determined in accordance with Section 4.4. As a result, a population of feasible designs is obtained.

4.8. Selection of the most promising design alternative

In order to find the most promising design alternative, a probabilistic performance assessment is carried out. This requires the determination of comparable Key Performance Indicators (KPIs) for each design alternative. A typical KPI for an AMTS is the costs per tonne of transported cargo. The transport costs depend both on stochastic environmental factors (e.g. the ice conditions) and stochastic financial factors (e.g. fuel price, maintenance costs, and IB tariffs). As a result, the costs vary from year to year. In order to find out which design results in the lowest expected or average costs, the technique of discrete event simulation in combination with the Monte Carlo method can be applied as demonstrated by Bergström et al. (2016).

4.9. Final AMTS design

Based on the determined probabilistic KPIs, the design that is deemed to have the best overall performance is selected as the final design. The following step would be to create a detailed design based on the determined parametric design. However, this topic is out of the scope of the current paper and will therefore not be further discussed.

5. System design

5.1. OPS system

As presented in Table 1, at fleet-level the OPS system consists primarily of a fleet of cargo vessels that serves at least two ports and is possibly assisted by IBs. General ship-level OPS systems include a buoyancy system, a propulsion system, and a cargo system. In the following we investigate the possibilities of applying the principles of GBD/RBD for the design of each of these systems. Specifically, we seek to determine what knowledge and data is required, and what is missing to estimate their performance.

5.1.1. Fleet of cargo vessels

The function of the fleet system is the transport of cargo in accordance with the transport task. Its main design variables are the number of cargo ships as well as the cargo capacity and ice thickness dependent speed (h-v curve) of each ship. Important parameters include the ice conditions along planned route, port turnaround time, waiting time for IB support, and convoy speed (speed with IB support). Typical design constraints include the locations of loading and unloading ports, the capacity of port-based storage facilities, port and fairway vessel size limitations, and ice class requirements.

The system's main performance measures are operational risk, operational reliability and robustness. The operational risk determines the risk of an AMTS not being able to meet its transport capacity, whereas the operational reliability determines the opposite, i.e. the likelihood that the system is able to meet its transport task. Thus, the sum of the operational risk and the operational reliability is 100%. The robustness is a measure of how sensitive the transport capacity is to variations in the operating conditions. Thus, robustness and operational reliability are strongly connected.

In accordance with the Fig. 3, the operational risk depends on a multiple of risk sources including uncertain ice conditions, uncertain IB waiting times, uncertain port-turn-around times, accidental risk events (e.g. groundings, collisions, and technical breakdowns), and model uncertainty (e.g. inaccurate performance assessment models and data). All of these risk sources can be prevented by reserve transport capacity, obtained by either reserve ship capacity or speed, or by a combination of the two. The risk caused by uncertain IB waiting times can in addition be prevented by minimizing the dependency on IB assistance (i.e. by using independently operating ships). Operational risks due to accidental events can, in addition to having a reserve capacity, be prevented by having a fleet consisting of multiple vessels so that an AMTS is able to meets its transport task even if one of its vessels would be out of service due to an accidental event. Risks due to model uncertainty are generally prevented by design conservatism.

In the case all risk prevention measures fail and the risk event occurs, i.e. the AMTS fails to meet its transport task (e.g. it fails to provide a specific transport capacity), the consequences can, depending on the type of operations, be mitigated by various means such as reserve port-based storage capacity (or by reserve stock) allowing a temporary shortage in transport capacity, or by controlling the transport demand (e.g. by stopping or reducing the production rate of an oil or gas production facility). Obviously, all of these risk prevention and mitigation measures results in additional costs. Thus, the costs for risk prevention and mitigation needs to be balanced against the costs related to the consequences of the risk event, i.e. the costs resulting from a failure to meet the transport task. Therefore, the optimal level of operational reliability is case specific as it depends on the case specific costs for risk prevention, mitigation, and consequences.

Bergström et al. (2016) presents a method that makes it is possible to assess the operational risk from non-accidental risk sources by applying a combination of the Monte Carlo method and the technique of discrete event simulation. This method makes it possible to quantify both the probability of a failure to meet the transport task (e.g. in terms of the number of occasions per year), as well as the operational consequences (e.g. the amount of cargo that was not transported in accordance with the transport task). In addition, the method makes it possible to determine various types of stochastic operational data such as a ship's annual average ice exposure (e.g. the average distance a ship operates in various ice conditions), ratio-between operation time in open water and in ice, and amount (e.g. number of hours) of IB assistance required. Such data can subsequently be utilized for the design of various ship specific subsystems such as the hull protection system, the propulsion and steering unit protection system, and the buoyancy system. Using the simulation model, it is also possible to carry out scenario-based simulations to assess the operational consequences (e.g. gap in transport capacity) of accidental events causing ship downtime. However, the simulation model is not able to calculate the probability of accidental events, which must to be estimated separately based on empirical data or based on a risk model such as a Bavesian network.

Obviously, the accuracy of the assessment depends on the accuracy of the input data and on the applied tools and methods. Of particular importance is the modelling of the ice conditions. In Arctic ship design, ice conditions are generally described in terms of various ice parameters including the ice type (e.g. first-year ice, multiyear ice), level ice thickness, ice concentration (coverage), and various ice ridging characteristics. Additional parameters might include the probability and magnitude of compressive ice.

The ice type can be determined with good accuracy based on satellite picture based ice charts. The level ice thickness and concentration can be determined based on historical data, such as on-site ice measurements, on-site temperature measurements (applied in combination with an ice-growth model), or ice charts (often based on satellite pictures). Alternatively, they can be determined based on a numerical climate/ice model. Ice ridging characteristic are generally determined based on historical on-site observations because neither satellite pictures nor numerical climate/ice models are able to capture such local ice features. We are not aware of any method for the determina-



tion of the probability or magnitude of compressive ice.

Sources of historical on-site ice and temperature measurements include Romanov (1995) and Riska (1995). Sources of historical ice charts include AARI (2016) providing ice charts for the Arctic, and SMHI (2016) providing ice charts for the Baltic Sea. A general weakness of the available on-site measurements is that the data is generally old (e.g. the data presented by Romanov (1995) is mostly from the 1970s and 1980s). In addition, the quantity of data is limited. A general weakness of ice charts, on the other hand, is that the data is quite rough (e.g. AARI (2016) determine ice prevailing ice conditions in terms of ice free, nilas (0–10 cm), young ice (10–30 cm), first-yearice (30–200 cm), or multi-year ice).

Numerical climate/ice model include for instance the Los Alamos Sea Ice Model (CICE), applied and presented by Stephenson et al. (2013), and the SINMOD climate model, presented by SINTEF (2015). A general overview of various model for the modelling of ocean environment data is provided by Bitner-Gregersen et al. (2014), which concludes that there are promising but still invalidated models for both short term (one to five days) and longer term (one to three months) ice condition forecasts. We are not in a position to assess the accuracy of existing climate/ice models. However, for instance Bergström et al. (2014) concluded that the SINMOD model appears to predict realistic ice concentration values but has a tendency to predict unrealistically high ice thicknesses.

Based on ice parameters such as the level ice thickness, ice concentration, and ridging characteristics, the prevailing ice conditions can be described in terms of a single value referred to as equivalent ice thickness. However, as pointed out by Riska (2009), there is no agreed definition of the equivalent ice thickness, indicating that there is uncertainty in terms of how to model the ice cover. As demonstrated by Bergström et al. (2015a), this can translate into significant uncertainty in terms of a ship's estimated propulsion power requirement, or in terms of the estimated transport capacity of an AMTS.

Ice parameters such as ice thickness and ridging characteristics are stochastic by nature. Thus, they are best described in terms of distributions. Naturally, different ice parameters follow different distributions. For instance, in accordance with Romanov (1995), annual variations in level ice thickness are normally distributed, whereas the spacing between ridges is exponentially distributed. As demonstrated by Bergström et al. (2016) among others, stochastic ice scenarios can be created based on stochastic ice parameters by using the Monte Carlo method.

As pointed out by Valkonen and Riska (2014), the concept of equivalent ice thicknesses is based on averaging, and fails therefore to consider the effect of individual ridges that are large enough to stop a ship. Methods for how to consider the effect of such large ridges are proposed by both Valkonen and Riska (2014) and Bergström et al. (2016). However, we assume that neither of these methods have been validated. Other knowledge and data gaps that might affect the design of the fleet system of an AMTS include the lack of a validated methods and related data for the estimation of IB waiting times and convoy speed (Bergström et al., in press). In addition, as mentioned there is no method for the consideration of compressive ice.

Naturally, the significance of various knowledge gaps is case specific. For instance, in the case of independently operating ships, neither IB waiting times nor convoy speed are relevant. Likewise, if a ship operates with a big margin in terms of ice-going capability, it is unlikely to be significantly affected by large individual ridges or compressive ice. On the other hand, if a ship operates on the limit of its ice-going capability, compressive ice and individual large ice features might cause the ship to get stuck and thereby have a very significant effect on its performance.

To sum up, there are techniques for the estimation of the operational reliability and robustness of an AMTS. However, for improved accuracy and a wider applicability, a number of gaps in the related methods and data need to be addressed.

5.1.2. Ship cargo system

The function of the cargo system is cargo handling and storage. Because the requirements on the cargo system are case specific, it is outside the scope of the present work and will therefore not be further discussed here.

5.1.3. Ship buoyancy system

The function of the buoyancy system is to provide sufficient buoyancy for the ship. Its main variables are the hull size and shape (e.g. ice or open water bow) and its most important parameters consist of ice data describing the ice conditions in which the ship operates. Constraints include ship size limitations set by ports and fairways as well as size requirements set by other ship systems such as the cargo system.

When designing the buoyancy system, the main challenge is to find an appropriate compromise between open water and ice resistance. In specific, the objective is to find a hull shape that minimizes the average resistance and thereby the total long-term (e.g. annual) fuel consumption. Towards this aim, the designer needs to consider the expected ice conditions along the planned route and their annual variations. Related data on for instance the average times a ship operates in various ice conditions and open water can, in accordance with Section 5.1.1, be retrieved from the simulation model used for the fleet design.

In search for the optimal hull shape, it is necessary to be able to determine the open water and ice resistance of a large number of alternative hull shapes. Open water resistance can be estimated either empirically based on full scale or model tests, or theoretically based on numerical methods. Like open water resistance, ice resistance can be estimated either empirically based on full-scale or model testing, or theoretically based on numerical models (von Bock und Polach and Ehlers, 2015). However, all of the available ice resistance assessment methods have significant limitations. When designing a new type of ship, the use of full-scale empirical data is generally out of the question for the simple reason that the application of full-scale data from ships of a different design might lead to misleading results (Riska, 2010). Model testing and existing numerical methods are, on the other hand, considered reliable. However, both of these methods are very costly and time consuming to apply, hampering the search for an overall energy efficient hull shape.

Model testing is the standard method for determining ice resistance because it is the least costly method providing a high level of accuracy (von Bock und Polach and Ehlers, 2015). However, since the potential to improve the efficiency of model testing is limited, an inexpensive and quick estimation of ice resistance can only be achieved by new or improved theoretical methods.

To sum up, the search for an overall fuel-efficient hull shape is mainly complicated by the lack of a time and resource efficient, simplified but still sufficiently accurate theoretical method for determining ice resistance.

5.1.4. Propulsion system

The function of the propulsion system is to provide a sufficient thrust to achieve the speed and ice-going capability required by a ship to fulfil its role in the transport system. The main design variable is the amount of propulsion power, which is limited in terms of the maximum installable amount of power. For a specific propulsion power and other characteristic of the propulsion system, the thrust can be reliably estimated based on existing theoretical and semi-empirical methods. Thus, the principles of GBD are fully applicable for the design of the system.

Nonlinear characteristics of the propulsion system, e.g. the type of power plant, type of power transmission, and type of propulsion unit(s) are determined as a part of the determination of the CONOPS at the start of the design process. These characteristics are very important as they affect properties like the fuel, maintenance, and investment costs of a ship. However, their impact on the overall performance of the ship

Table 2

Status of prerequisites for GBD/RBD of various OPS systems..

	Knowledge	Data
Fleet of cargo ships	Sufficient. A draft simulation model for the assessment of the reliability and robustness of the fleet is available. However, especially the modelling of the ice cover needs to be clarified.	Sufficient. Additional data on local ice features such as ice ridging is sought after to enable a more accurate modelling of the ice conditions.
Buoyancy system	Sufficient. A faster and more cost-efficient method for the determination of a ship's ice resistance is sought after.	Sufficient. Relevant data can be produced by simulation.
Propulsion system	Sufficient. For a given type of propulsion system, the propulsion power required to achieve a specific h-v curve can be determined theoretically.	Sufficient. The required speed characteristics (<i>h</i> -v curve) are determined as a part of the fleet design

cannot be analysed only considering the propulsion system. Instead, they need to be treated as features of a design concept that is evaluated as a whole and compared to alternative design concepts towards the end of the design process.

5.1.5. Overview of the OPS systems

An overview of the situation regarding the knowledge and data required for theoretical performance assessments of various OPS systems is presented in Table 2. It should be pointed out that classification of the available knowledge and data as sufficient or insufficient reflects the author's option.

5.2. Safety systems

5.2.1. In general

The safety of Arctic ships is to be regulated by the International Code for Ships Operating in Polar Waters, commonly referred to as the Polar Code, which is due to enter into force on 1 January 2017 (IMO, 2015). Flag and port states might impose their own additional regulations. However, the present paper is limited to the regulations set by the Polar Code.

The Polar Code, which is presented by IMO (2014a), aims to ensure the same level of safety for ships, persons and the environment in polar waters as in other waters (Kvålsvold, 2012). To this aim, it supplements the existing International Convention for the Safety of the Life at Sea (SOLAS) to account for Arctic specific safety hazards such as ice, icing, low temperatures, darkness, high latitude, remoteness, the lack of relevant crew experience, and unpredictable and severe weather conditions. Safety risks related to these hazards are addressed in terms of regulations concerning design, construction, equipment, operations, training, and SAR. The Polar Code regulates thereby both active and passive safety risk prevention and mitigation measures.

The Polar Code determines mandatory provisions in terms of goals, FRs, and regulations to meet the FRs. A ship design meets an FR either if it complies with all the regulations associated with that FR, or if part(s) or all of the design have been approved in accordance with Regulation 4 of SOLAS Chapter XIV, and any remaining parts of the ship comply with the relevant regulations (IMO, 2014a). Regulation 4 of SOLAS Chapter XIV, presented by IMO (2014b), deals with alternative design and arrangement, i.e., designs that to some degree deviate from the prescriptive requirements. It states that parts of a ship's design may deviate from the prescriptive requirements, provided that the design meets the goal and FRs concerned and provide an equivalent level of safety as a corresponding prescriptive design, i.e. a design that meet all relevant prescriptive regulations. This approach is known as safety equivalence and can be considered a variant of RBD (Papanikolaou, 2009). In order to prove the equivalence, the design needs to be analysed, evaluated, and approved in accordance with IMO guidelines. Since the safety level of a prescriptive design is unknown, it is first necessary to determine the required performance criteria. In case the performance criteria are not determined by the regulations, they have to be determined by evaluating the intended performance of a generally accepted prescriptive design (IMO, 2006a).

There are a number of open questions related to safety equivalence. For instance, Papanikolaou (2009) points out that it is unclear if it relates to individual or societal risk. In addition, it is unclear if the rules enable trade-offs between active and passive safety measures. The determination of the equivalence between passive and active measures is anyhow a particular challenge because, since risk has traditionally been regulated by passive measures, there are no established approaches for this purpose.

An alternative to safety equivalence is to carry out a complete RBD in which the total safety risk of a design is analysed. Acceptance criteria for the total safety risk are determined by the IMO in terms of the maximum acceptable individual and societal risk, separately for crew, passengers, and third parties, in accordance with the principle of As Low As Reasonably Possible (ALARP). The detailed criteria are presented by IMO (2000). Complete RBD would enable a truly holistic design optimization as it would enable trade-offs between different safety systems. Obviously, the trade-offs between for instance the safety and the ENVP systems, i.e. shortages in the safety system.

In principle, complete RBD requires the estimation of the likelihood and consequences of all possible risk events. However, in accordance with Papanikolaou (2009), in the case of passenger ships, some 90% of the safety risks come from flooding and fire related events. Assuming that this also applies for Arctic cargo ships, it would be possible to obtain a good estimate of the total risk by just addressing these two types of risk events. Anyhow, the estimation of the total risk of flooding and fire and how various active and passive risk prevention and mitigation measures as well as the operating conditions affect these risks is very challenging.

In accordance with Table 1, safety systems of an Arctic ship include a hull protection system, a flooding mitigation system, a propulsion and manoeuvring systems protection system, a fire protection system, an icing protection system, and an evacuation system. In the following, we analyse challenges related to the design of each of these systems. Specifically, for each system we seek to determine the following: (1) Does the regulations support goal- or risk-based design approval? (2) Is the available knowledge and data sufficient for GBD/RBD?

5.2.2. Hull protection system

The function of the hull protection system is to prevent flooding by protecting the buoyancy system, i.e., the hull, from structural loads (e.g. ice loads) that could lead to a loss of its watertight integrity.

Protection of the hull can be achieved by increasing the hull's structural strength and/or by limiting the structural loads that it is exposed to. The structural strength is mainly determined by the hull scantlings, whereas the ice loads can be affected by the choice of hull shape, by the means of IB assistance, and by the choice of route and operating schedule.

The Polar Code requires that a ship's structure is able to resist both global and local structural loads anticipated under the foreseen ice conditions. To comply with this requirement, the scantlings need to be determined in accordance with an International Association of Classification Societies (IACS) Polar Class (PC) standard that is sufficient for the ice conditions or another standard offering an equivalent level of safety. In total there are 7 PC standards, which are all described in IACS (2016). In accordance with IACS (2016), the required PC standard is to be determined based on the maximum ice conditions in which a ship is supposed to operate. For instance, PC 4 is

required for a ship that is expected to operate year-round in thick (> 1.2 m) first-year ice, whereas PC 5 is sufficient for a ship that is expected to operate year-round in medium thick (0.7 - 1.2 m) first-year ice.

We think that the above described approach to determining the required level of ice-strengthening has three main weaknesses. First, by selecting the required ice class based on the maximum ice conditions in which a ship is supposed to operate, the probabilistic nature of ice loading is ignored. Because ice loading is probabilistic, the maximum ice conditions in which it operates, but also on the duration the ship operates in various ice conditions. Second, as pointed out by Kim and Amdahl (2015), the PC standards are semi-empirically determined. Because the experimental data based on which the rules are determined is mostly from relatively small ships, there is a significant level of uncertainty regarding ice loads on larger ships LR (2015). Third, the PC rules do not relate to any specific safety performance measure(s) or criteria.

In order to consider the probabilistic nature of sea ice and the effect of ship speed, we propose the application of a probabilistic design method first developed by Jordaan et al. (1993), and later applied on ships operating on the Northern Sea Route (NSR) by Tons et al. (2015). Using this method, probabilistic ice loads (e.g. 100-year max load) of an Arctic ship can be estimated based on a vessels average annual ice exposure, determined in terms of the annual average distance a ship operates in various ice conditions. (e.g. thin, medium, and thick firstyear, second-year, multi-year, or brash ice). The required data can be retrieved from the simulation model used for the fleet design described in Section 5.1.1. Once the probabilistic extreme loads have been determined, they can be used as input for direct analyses (e.g. finite element method analyses) to determine the required level of ice strengthening, or to verify that a design determined in accordance with the PC rules provide a sufficient level of strength. Thus, the method is applicable on ships of any size.

The above mentioned probabilistic load method by Jordaan et al. (1993) limits the required empirical data to so-called parent distributions, i.e. distributions of full scale ice load measurements based on which the probability of a ship being exposed to a particular level of load during a specific period (e.g. one year) can be estimated. Existing parent distributions, some of which are presented by Taylor et al. (2009), cover already a wide range of sea areas and ice conditions. However, for improved accuracy and wider applicability of the method, more parent distributions are sought after, in particular for the Baltic Sea.

Using first-principle methods only, the determination of the required level of ice-strengthening for a ship would require a sufficient level of understanding of the ship-ice interaction as well as a sufficient amount of ice data. However, as pointed out by Ehlers et al. (2014), the ship-ice interaction is still not sufficiently understood. In addition, as pointed out by Riska (1995), the amount of ice data relevant for engineering applications (e.g. data on local ice features such as ridges) is limited. As a result, until these issues gave been properly addressed, we remain dependent on empirical data.

The fact that the PC rules do not relate to any specific performance measure(s) or criteria needs to be addressed by the rule-making authorities. As a first step towards goal/risk-based approval of a hull design in accordance with the principle of Safety Equivalence, the IMO needs to agree on clear safety performance measure(s) and criteria. The design load applied for the determination of the PC rules corresponds to the plastic limit load. According to Riska (2010), it has been stated that the return period of ice loads causing a structural response up to the limit is one year. However, as pointed out by LR (2014), the return period is not documented, i.e., it is not stated as an official goal. Anyhow, we think that it would make an appropriate safety measure for the hull structure. Ocean Engineering 128 (2016) 183-198

load corresponds to the damage frequency of the hull. Thus, it is not only important in terms of safety, but also in terms of costs (Kujala and Ehlers, 2014). An increase in the hull scantlings, i.e., the amount of structural steel, results in a lower damage frequency and thereby also lower maintenance and repair costs. On the other hand, it also results in higher investment and fuel costs. Thus, minimizing the total cumulated costs requires finding the optimal balance between structural strength and weight, i.e., the optimal damage frequency. If the designer determines that the financially optimal damage frequency is lower than the maximum acceptable damage frequency, the designer should aim for a design resulting in the former in accordance with Eq. (2). If the opposite is true, the designer should aim for a solution resulting in the maximum acceptable damage frequency.

5.2.3. Flooding mitigation system

The function of the flooding mitigation system is to mitigate the risk of flooding. Flooding mitigation is primarily achieved by compartmentation, i.e., by passive means. Active means include the operation of watertight doors and valves.

The natural performance measure of the flooding mitigation system would be the probability of sinking/capsizing due to flooding. However, since it would be very challenging to determine that probability considering all the contributing factors, a goal-based method known as probabilistic damage stability is used instead. In this method, a ship's degree of subdivision is quantified in terms of the subdivision index A, which is a measure of the ship's probability of surviving various flooding conditions (IMO, 2008). Different designs with the same subdivision index are considered equally safe (IMO, 2008).

The subdivision index is determined in accordance with $A=\sum (p_i s_i)$, where p_i = the probability that the compartment or group of compartments under consideration may be flooded, and s_i = the probability of survival after flooding of the compartment or group of compartments in question (IMO, 2008). The rules require that a ship's subdivision index A is not less than a specific minimum required subdivision R (IMO, 2008). In addition, specifically for Arctic ships, the Polar Code determines that the factor s_i is equal to one for all loading conditions. In other words, the ship's survival time must be infinite for all plausible flooding conditions. For each damage condition, the ships GZ curve is calculated, based on which the survivability is determined. For the calculation of the GZ curve, the Polar Code prescribes an icing allowance in terms of an assumed amount of ice accumulated on its exterior surfaces.

In order to make the determination of the factors p_i and s_i practicable, they are determined based on simplifying formulas determined based on actual statistic of casualties (MSA, 1999). The formulas make it possible to automate the calculations, making it possible to determine the subdivision index by computer. The required subdivision index R is determined by a function of the ship's length that is derived from subdivision indexes of ships whose level of damage stability is considered satisfactory (IMO, 2008). Operational aspects are not considered (Papanikolaou et al., 2009).

The main advantage of the probabilistic damage stability method is that it does not specify any prescriptive rules in the form space giving the designer the freedom to optimize the use of space with regards to for instance operational requirements. Its main weakness is that it does not relate to any specific level of safety risk. Thus, as pointed out by Papanikolaou et al. (2009), the required subdivision R is by nature prescriptive. In order to enable the application of the principle of safety equivalence, it would be necessary to determine a model relating the subdivision index to quantifiable safety risks. However, until a sufficient amount of empirical data on Arctic ships has been collected, it is questionable if it is feasible to determine such a model.

5.2.4. Propulsion machinery and steering unit protection system

It should be pointed out that the return period of the plastic limit protection sy

The function of the propulsion machinery and steering unit protection system is to prevent the risk of a ship losing its manoeuvrability due to ice damages to its propulsion machinery and or steering unit(s).

When operating in ice, a ship's propulsion and steering unit(s) are exposed to ice loads. Thus, in order to ensure that the ship remains operable, adequate protection against the anticipated ice loads is necessary. Like in the case of the hull protection system, a sufficient protection of the propulsion and steering unit(s) can be achieved by managing the structural strength of the exposed components and/or by managing the structural loads that they are exposed to. The structural strength is primarily managed passively by adjusting the scantlings of the components, whereas the structural loads are primarily managed actively by managing the ice conditions in which the vessel is operating.

Increasing the scantlings of propeller blades and shaft(s) result in lower propeller efficiency and higher initial costs. Lowering the scantlings, on the other hand, result in a higher damage frequency resulting in increased repair costs and downtime. Thus, the challenge is to find an appropriate balance between structural strength and hydrodynamic efficiency.

The Polar Code requires that the scantlings of the propeller blades, transmission line, steering equipment, and other appendages are determined in accordance with an appropriate PC or other standard offering an equivalent level of safety. However, the PC standard does not specify any specific safety performance measure or risk criteria. It is understood that the PC standard aims to result in a damage frequency that is "acceptable". Thus, we think the maximum acceptable damage frequency would be an appropriate safety performance measure.

The estimation of the damage frequency would require an icepropeller model that, based on the ice exposure and the hull shape, would be able to estimate the size and shape of the ice blocks hitting the propulsion and steering units, and the resulting ice loads. Existing icepropeller models can be divided into two groups: (1) those based on model testing, and (2) those based on inverse models utilizing empirically determined propeller shaft responses. Models belonging to the former group include ones by Veitch (1995) and Wang (2007), whereas models belonging to the latter group include ones by Browne et al. (1998), Ikonen et al. (2015) and Polić et al. (2014). However, all of these models appear to be based on rough simplification and cannot therefore be expected to provide a sufficient level of accuracy. In addition, the validation of any high-fidelity ice-propeller model would require additional full-scale ice propeller load measurements. Therefore, because both the required knowledge and data are still insufficient for the application of GBD/RBD, the system needs to be determined in accordance with the existing prescriptive ice class rules on order to achieve compliance.

5.2.5. Evacuation system

The function of the evacuation system is to provide for safe escape, evacuation and survival. In other words, in case of an emergency, the system must enable all persons on-board to escape the ship and to survive until help arrives. The system's main performance measures are time to evacuate and post-evacuation survival time. These depend both on passive measures such as escape routes, embarkation arrangements, survival crafts, and life-saving equipment, and on active measures such as of training and procedures.

SOLAS requires that the evacuation time for any cargo ship is no more than 10 min. In addition, the Polar Code requires measures to ensure that the evacuation time is not prolonged by Arctic specific challenges such as icing and snow. Regarding the post-evacuation survival time, the Polar Code requires that the survival craft, together with the required equipment, provide safe evacuation for the maximum rescue response time, which must not be less than 5 days.

The evacuation time can be estimated by simulation methods such as the ones presented by Papanikolaou et al. (2009). Thus, the principles of GBD can be applied. In order to achieve the required post-evacuation time, Arctic life-saving (e.g. life boats and rafts) equipment is required. A report on the availability of such equipment

is provided by Myland (2013).

The expected rescue response time depends on multiple factors including the distance to available SAR units, the type of available SAR units (e.g. helicopters or ships), and the environmental conditions (e.g. ice and weather conditions). We think it could be possible to determine the maximum expected response time by the means of simulation. However, we are not aware of any well-proven readily available method for this purpose and the required data (e.g. on the location and performance characteristics of available SAR units) appear incomplete. Thus, we do not think it is feasible to consider the availability of external SAR resources for instance for the purpose of applying the principle of safety equivalence.

5.2.6. Fire protection system

The function of the fire protection system is to prevent and mitigate on-board fires. Its performance depends both on passive measures such as fire zones, thermal insulation, and fire extinguishing systems, and on active measures such as training and procedures for fire prevention and protection. The system is regulated by a comprehensive set of prescriptive fire regulations determined by SOLAS that are complemented by requirements determined by the Polar Code intended to make sure that all the systems are functional in the expected Arctic conditions.

It is possible to deviate from the prescriptive rules by demonstrating safety equivalency using simulation-based approaches such as the ones described by Papanikolaou et al. (2009). In accordance with the same source, by combining fire and evacuation simulations, it is possible to assess the performance of a fire protection system in terms of safety risks. This makes it possible to compare the fire related safety risks associated with a design that meets the prescriptive rules with those of an alternative design, which in turn makes is possible to apply the principle of safety equivalence. However, it should be pointed out that this is based on the assumption that existing fire simulation models and data that are applicable on non-Arctic ships are also applicable on Arctic ships, i.e., that they are able to consider the potential effect of Arctic specific challenges such as low temperatures and icing.

5.2.7. Overview of the safety systems

An overview of the status of prerequisite requirements for applying GBD/RBD on the various safety systems is presented in Table 3. It should be pointed out that classification of the available knowledge and data as sufficient or insufficient reflects the author's option.

5.3. ENVP systems

5.3.1. In general

Environmental risks of Arctic shipping are to be regulated by the Polar Code, which is due to enter into force on 1 January 2017 supplementing the current regulations of the International Convention for the Prevention of Pollution from Ships (MARPOL). Flag and port states might impose their own additional regulations. However, the current work is limited to dealing with the regulations set by the Polar Code.

According to the Arctic Council (2009), accidental release of oil or toxic chemicals is the most serious risk to the Arctic environment. Thus, the ENVP system consists primarily of an accidental discharge prevention system.

5.3.2. Accidental discharge prevention system

The function of the accidental discharge prevention system is to prevent and mitigate discharges due to accidental damages to a ship's cargo holds.

Protection against accidental discharges is primarily achieved by structural design, i.e., by passive means. The most important environmental convention in terms of ship design, MARPOL Annex I-

Table 3

Status of prerequisites for GBD/RBD of various safety systems.

System	Knowledge	Data	Regulations
Hull protec- tion	Sufficient. Further development and validation of the proposed probabilistic ice load method is recommended for higher accuracy and confidence.	Sufficient. Additional data (parent distributions) in particular for the Baltic Sea is sought after.	Unavailable. There are no established risk measures or performance criteria for the hull protection system, making it difficult to apply the principle of safety entivalence
Propulsion machin- ery and steering unit protec- tion	Insufficient. An ice-propeller model that makes it possible to estimate the size and shape of the ice blocks hitting the system as well as the resulting ice loads	Insufficient. There is a lack of full-scale propeller ice load measurements, making the validation of any ice- propeller model difficult.	As above.
Flooding mitiga- tion	is sought after. Sufficient . There are models for the calculation of a ship's subdivision index, which is considered an adequate measure of a ship's ability to resist flooding. However, there is no model for relating the subdivision index to safety risks, making it difficult to apply the principle of safety enuivalence	Sufficient. The data applied for non-Arctic ships is assumed applicable on Arctic ships.	Available. The probabilistic damage stability method is goal- based.
Evacuation system	Sufficient. There are models for estimating the evacuation time, making the application of GBD possible. However, we are not aware of any existing models for the consideration of factors beyond the design of the individual ship (e.g. external SAR resources), limiting the application of the principle of	Sufficient. We assume that there is data based on which the performance of life saving equipment can be demonstrated. Additional data on the location and performance characteristics of available SAR units and their operating conditions is needed in order to make it possible to consider the effect of external SAR resources.	Available. The regulations are mainly goal-based.
Fire protec- tion system	safety equivalence. Sufficient. Available fire simulation models are sufficient to quantify the performance of a ship's fire safety system in terms of	Sufficient. Data required for the fire simulations is available (data from non-Arctic ships is assumed to be applicable on Arctic ships)	Available. Because the fire safety risk of various designs can be compared, approval based on safety equivalence is possible.

Regulations for the Prevention of Pollution by Oil, which is presented by IMO (1978), requires all tankers to be fitted with a double hull. In addition, it regulates the maximum allowed tank size and determines minimum required clearances between the outer shell and cargo and fuel oil tanks. The allowed tank size and required clearances are

safety risk.

determined based on formulas taking into account the size of the ship and its tanks. The Polar Code complement these requirements by specifying a minimum allowed clearance that is specific for category A and B ships.

In order to optimize the arrangement of the cargo and ballast tanks, if necessary, it is possible to deviate from the above-described prescriptive design rules by applying IMO's Probabilistic Oil Outflow Method. In this method, the performance of the discharge prevention system in limiting oil outflow is quantified in terms of a measure referred to as oil outflow performance (also referred to as pollution prevention index). An alternative design can be accepted on the conditions that its oil outflow performance is at least as good as that of a comparable standard design that complies with the prescriptive requirements. The oil outflow performance is determined based on a probabilistic approach utilizing damage statistics of real life incidents (Papanikolaou, 2009). The related calculations, which are described by IMO (2006b) are complex and extensive and therefore carried out using dedicated software tools.

A double hull structure is generally considered the most efficient type of accidental discharge prevention system. For a specific ship and mission, the cost-effectiveness of a double hull structure can be optimized by varying its level of cargo tank subdivision, double bottom height, and side tank width (Konovessis, 2012). However, in comparison with a single hull structure, a double hull structure does have a number of weaknesses related to stability, maintenance costs, and fatigue (Kantharia, 2015). The Marine Board (2001) list a number of alternative accidental discharge prevention concepts, such as the Coulombi Egg Tanker, that have been developed in an attempt to find a better solution.

The weakness of the probabilistic oil outflow method is that it, like the probabilistic damage stability, is prescriptive by nature and does not relate any explicit level of environmental risk. Also, it does not consider active risk mitigation measures. The lack of measures and criteria for environmental risk is not specific for the probabilistic oil outflow method. In fact, the IMO has not agreed on any such measures or criteria (Psaraftis, 2008). Proposals to fill this regulatory gap include a measure referred to as Cost of Averting a Tonne of oil Spilt (CATS) presented by Skjong et al. (2007). The determination of a performance measure and risk criteria would be the first step towards equivalence based approval, enabling a holistic optimization of the ENVP system considering the effect of external resources such as IBs and OSR resources.

5.3.3. Overview of the ENVP systems

An overview of the prerequisite requirements for applying GBD/ RBD on the ENVP system is presented in Table 4. It should be pointed out that classification of the available knowledge and data as sufficient or insufficient reflects the author's option.

Table 4

Status of prerequisites for GBD of the ENVP system.

System	Knowledge	Data	Regulations
Accidental discharge preven- tion system	Sufficient. There are models for the calculation of a ship' s oil outflow performance, which is a measure of its ability to mitigate oil spills. However, there are no models for relating the oil outflow performance to ENV risks.	Sufficient. The data required for the calculation of a ship's oil outflow performance is available (data from non-arctic ships is assumed to be applicable on Arctic ships)	Available. The regulations are goal based. There are no established ENV risk measures or criteria. Thus, application of the principle of design equivalence is difficult.
6. Discussion

The applicability of GBD/RBD depends primarily on the ability to assess the performance of a design. Thus, we are convinced that the application of GBD/RBD will increase as the available database of empirical data increases, and better knowledge based performance assessments tools becomes available. Consequently, we do not expect a design revolution, but a gradual increase in the use of GBD/RBD. However, for the foreseeable future, we predict that the prescriptive rules, due to their strengths over goal-and risk-based rules, for instance in terms of fast and straightforward application and monitoring, will endure and co-exist as an alternative to the latter. It should also be pointed out that much of the criticism of existing prescriptive rules relates to the possibility that the rules result in sub-optimal designs. In particular, this is the case with the PC rules. However, better prerequisites for goal- and risk-based design also means better prerequisites for the determination of more efficient prescriptive rules, increasing their competitiveness.

In Tables 2-4 we classify the knowledge and data required for GBD or RBD as either sufficient or insufficient, and the regulations as available/unavailable. In cases where the knowledge and data related to a system is classified as sufficient, we argue that the knowledge and data is sufficient to carry out a performance assessment relevant for GBD or RBD of the system. However, sufficient knowledge or data does not mean that the available knowledge or data is complete. Generally, the available knowledge and data can be improved for quicker, less costly, and more accurate performance assessments. In cases where we classify the required regulations as available, we mean that the existing regulations determine relevant quantified FRs (performance criteria) enabling goal- or risk-based approval. However, the availability of goaland risk-based rules does not mean that there is no demand for additional, or perhaps more relevant, performance measures and criteria. For instance, the ENVP system can be approved based on its calculated oil outflow performance index. However, perhaps it would be more relevant to approve a design for instance based on the CATS approach mentioned in Section 5.3.2. In cases where the required regulations are classified as unavailable (e.g. in the case of the hull protection system), the regulations do not determine any relevant performance measures or criteria that the designer can relate to, making it difficult to seek goal-or risk-based approval.

In general, new maritime regulations are determined by the IMO in cooperation with its members and various stakeholders such as classification societies. With regards to GBD/RBD, an important regulatory gap is the lack of performance measures and criteria for a number of ship functions (e.g. ice-load protection). The rules (e.g. the Polar Code) determine that any design that provides the same level of safety as the required standard (e.g. polar class standard) is acceptable. This means that individual industry players (e.g. classification societies, shipbuilders) are free to carry out performance assessments demonstrating that an alternative design performs at least as well as a standard design using any method they see fit. Once such a performance assessment has been prepared, submitted to the IMO, and accepted, the applied approach and performance measures are likely to become part of a new standard. Thus, we believe that individual industry players can lead the transition towards a more goal- and risk-based regulatory system. However, to enable the development of the required tools and methods, we believe concerned industry players need to cooperate, e.g. through joint research projects, both to share the related costs, and to avoid any intellectual property rights (IPR) issues.

In the present paper we propose the application of specific performance assessment methods and tools. Obviously, the selection of performance assessment tools is a critical issue as the application of faulty or inaccurate performance assessments methods might result in bad designs. This is also one of the main weaknesses of GBD/RBD. Generally, we expect it will be challenging for the maritime industry to agree on what assumptions, methods and tools are sufficient accurate to prove compliance with specific FRs. Without consensus on these matters, ship owners could find themselves in an on-going struggle to gain compliance by all relevant stakeholders.

In the spirit of GBD/RBD, designers should be allowed to use any method that they see fit, and that is acceptable to the regulators, to demonstrate that a design meets the mandatory FRs. However, because ship design is generally carried out with the constrains of limited time and resources, designers need to get access to quick, cost-efficient, and generally acceptable performance assessment methods. Towards this aim, we believe the regulators, once well-proven performance assessment methods have been agreed on, need to provide the designers with step-by-step instructions and examples on how to apply these methods in order to achieve compliance. However, until such methods have become established, the utilization of GBD/RBD might be limited to industry players with the necessary resources to carry out the required performance assessments on their own, or in cooperation with partners. Over time we expect that there will be competing performance assessment methods and tools, so that rule compliance can be demonstrated by various paths, and with limited resources.

It should be pointed out that the objective of this paper is not to make a case either for or against GBD/RBD. Instead, the aim is to explore the applicability of these design methods and to initiate a discussion about how they should be applied in practise, and what additional knowledge and data is required to advance their application. Given that upcoming IMO regulations, in particular the Polar Code, are increasingly goal/risk-based, these are highly relevant issues.

7. Summary and conclusions

In terms of how to best apply the principles of BGD/RBD when designing an AMTS we conclude the following. First, because it does not appear feasible to quantify the total safety and environmental risks associated with an AMTS, risk-based approaches can only be applied in the context of design equivalence, and the primary rules need to be either prescriptive or goal-based. In other words, a hybrid approach is required allowing the application of risk- and goal-based rules where feasible and relevant, and prescriptive rules where not. Second, in order to enable a hybrid regulatory approach, a system-based approach is needed. A system-based approach makes the design process more manageable, as it makes it possible to divide an AMTS into a number of single-function subsystems that can be designed separately. We propose to divide an AMTS into three main subsystems - an OPS system, a safety system, and a ENVP system - each consisting of a number of subsystems. The criteria for the OPS systems are determined based on a combination of operational and financial considerations, whereas the criteria for the safety and the ENVP systems are determined based on a combination of financial and regulatory considerations. All the systems are required for successful operations. Third, we conclude that a holistic approach is highly advisable when designing an Arctic ship. By extending the design boundaries beyond the individual ship, it becomes possible to optimize the performance of the system as a whole. In addition, it makes it possible to produce stochastic operational data (e.g. a vessel's average annual ice exposure) based on for instance the required level of ice-strengthening can be determined. Forth, in order to enable a holistic design approach, to deal with the complexity and uncertainties of an AMTS, and to maximize the utilization of GBD/RBD, it is necessary to integrate simulations into the design process.

In order to increase the applicability of GBD/RBD, the following knowledge gaps needs to be addressed. First, the general understanding of the ship-ice interaction process needs to be increased. This is important both to be able to estimate the ice loading acting on a ship's hull with a higher degree of confidence, and to be able to develop a more cost-efficient method for the estimation of a ship's ice resistance. Second, a sufficiently detailed ice-propeller model is sought after to enable a theoretical determination of the required scantlings of a ship's propulsion and steering units considering the ship's actual ice exposure. Third, the prevailing uncertainty in terms of how to model the sea ice cover, i.e., how to define the equivalent ice thickness, need to be addressed. This is important both for the determination of the required level of ice-strengthening, and for the determination of the required propulsion power. Forth, methods that would make it possible to carry out holistic safety and environmental risk assessments (e.g. by considering the effect of external SAR and OSR resources), are sought after. Fifth, there is no method for the estimation of the effect of compressive ice, both in terms of ice loading and in terms of hull resistance. Sixth, there is no method that would make it possible to estimate IB waiting times based on the ice conditions, the number of ships in need of assistance, and the number of IBs in service.

In terms of data, the following gaps need to be addressed. First, there is a lack of ice data, in particular on ridging characteristics and the occurrence of compressive ice. This results for instance in uncertainty in the required propulsion power and the estimated transport capacity. Second, there is a lack of full-scale hull ice load measurements (parent distributions). This causes uncertainty in terms of the estimation of the ice loading and thereby the required level of ice-strengthening. Third, there is a lack of full-scale propeller ice load measurements, making it difficult to validate any proposed propellerice model. Forth, there is a lack of operational data (e.g. data on average waiting times for IB assistance and convoy speeds), causing uncertainty in the estimated transport capacity.

In terms of regulations, the following gaps needs to be addressed. First, the authorities need to agree on clear and relevant performance measures and criteria for the hull and propulsion and steering unit(s) with regards to the protection against ice loading. Second, the authorities need to agree on quantifiable risk measures and criteria with regards to environmental risks. Third, in the current regulations there is no clear link between active and passive risk prevention and mitigation measures, preventing trade-offs between the two. For instance, the Polar Code does not determine how the use of IB assistance should be considered with regards to the mitigation of safety and environmental risks. Also it does not consider the presence, or absence of, SAR and OSR resources. Forth, there are no models for relating established deterministic safety criteria (e.g. ice class, subdivision index) to safety risks, hampering the application of the principle of design equivalence.

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Paper 2

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Paper 3

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An approach towards the design of robust arctic maritime transport systems

M. Bergström, S. Ehlers, and S.O. Erikstad

Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Trondheim, Norway

ABSTRACT: This paper describes a simulation-based approach towards the design of robust arctic maritime transport systems that are adaptable to uncertain future ice conditions. It makes it possible to simulate the performance of the transport system for various future ice scenarios and to compare various ice mitigation strategies in terms of cost. A case study is carried out to demonstrate how the approach could be applied in practice. The outcome from the case study indicates that the approach can provide valuable insights into the economics of an arctic maritime transport system and that its components can easily be modified or replaced for improved accuracy.

Key words: Arctic ship, arctic maritime transport system, ice class, icebreaker assistance, simulation

1 INTRODUCTION

Shipping in the Arctic is predicted to grow both in volume and diversity over the coming years. This prediction is due to the large oil, gas, and mineral discoveries found in the arctic region, as well as due to the increased interest in the Northern Sea Route.

When designing an arctic maritime transport system, here defined as a system consisting of any number of vessels transporting cargo between two or more ports through partially ice-covered waters, several arctic specific challenges, such as uncertain future ice conditions, need to be considered. To make such a transport system robust, in the sense that it is adaptable to such uncertain future ice conditions, it is necessary to consider a range of various possible future ice conditions along the intended route and to define an ice mitigation strategy that is able to deal with each of those conditions. To this aim, a simulation based approach is developed that can be used to simulate the performance of an arctic maritime transport system for various future ice scenarios and to compare various ice mitigation strategies for those scenarios in terms of cost.

In the current approach, the ice-vessel interaction is limited to the ice resistance, i.e., only the power demand of the vessel is considered. As a simplification, the ice is assumed to be level ice, i.e., possible ridges, ice channels, etc. are not considered. In addition, the ice thickness is assumed to remain constant between consecutive waypoints along the route. A case study is carried out to demonstrate how the developed approach could be applied in practice. The results of the case study indicate that it can provide valuable insights into the economics of an arctic maritime transport system and that it can be developed further as it's components can easily be modified or replaced for improved accuracy.

The developed approach can be considered a further development of an approach towards missionbased design of arctic maritime transport systems developed by (Bergström, et.al., 2014), which in turn was partly based on an approach developed by (Erceg, et. al., 2013). Other related work include (Valkonen, et.al., 2013) and (Riska, et.al., 2001).

2 DESCRIPTION OF THE APPROACH

The transport task is defined by the route, the transport demand, and the period of time the transport will be taking place (for instance within the period 2016-2025). The transport route is determined by waypoints (coordinates along the route). Waypoint and date (voyage) specific ice thickness estimates are obtained from ice scenarios determined based on the prevailing ice conditions and various possible future development trends determined by the user.

In case of independent operation in ice, i.e., operation without icebreaker support, the speed of the vessel is calculated using a so-called h-v curve described by (Juva, et.al., 2002) that determines the speed of a ship as a function of the ice thickness. The speed of a vessel being escorted by an icebreaker is assumed to correspond to an assumed average speed of the icebreaker. Icebreaker assistance is assumed to be required from the first to the last waypoint along the route where the ice thickness exceeds a specific value determined by the user based on the ice class and the propulsion power of the ship. A flowchart describing the developed approach is presented in Figure 1.



Figure 1. Flow chart describing the developed approach

Possible ice mitigation strategies, i.e., strategies for how to deal with sea ice include for instance the following:

- Use of ships with a low ice class that are able to operate independently in thin ice only and use of icebreaker assistance when the ice conditions exceeds the class capabilities.
- 2. Use of ships with a high ice class and propulsion power to reduce/minimize the amount of icebreaker assistance required.
- 3. Avoidance of difficult ice conditions by limiting the operation to periods with little or no ice.

Costs related to various ice mitigation strategies are calculated based on estimates for the following cost items:

- Daily cost for icebreaker assistance.
- Additional investment and operating cost related to a higher ice class and propulsion power.
- Additional fuel costs due to additional ice resistance.

The total voyage specific sailing times are calculated based on the leg distances and the corresponding leg specific speeds. Calculated sailing times for the time span simulated are then imported into a SimEvents (a discrete event simulation tool developed by MathWorks) simulation model. By using the simulation tool, it is then possible to simulate stochastic transit time including stochastic factors such as time spent waiting for icebreaker assistance, loading and unloading times, variations in the transit time caused by weather etc. Additional parameters can be included as needed.

The simulation model can then be used to simulate how the transit times vary during the time span simulated due to varying ice conditions, to simulate the total accumulated amount of cargo transported from location A to location B, and to simulate the required number of days of icebreaker assistance.

3 CASE STUDY

3.1 Transport task

The case study deals with the maritime transport of Liquefied Natural Gas (LNG) from the port of Sabetta (Russia), which is still under construction, to the port of Narvik (Norway), from where the LNG is assumed to be transported onwards. The transport from Sabetta to Narvik is carried out by ice-strengthened LNG carriers, while the onwards transport from Narvik to the large transhipment terminals in central Europe and Asia is carried out by more cost efficient LNG carriers without ice class. The route, which is approximately 1489 NM, is presented in Figure 2.



Figure 2. The route of the case study plus ice conditions along the route in mid-march 2014 as determined by (AARI, 2014)

The average LNG production rate in Sabetta is assumed to be 100,000 m3/day (Total S.A., 2014). Thus, to avoid production stops the average transport capacity of the system needs to be at least 100,000 m3/day x 365 days/year = 36,500,000 m3/year. The objective of the case study is therefore to design a transport system with sufficient capacity to avoid production stops resulting in very significant economic losses.

The assumed transport task can be seen as an alternative to the plan to use Arc 7 classified 170,000 m3 LNG carriers to transport the LNG directly from Sabetta to the large transhipment terminals in central Europe and Asia (Renton, M., 2013,). Such heavy ice-strengthened ships are, in open waters, general significantly less cost-effective than lighter non-icestrengthened ships. Thus, it could be more economical to limit the use of ice-strengthened vessels to the part of the distance where ice strengthening is needed, and carry out the onward transport using normal ships. The planning of the transport system is assumed to be in the conceptual design phase. Operation is assumed to start at January 1 2016 and to continue for at least 10 years. The time span simulated is therefore 01.01.2016 - 31.12.2025.



Figure 3. Applied ice thickness development trends

3.2 Determination of ice scenarios

The starting point, i.e., the assumed prevailing ice conditions, was determined by modifying ice data obtained from a numerical climate model developed by SINTEF called SINMOD (Slagstad, et.al., 2005) (SINTEF, 2014) to correspond to ice data from satellite imagery from year 2012 and 2013 provided by (AARI, 2014). Based on the assumed prevailing conditions, four possible future ice scenarios were then generated for the time span simulated based on four assumed ice thickness development trends presented in Figure 3. The trends, which include one trend of increasing ice thicknesses, two trends of decreasing ice thicknesses, and one trend of more or less unchanged ice thickness, were determined based on coefficients generated at random between predetermined intervals. Ice scenario specific average ice thicknesses along the distance Kara Strait- Sabetta, where first-year ice occurs, are shown in Figure 4.

3.3 Ice conditions along the route

The route goes through the Kara and the Pechora Sea, both of which according to satellite imagery based ice maps provided by (AARI, 2014) are normally covered by first year ice in the winter. An ice map, that was determined based on one of the ice maps from (AARI, 2014) showing the ice conditions along the route in mid-march 2014, is presented in Figure 2.



Figure 4. Determined ice scenarios

An example of applied date specific ice forecast for the route is shown in Figure 5, which shows the predicted ice thicknesses along the route for 31.03.2026 in accordance with ice scenario 1. On that date, as shown in Figure 3, the predicted maximum ice thickness along the route is around 2.0 m. This is assumed to be the maximum ice thickness that can occur along the route during the simulated period of time.

The sailing time is determined based on the date of departure, i.e., based on the ice conditions that occur along the route as the ship leaves the harbour. This means that the ice thicknesses estimated for the various legs are assumed to remain constant during a voyage. In addition, the ice thickness is assumed to be homogenous between waypoints, which in the case study are between 7 and 22 nautical miles (nm) apart along the part of the route where ice occur.

3.4 Ice mitigation strategies considered

Three different ice mitigation strategies were considered:

- 1. Use of Polar Class (PC) 7 classed ships that are able to operate independently in up to 0.7m thick ice. Use of icebreaker assistance when the ice thickness exceeds 0.7 m.
- 2. Use of PC 5 classed ships that are able to operate independently in up to 1.2 m thick ice. Use of icebreaker assistance when the ice thickness exceeds 1.2 m.
- 3. Use of PC 4 classed ships that are able to operate independently in up to 1.7 m thick ice. Use of icebreaker assistance when the ice thickness exceeds 1.7 m.

Periods with little or no ice are expected to be very short along the present route. Thus, one of the in section 2 mentioned possible ice mitigation strategies, to avoid difficult ice conditions by limiting the operation to periods with little or no ice, was excluded while it was considered infeasible.

A single icebreaker is assumed to cost USD 50,000 per day. Convoys are not considered, i.e., the icebreaker costs are not divided on multiple ships.



Figure 5. Ice thickness along the route at 31.03.2026 in accordance with ice scenario 1.

Estimation of vessel parameters and costs 3.5

The assumed vessel parameters are presented in Table 1. The main dimensions of the vessel were determined based on a LNG carrier of the fleet of Knutsen OAS Shipping (Knutsen OAS Shipping AS, 2014). The initial investment costs were determined assuming that a PC 7 vessel costs 10 % more than a standard vessel without ice class that is assumed to cost USD 220 M. The corresponding additional investment cost for PC 5 and PC 4 vessels are assumed to be 20 % and 30 %, respectively.

The additional operating costs related to PC 5 and PC 4 were determined assuming that the annual operating costs correspond to around 3 % of the initial investment.

The required propulsion power for each ice class were determined so that the ship at 85 % MCR is able to operate with a speed of around 3 kn in the maximum ice thickness for independent operation specified for the ice class in question. The 15 % sea margin can be utilized, for instance, in case the vessel gets stuck in an ice ridge.

Table 1: Assumed ship parameters

Length w.l.	280 m
Breadth	45.8 m
Draft	12 m
Cargo capacity	172,000 m3
Tonnage	110,920 GT
Speed o.w.	19.5 kn
Ice class	PC7/ PC 5/ PC4
Propulsion power at 0.85	30,000 kW/ 57,000 kW/ 90,000
% MCR	kW
Specific fuel consumption	180 g/ kWh
(HFO)	
Initial investment	USD 242 M/ USD 264 M/ USD
	297 M
Annual operating costs re-	USD 0/ USD 3.96 M/ USD 9.9 M
lated to a higher ice class	

3.6 Transit times

Regardless of ice scenario and ice mitigation strategy, the transit times vary significantly between seasons. Simulated transit times for ice scenario 2 and PC 7 vessels are shown as example in Figure 6.



Figure 6. Example of simulated transit times

In this case, the total duration of a return trip varies between 16 days (2 x 8 days) during peak ice conditions and 6.5 days (2 x 3,25 days) during periods with no ice. The average return trip is around 10.2 days (2 x 5.1 days) and the median is around 9.2days (4.6 x 2 days). Please note that the abovementioned transit times are examples only. All transit times applied in the simulations are voyage and date specific, i.e., unique.

3.7 Determination of transport capacity

The ensure a sufficient transport capacity also in the worst assumed ice conditions, i.e., ice scenario 1, six vessels each with a capacity of 172,000 m3 are, regardless of the polar class of the vessels, needed to meet the transport demand. If the cargo capacity of the vessels is reduced to for instance 165,000 m₃, the amount on LNG waiting to be transported from Sabetta will start to increase. This is demonstrated in Figure 7, which in case of ice scenario 1 and use of PC 5 vessels, shows the amount of LNG waiting to be transported from Sabetta for various vessel capacities. As the storage capacity in Sabetta is limited, an increasing amount of LNG waiting for onward transport will eventually enforce a production stoppage. Therefore, assuming the costs related to such a production stoppage are very significant, it was decided that the vessels need to have a capacity of at least 172,000 m3.



Figure 7. The amount of LNG waiting to be transported from Sabetta for various vessel capacities (Ice scenario 1, PC 5)

The drawback of having a transport capacity that is adjusted to the worst assumed ice conditions is that there inevitable will be some overcapacity in less severe ice scenarios. However, the amount of overcapacity depends on the selected ice mitigation strategy. Thus, the various ice mitigation strategies are in the following investigated to find out which of them is the least sensitive to uncertain future ice scenarios, i.e., which of them represents the most robust solution.

In case of ice scenario 2, in which there is a trend towards decreasing ice thickness, the overcapacity is limited to around 1 % for both PC 5 and PC 7. However, for PC 4, the overcapacity is around 7 %. In case of ice scenario 3, with the least amount of ice, i.e., the overcapacities for PC 7 and PC 5 are around 4 % and 5 % respectively while the overcapacity for PC 4 is up to 13 %. In case of ice scenario 4, in which the ice thickness does neither significantly increase nor decrease, the overcapacity for both PC 7 and PC 5 is around 1 % while the overcapacity for PC 4 is around 5 %. Transport capacity utilization per ship for the various ice scenarios and ice mitigation strategies is presented in Table 2.

Table 2: Capacity utilization per ship for various ice scenarios and ice mitigation strategies

		Capacity u	ıtilizatio	on per ship
Ice class	Number of ships	Cubic m	eters	Percent
	Ice sce	nario 1		
PC 7	6	172000	m3	100%
PC 5	6	172000	m3	100%
PC 4	6	172000	m3	100%
	Ice sce	nario 2		
PC 7	6	170000	m3	99%
PC 5	6	170000	m3	99%
PC 4	6	160000	m3	93%
	Ice sce	nario 3		
PC 7	6	165000	m3	96%
PC 5	6	163000	m3	95%
PC 4	6	150000	m3	87%
Ice scenario 4				
PC 7	6	171000	m3	99%
PC 5	6	171000	m3	99%
PC 4	6	163000	m3	95%

3.8 Determination of the number of days of icebreaker assistance required

Icebreaker assistance is assumed to be required when the ice thickness exceeds the maximum ice thickness for independent operation specified for each ice mitigation strategy. Since the present LNG carriers are 45.8 m wide, two icebreakers will be required to escort them. The time spent waiting for icebreaker assistance is drawn from a normal distribution with a mean value of 2 hours and a standard deviation of 1 hour. The relatively low waiting time was determined on the assumption that the icebreaker service in the area would be adjusted to the demands of the assumed regular service route. The icebreakers are assumed to assist the vessels from the first to the last waypoint along the route where the ice thickness exceeds the determined maximum value for independent operation. The average speed of the icebreakers and the assisted vessel is assumed to be 8 kn. Figure 8 shows an example of how the speed of a ship that operates in up to 1.2 m thick ice is affected by icebreaker assistance when the ice thickness exceeds 1.2 m.

The number of days of icebreaker assistance required for the whole fleet of 6 vessels for various ice scenarios and ice mitigation strategies is shown in Table 3.

Table 3: Required icebreaker assistance in days for various ice scenarios and ice classes (for the whole fleet of LNG carriers).

	Ice scenario 1		Ice scenario 2			
Year	PC 7	PC 5	PC4	PC 7	PC 5	PC4
2016	521	198	0	438	110	0
2017	523	185	0	433	104	0
2018	560	238	5	424	100	0
2019	541	220	1	492	175	0
2020	582	257	8	403	61	0
2021	554	231	2	428	97	0
2022	523	191	0	456	125	0
2023	597	273	21	441	111	0
2024	610	278	58	296	0	0
2025	636	316	133	421	97	0
Total	5647	2385	227	4233	979	0
	Ice scenario 3		Ice scenario 4			
	Ice	scenari	o 3	Ice	scenari	o 4
Year	Ice PC 7	scenari PC 5	o 3 PC 4	Ice PC 7	scenari PC 5	o 4 PC4
Year 2016	Ice PC 7 427	scenari PC 5 101	o 3 PC 4 0	Ice PC 7 469	scenario PC 5 153	o 4 PC4 0
Year 2016 2017	Ice PC 7 427 395	scenari PC 5 101 46	o 3 PC 4 0 0	Ice PC 7 469 424	scenario PC 5 153 98	o 4 PC4 0
Year 2016 2017 2018	Ice PC 7 427 395 405	scenari PC 5 101 46 58	o 3 PC 4 0 0	Ice PC 7 469 424 424	scenarie PC 5 153 98 99	0 4 PC4 0 0 0
Year 2016 2017 2018 2019	Ice PC 7 427 395 405 378	scenari PC 5 101 46 58 22	o 3 PC 4 0 0 0 0	Ice PC 7 469 424 424 409	scenarie PC 5 153 98 99 61	0 4 PC4 0 0 0 0
Year 2016 2017 2018 2019 2020	Ice PC 7 427 395 405 378 289	scenari PC 5 101 46 58 22 0	o 3 PC 4 0 0 0 0 0	Ice PC 7 469 424 424 409 488	scenario PC 5 153 98 99 61 164	0 4 PC4 0 0 0 0 0
Year 2016 2017 2018 2019 2020 2021	Ice PC 7 427 395 405 378 289 317	scenari PC 5 101 46 58 22 0 0	o 3 PC 4 0 0 0 0 0 0 0 0	Ice PC 7 469 424 424 409 488 557	scenario PC 5 153 98 99 61 164 231	0 4 PC4 0 0 0 0 0 0 3
Year 2016 2017 2018 2019 2020 2021 2022	Ice PC 7 427 395 405 378 289 317 298	scenari PC 5 101 46 58 22 0 0 0 0	o 3 PC 4 0 0 0 0 0 0 0 0 0 0	Ice PC 7 469 424 424 409 488 557 439	scenario PC 5 153 98 99 61 164 231 107	0 4 PC4 0 0 0 0 0 0 3 0
Year 2016 2017 2018 2019 2020 2021 2022 2023	Ice PC 7 427 395 405 378 289 317 298 301	scenari PC 5 101 46 58 22 0 0 0 0 0 0	o 3 PC 4 0 0 0 0 0 0 0 0 0 0 0	Ice PC 7 469 424 424 409 488 557 439 437	scenario PC 5 153 98 99 61 164 231 107 104	0 4 PC4 0 0 0 0 0 3 0 0 0
Year 2016 2017 2018 2019 2020 2021 2022 2023 2023	Ice PC 7 427 395 405 378 289 317 298 301 130	scenari PC 5 101 46 58 22 0 0 0 0 0 0 0 0	o 3 PC 4 0 0 0 0 0 0 0 0 0 0 0 0	Ice PC 7 469 424 409 488 557 439 437 526	scenarie PC 5 153 98 99 61 164 231 107 104 194	0 4 PC4 0 0 0 0 0 0 3 0 0 0 0
Year 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025	Ice PC 7 427 395 405 378 289 317 298 301 130 126	scenari PC 5 101 46 58 22 0 0 0 0 0 0 0 0 0 0 0	o 3 PC 4 0 0 0 0 0 0 0 0 0 0 0 0 0	Ice PC 7 469 424 409 488 557 439 437 526 561	scenarie PC 5 153 98 99 61 164 231 107 104 194 241	0 4 PC4 0 0 0 0 0 0 0 3 0 0 0 4

3.9 Fuel costs related to the choice of ice mitigation strategy

Operation in ice-covered water requires large amount of propulsion power to overcome the resistance between the ice and the ship's hull. A ship built to operate independently in up to 1.7 m of ice requires therefore significantly more propulsion power than a ship built to operate independently in maximum 0.7 m of ice. This is shown in Table 1 that presents propulsion power requirements for vessel with various ice-going capabilities or polar classes.

A larger power requirement results in both higher investment costs and significantly higher fuel consumption as the fuel consumption can be considered directly related to the power demand. Thus, the additional fuel costs related to the PC 5 and PC 4 ships in the present study need to be considered. To this aim, the number of days when the PC 5 and PC 4 vessels need their additional power was determined as shown in Table 4.



Figure 8. Example of how the speed of a ship that operates independently in up to 1.2 m thick ice is affected by icebreaker assistance when the ice thickness exceeds 1.2 m: (a) The ice thickness along the route; (b) The corresponding speed of the vessel

The PC 5 classified ship is assumed to need its additional power of 57,000 kW - 30,000 kW = 27,000kW when the ice thickness is larger than 0,7 m and smaller than 1.2 m. The PC 4 vessel is assumed to need the same amount of additional power as the PC 5 ship as long as the ice thickness is less than 1.2 m. When the ice thickness is larger than 1.2 m and less than 1.7 m, the PC 4 ship is assumed to need an additional power of 90,000 kW - 30,000 kW = 60,000kW. With icebreaker assistance both the PC 5 and the PC 4 vessels are both assumed to have the same power requirement as the PC 7 vessels. Assuming use of HFO as fuel, an average HFO price of USD 750 per ton, and a specific fuel consumption of 180 g/kWh, the additional fuel cost for a fleet of PC 5 vessels amount to 6 x USD 87,000 per day = USD 524,000 per day (when the additional power is required). The corresponding figure for a fleet of PC 4 vessels is 6 x USD 194,000 = USD 1,166,000.

In the above fuel cost calculation, only the use of HFO as fuel is considered. It should be mentioned that LNG carriers are typically fitted with a so-called dual-fuel engine that can run on either natural gas or HFO. However, currently most LNG carriers use HFO as fuel as it for the moment is cheaper than natural gas. Thus, use of natural gas as fuel with not be further discussed in the present paper.

Table 4: Number of days when the additional power of the PC 5 and PC 4 vessels is needed for various ice scenarios (for the whole fleet of LNG carriers)

PC 5: Number of days when 0.7m <ice <<="" th="" thickness=""></ice>				
1.2 m				
IS = Ice Scenario				
Year	IS 1	IS 2	IS 3	IS 4
2016	323	328	326	316
2017	338	330	349	325
2018	322	324	347	325
2019	321	316	356	348
2020	326	342	289	324
2021	323	332	317	325
2022	332	331	298	332
2023	324	330	301	333
2024	332	296	130	332
2025	321	324	126	319
PC 4: Number of days when 1.2m <ice <<="" td="" thickness=""></ice>				
Year	IS 1	IS 2	IS 3	IS 4
2016	198	110	101	153
2017	185	104	46	98
2018	233	100	58	99
2019	219	175	22	61
2020	249	61	0	164
2021	229	97	0	228
2022	191	125	0	107
2023	251	111	0	104
2024	221	0	0	194
2025	183	97	0	237

3.10 Comparison of ice mitigation related costs for the various ice mitigation strategies

To enable a holistic comparison of the various ice mitigation strategies, the Net Present Cost (NPC) of all their related costs were calculated. All costs except the additional investment costs related to the PC 5 and PC 4 vessels were discounted using an assumed interest of 8 %. The obtained NPC values are presented in Table 5.

The figures presented in Table 5 indicate clearly that ice mitigation strategy 1 with PC 7 vessels is the

most economical alternative for all ice scenarios. However, the outcome is quite sensitive to the assumed costs for icebreaker assistance. Assuming that the two icebreaker required to escort one of the LNG carriers would cost USD 80,000 x 2 = USD 160,000 or more per day instead of the USD 50,000 x 2 = USD 100,000, ice mitigation strategy 2 with PC 5 built ships would be more economical.

Table 5: NPC of ice mitigation costs for various ice scenarios and ice mitigation strategies

IS 1	PC 7	PC 5	PC 4
IB support (days)	5,647	2,385	227
Addl. fuel cons. (t)	0	380,000	940,000
NPC (USD)	3.7E+08	5.1E+08	8.8E+08
IS 2	PC 7	PC 5	PC 4
IB support (days)	4,233	979	0
Addl. fuel cons. (t)	0	380,000	633,000
NPC (USD)	2.9E+08	4.2E+08	7.2E+08
IS 3	PC 7	PC 5	PC 4
IS 3 IB support (days)	PC 7 3,065	PC 5 227	PC 4 0
IS 3 IB support (days) Addl. fuel cons. (t)	PC 7 3,065 0	PC 5 227 331,000	PC 4 0 390,000
IS 3 IB support (days) Addl. fuel cons. (t) NPC (USD)	PC 7 3,065 0 2.2E+08	PC 5 227 331,000 3.5E+08	PC 4 0 390,000 6.1E+08
IS 3 IB support (days) Addl. fuel cons. (t) NPC (USD) IS 4	PC 7 3,065 0 2.2E+08 PC 7	PC 5 227 331,000 3.5E+08 PC 5	PC 4 0 390,000 6.1E+08 PC 4
IS 3 IB support (days) Addl. fuel cons. (t) NPC (USD) IS 4 IB support (days)	PC 7 3,065 0 2.2E+08 PC 7 4,734	PC 5 227 331,000 3.5E+08 PC 5 1,453	PC 4 0 390,000 6.1E+08 PC 4 8
IS 3 IB support (days) Addl. fuel cons. (t) NPC (USD) IS 4 IB support (days) Addl. fuel cons. (t)	PC 7 3,065 0 2.2E+08 PC 7 4,734 0	PC 5 227 331,000 3.5E+08 PC 5 1,453 383,000	PC 4 0 390,000 6.1E+08 PC 4 8 757,000

4 CONCLUSIONS

The present study resulted in an approach towards the design of robust arctic maritime transport systems that are able to deal with various possible future ice scenarios. It makes it possible to assess how a complex arctic maritime transport system, consisting of a single or multiple vessels, with or without icebreaker assistance, is able to cope with various possible future ice scenarios.

A case study was carried out to demonstrate how the approach could be applied in practice. The outcome from the case study indicates clearly that it, for the investigated route, is more economical to use vessels with a low or medium level ice going capabilities in combination with icebreaker assistance instead of vessels with high ice going capability and a minimum demand for icebreaker assistance. In other words, the results indicate that costs related to higher ice going capabilities are high in comparison with the costs for icebreaker assistance. Especially in case of decreasing ice conditions, the transport system with PC 4 vessels performed poorly while the utilization of the vessels ice going capabilities was limited to the start of the 10-year period, and resulted only in additional capital costs and operating costs towards the end of the period. In reality the PC 4

vessels would most likely perform even worse in comparison with the vessels with lower ice classes as their additional weight would significantly harm their fuel consumption in all ice conditions including open water.

The presented approach can be further developed as its components can easily be modified or replaced for improved accuracy. Components that should be improved include for instance the method for calculation of differences in fuel costs between ships with various ice going capabilities as well as the applied ice data, which should be extended to include openings, ridges, etc.

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ABBREVIATIONS

- LNG Liquefied Natural Gas (LNG)
- IB Icebreaker
- IS Ice Scenario Liquefied
- NM Nautical Mile
- NPC Net Present Costs
- PC Polar Class
- USD United States Dollars

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Paper 4

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The influence of model fidelity and uncertainties in the conceptual design of arctic maritime transport systems

Martin Bergström¹, Stein Ove Erikstad¹, and Sören Ehlers²

1. Norwegian University of Science and Technology, Department of Marine Technology, 7491 Trondheim, Norway

2. Technical University of Hamburg, Department of Ship Structural Design and Analysis, Schwarzenbergstraße 95 (C), D-21073 Hamburg, Germany

Abstract

This paper aims to help the designer of an arctic maritime transport system (AMTS) to determine an appropriate level of model fidelity with regards to the estimation of transport capacity and ice loading, as well as to understand and manage related design uncertainties. The study is centred around two different case studies: 1. The design of an AMTS for the transport of LNG along an arctic route using independently operating ship, 2. The design of an AMTS for the transport of steel along a Baltic route using icebreaker assisted ships. Due to the different types of operations, the two case studies are characterized by different types of modelling challenges and uncertainties. The outcome of the study indicate that the required model fidelity and the related model uncertainties are case specific. In comparison with the Baltic case, the arctic case required a higher level of model fidelity, and demonstrated a higher sensitivity to possible uncertainties. In both cases it proved feasible to mitigate uncertainty with regards to the estimated transport capacity either by increasing the payload capacity of the fleet, or by increasing ship speed.

Key words: Arctic maritime transport system; Arctic cargo ship; Ship design; Risk-based design; Goalbased design; Ice loads; Ice class; Ice conditions

1 Introduction

An arctic maritime transport system (AMTS), i.e., a system for the transport of cargo in or through arctic waters, might consist of multiple cargo ships, icebreakers (IBs), and ports. In the conceptual design of an AMTS, it is necessary to determine important system characteristics such as the fleet size as well as the cargo capacity, speed, and ice class of each ship, with the aim to obtain a safe and cost-efficient solution. Due to the nature of arctic shipping, this process is characterised by complexity, stochasticity and uncertainty. The complexity arises from the interaction between the various components of an AMTS, as well as from the interaction between these components and their operational environment. The stochasticity and uncertainty, in turn, arise from the multitude of stochastic and uncertain factors, in particular those related to sea ice, affecting the performance of the system's individual components, and thereby the performance of the system as a whole.

In the design process, in order to manage the complexity of an AMTS, it is necessary to determine simplified design models. This concerns for instance the modelling of the interaction between the cargo ships and the IBs, as well as the modelling of the operating conditions of the ships. As a part of this process, it is necessary to determine appropriate design boundaries, i.e., to determine what factors to include, and what factors to exclude from the design process. The challenge in all of this is to find an appropriate level of model fidelity. An overly detailed and complex design model might not only result in a waste of design resources (e.g. time and money), but also in an increased risk of design model faults. In addition, using an overly detailed and complex model, there is a risk of focusing on details of

minor importance, rather than on those that matter. On the other hand, an overly simplified model might fail to capture relevant phenomena and behaviours of the system, and thereby also fail to provide an adequate estimation of its performance.

Because the performance of an AMTS is stochastic, it can only be determined probabilistically. This require the integration of probabilistic methods into the design process, enabling the determination of stochastic design factors in terms of distributions. However, there might be uncertainty in terms of how to determine a specific distribution, resulting in uncertainty in the estimated probabilistic performance. Other sources of uncertainty include possible faulty or incomplete design tools, methods, and assumptions as well as uncertainty in terms of long-term future trends (e.g. climate change reducing or increasing the amount of sea ice). Because it is generally not possible to eliminate such uncertainties within the course of a design process, the designer needs to find ways to manage them. This requires the understanding of their effects, as well as the determination of relevant risk mitigation measures.

The objective of the present paper is to help those involved in the design or analysis of AMTS:s to determine a design model with an appropriate level of model fidelity, as well as to understand and manage the uncertainties that they are dealing with. In specific, the paper aims to address the following questions:

- 1. What level of model fidelity is required to capture behaviours of an AMTS relevant for its conceptual design?
- 2. How sensitive is the outcome of the design process to uncertainties in design inputs and tools?
- 3. What are the options in terms of uncertainty mitigation?

The study is limited to the consideration of various environmental and operational factors affecting the performance of an AMTS. In particular, the study focuses on factors related to the description and modelling of the ice conditions, both with regards to their effect on the transport capacity, as well as with regards to their effect on the ice loading of a ship. The study does not directly link the analysed design uncertainties to for instance safety, environmental, financial, or legal risks. However, the findings of the study could be relevant for the assessment of such risks.

The paper is organized as follows. First, it presents the applied research method. Second, it presents analyses addressing the above listed research questions for two different design cases: (1) The conceptual design of an AMTS for the transport of LNG in the Arctic, and (2) the conceptual design of an AMTS for the transport of bulk cargo on the Baltic Sea. Third, it discusses the outcome of the analyses and draws conclusions.

2 Research method

2.1 Simulation-based design

The case studies are carried out using a design method presented by (Bergström, et al., 2016b) referred to as simulation-based design (SBD), which is especially developed for the conceptual design of arctic ships and AMTS:s. In order to estimate the probabilistic performance of an AMTS, the method relies on Monte Carlo simulations carried out using SimEvents, which is a MATLAB based discrete event simulation (DES) package. A generalized SimEvents model of an AMTS is presented in Figure 1 (Bergström, et al., 2016a). In this simulation model, ships and cargo units are represented by entities moving in or through the system. Loaded ships are represented by merges between ships and shipload entities. Shipload entities, in turn, consist of merges between a number of cargo entities corresponding to the cargo carrying capacity of the ship. Ship entities are created at the start of the simulation and circulate thereafter in a closed loop until the simulation stops. Cargo entities, on the other hand, are

produced at a fixed rate and leave the system once they have been transported to their destination port. During the simulation, the ship and cargo entities are stopped for various lengths of time corresponding to the duration of events such as sailing a specific distance, port visits, and waiting for IB assistance.

The probabilistic operational performance of the system is assessed in accordance with the Monte Carlo method by simulating the operational performance of the system for a specific period (e.g. one year) repeatedly (e.g. 100 times) so that each simulation run is characterized by a unique combination of parameter values drawn at random from predetermined distributions. Throughout the simulation, operational data is determined and logged. This data, replacing missing empirical data, can subsequently be used both for the design of various ship systems (e.g. the hull structure or the ship machinery) and for the assessment of the cost-efficiency of various competing AMTS design alternatives.



Figure 1: A generalized DES model of an AMTS (Bergström, et al., 2016a).

In accordance with Figure 2, input for the DES model consists of design variables, constraints, and parameters. The design variables are determined by the designer and consist essentially of the number of cargo ships (fleet size), as well as the cargo capacity and speed characteristics of each ship. The feasible range of design variables are limited by various types of constraints (e.g. regulatory and engineering constraints). External factors affecting the performance of the system, such as ice conditions and port turnaround times, are described in terms of design parameters. In order to assess the interaction between the determined design variables and parameters, the simulation model integrates various types of performance assessment tools and methods. These include for instance the concept of equivalent ice thickness, making it possible to describe the prevailing ice conditions in an area with a single value corresponding to the average thickness of all ice features in the area.



Figure 2: In- and output of the simulation model.

For the determination of a ship's required level of ice-strengthening, SBD utilises a probabilistic method developed by (Jordaan, et al., 1993), and later applied on ships operating on the Northern Sea Route

(NSR) by (Tõns, et al., 2015). In accordance with this method, the 100-year extreme ice load z that a ship is exposed to can be estimated using Eq. 1.

(1)

$$z = [4.6 + \ln(xf)]CA^{D}$$

, where x = average annual distance travelled in ice [NM], f = ice condition specific impact frequency [impacts/NM], [C, D] = ice condition specific coefficients, and A = impact area [m²].

The average annual distance travelled in ice (x) is simulated in accordance with the above described DES-based Monte Carlo approach. Once the extreme load has been determined, it can be used as input for direct structural analyses (e.g. finite element method analyses) to determine the required level of ice strengthening. Alternatively, it can be used to assess whether a specific prescribed ice class is appropriate by comparing the calculated extreme load with the ice class specific design load. In the present study, we apply it for the latter purpose.

Naturally, when designing an AMTS, the outcome of the design process depends on a multitude of considerations, some of which might be difficult to quantify. Thus, the primary purpose of the above described simulation-based design method is not to determine an absolute set of design variables (e.g. number of ships) but to enable better informed design decisions for instance by making it possible to assess and compare the stochastic performance of various AMTS designs in accordance with the above description.

2.2 Research procedure

The study is centred around two case studies, each of which deals with the design of an AMTS, which are carried out as follows. First, we determine a number of versions of the same design model representing various levels of model fidelity. Second, in accordance with Figure 3, we apply each of the determined design models and compare the outcomes, Third, we determine the required level of model fidelity based on the principle that any increase in model fidelity that results in a significantly different performance estimate is justified. Forth, once the required level of model fidelity has been determined, we carry out a sensitivity analysis aiming to determine how sensitive the determined design model is to various identified design uncertainties. Fifth, we identify, apply, and assess various uncertainty mitigation measures.



Figure 3: Assessment of the influence of model fidelity.

Differences in the applied design models include, among others, differences in the level of detail with which the ice conditions are described. Because, natural sea ice is highly inhomogeneous, any model need to be an approximation of reality. A common approach for the description of ice conditions is to apply the concept of equivalent ice thickness (H_{eq}) , according to which the prevailing ice conditions can be described in terms of the average thickness of all ice features (e.g. level ice, ice openings, and ice ridges) in an area (Riska, 2010). However, there is no single agreed on precise definition of H_{eq}

(Riska, 2009). Differences between various definitions concern for instance the level of detail with which ridged ice is modelled. Some definitions only consider average ridging characteristics, whereas other enable the consideration of the characteristics (size and shape) of individual ice ridges. Also, it is not clear with what level of detail variations in the ice conditions along a specific leg need to be modelled.

Differences in the applied design models include also differences with regards to the modelling of intermediate ice conditions. Most studies dealing with arctic shipping consider either the maximum or the average ice conditions along a route. However, for instance to estimate the annual transport capacity of an AMTS, or to estimate the ice loading of a ship, it is necessary to consider how the ice conditions change over time. Naturally, intermediate ice conditions can be modelled by different means, and by different levels of details. For instance, as a simplification, it can be assumed that the ice conditions change only once per month. In comparison with a design model in which the ice conditions change daily, this would simplify the design process. However, it is possible that it would result in a significantly more conservative design, as peak ice conditions would be assumed to last for a full month.

3 Case study A

3.1 Introduction

This case study deals with the design of an AMTS for the transport of LNG from the port of Sabetta (Russia) to the port of Zeebrugge (Belgium). The route, which is presented in Figure 5, is approx. 2,600 NM (one-way). The annual transport demand is 16.5 million metric tonnes, which assuming an LNG density of 450 kg/m³, corresponds to an average daily transport demand of some 100,000 m³ LNG (Yamal LNG, 2015). Because the port-based LNG storage in Sabetta is assumed to be limited to 640,000 m³, continuous operation is required to avoid production stops caused by a lack of storage capacity (Yamal LNG, 2015). Any production stop due to a shortage in transport capacity is assumed to result in a very significant economic loss and should therefore be avoided.

The design task is to determine the required fleet parameters to meet the functional requirements (FRs) of the system. The fleet parameters are determined in terms of the number of ships, as well as the speed and ice class of each ship. The capacity of each ship is fixed at 170,000 m³, which we assume correspond to the maximum feasible ship size considering draft limitations set by route. The FRs of the system are the following: 1. The system must be able to meet the transport demand in 100-year operating conditions, i.e., the worst operating conditions that are expected within a period of 100 years, 2. The ice class of the ship's expected 100-year maximum ice load. As general requirement, all the cargo ships are to be able to operate independently. This means that they must be of so-called double acting type as defined by (Niini, et al., 2012) so that they can operate stern-first in heavy ice conditions.

During approximately the period December-May, the route typically features medium to thick first-year ice. Month-specific average level ice thickness (t) values for the Kara Strait and the southwestern Kara Sea, as determined by (Østreng, 1999), are presented in Figure 4. In accordance with the figure, the average ice thickness for Kara Strait and southwestern Kara Sea are around 1.0 and 1.3 m respectively. In accordance with (Romanov, 1995), the maximum ice thickness for the Kara Strait is assumed to be 1.6 m, whereas the corresponding value for the southwestern Kara Sea is, in accordance with (Romanov, 1995), assumed to be 1.8 m. Also presented in Figure 4 are month-specific average ice coverage (c) values for the concerned sea areas as determined by (Riska, 1995). In accordance with the figure, a high ice coverage of 90-100 % is common in the period December-May.

Because our ice data is for the Pechora Sea / Kara Strait and the south/southwestern Kara Sea, we divide the route accordingly into three legs in accordance with Figure 5 so that we assume that the ice data provided for the Pechora Sea / Kara Strait applies for leg 2 and the ice data provided for the southwestern/western Kara Sea applies for leg 3. Leg 1 is assumed ice free.



Figure 4: Average month-specific (a) level ice thickness, and (b) ice coverage along the route.

In accordance with (Romanov, 1995), the annual maximum level ice thickness on the western Kara Sea is normally distributed with a mean value of 1.2 m and a standard deviation of 0.23 m. Assuming that that the standard deviation is proportional to the level ice thickness, we obtain a coefficient of variation of 0.23 /1.2 m = 19 %. We assume that this coefficient of variation also applies for the Pechora Sea.

The transport capacity of a ship on a fixed route depends on its cargo carrying capacity and turnaround time. The turnaround time depends on the ship's transit times, i.e., the time it takes for the ship to sail between the ports, as well as on its port turnaround times. In the specific case, because the route is assumed fixed and does not feature any speed limits, and because the ships are expected to operate independently at all time, we assume that speed is the only variable affecting their transit time. When operating in open waters, the speed of the ships is assumed to correspond to their service speed, whereas when operating in ice, the speed is assumed to correspond to the ship's achievable speed determined as a function of the ice thickness. The port turnaround times are assumed to follow a triangular distribution with a mean of 24 hours, a minimum of 23 hours, and a maximum of 36 hours as determined by Eq. 2.

 $T_{port_turnaround} \sim Tri(23, 24, 36) hr$ (2)



Figure 5: The route and legs of case study A.

The construction and operation of arctic ship is regulated by the mandatory Polar Code, which is entered into force on January 1st, 2017, aiming to protect ships operating in the Arctic against arctic specific risks (IMO, 2016). In accordance with the Polar Code, for a ship to be permitted to operate in at least medium first-year ice (70-120 cm), the ship needs to be classified as a category A ship (IMO, 2015). This requires the ship to be built in accordance with an International Association of Classification Societies (IACS) Polar Class (PC) 1-5 standard as determined by (IACS, 2016). Specifically, because the ships of the present case study are expected to encounter thick (> 120 cm) first-year ice, (IACS, 2016) requires that they are to be built in accordance with PC 4. In the present study, we apply the probabilistic ice load method presented in section 2.1 to assess whether this requirement is appropriate considering the actual ice exposure of the ships.

3.2 Analysis of the required level of model fidelity

We divide the analysis of the required level of model fidelity into two parts. In the first part, we focus on the required model fidelity for the estimation of the transit time. In the second part, we focus on the required model fidelity for the estimation of the required fleet size and ice class. In the following we present the analysed design model representing various levels of model fidelity.

Arctic design model 1

In this model, we define the ice conditions solely based on the level ice thickness (t) and the ice coverage (c) in accordance with Eq. 3.

$$H_{eq} = tc \tag{3}$$

The t-values are determined in accordance with Table 1 as 0.83 m, 1.18 m, and 1.34 m, corresponding to the average values for the southwestern Kara Sea in January, March, and May (Østreng, 1999). The ice coverage is assumed to be 100 % in all cases. The speed of the ship is determined in accordance with the simplified linear *h*-*v* curve represented by the dashed line in Figure 6.



Figure 6: Actual vs. simplified *h-v* curve.

Arctic design model 2

In this model we increase the model fidelity by applying the more realistic non-linear h-v curve represented by the continuous line of Figure 6. The h-v curve was calculated using a semi-empirical ship-ice performance prediction tool determined based on (Juva & Riska, 2002). However, as pointed out by (Bergström, et al., 2016b), such semi-empirical tools are generally determined for relatively small ships and might therefore not be accurate for large ships. Thus, in the present study we do not consider the estimated propulsion power requirement, which the applied ship-ice model appears to significantly overestimate.

Arctic design model 3

In this model, we increase the model fidelity by considering the effect of ice ridging by applying the concept of H_{eq} , which is based on the assumption that the speed of a ship depends on the average thickness of all ice features occurring in the area where the ship is operating. In the present model we assume that H_{eq} is determined in accordance with Eq. 4 as proposed by (Riska, 2010).

$$H_{eq} = \left(c - 2\frac{1}{\tan\alpha}\rho H_{r_{avg}}\right)t + \frac{1}{\tan\alpha}\rho H_{r_avg}^2 \tag{4}$$

where t = level ice thickness [m], c = ice coverage [percentage], $\alpha =$ average ridge slope angle [degrees], $H_{r_avg} =$ the average ridge keel draft [m], and $\rho =$ the average ridge density [1/m].

Eq. 4 is based on the simplifying assumption that each ridge has the form of a quadrangle formed by two isosceles triangles, one representing the ridge sail and the other representing the ridge keel, making it possible to describe the size of a ridge in terms of its keel draft H_r , slope angle α , and the ridge sail height H_s in accordance with Figure 7.

The average ridge sail height (H_{s_avg}) is determined based on the level ice thickness (t) assuming that the ratio $\frac{t}{H_{s_avg}}$ is normally distributed with a mean value of 0.91 and a standard deviation of 0.14 (Romanov, 1995). The average ridge keel draft (H_{r_avg}) is subsequently determined based on H_{s_avg} assuming that the ratio $\frac{H_{r_avg}}{H_{s_avg}}$ is uniformly distributed between 4 and 5 (ISO, 2010). We further assume that the feasible range of $\frac{t}{H_{s_avg}}$, i.e. the ratio between the level ice thickness and the average (prevailing) ridge sail height, is limited to 0.9 - 1. As a result, for an assumed average level ice thickness of 1.34 m, the average ridge sail height is within the range 1.3 - 1.5 m, and for the assumed maximum ice thickness of 1.8 m, the average sail height is within the range 1.8 - 2 m. The corresponding average keel depths (H_{r_avg}) ranges are 5.4-7.4 m and 7.2- 10 m respectively. The reader should note that these are average values and that the size of individual ice ridges might be significantly larger, something that is considered in Arctic design model 4-7.



Figure 7: Parameters describing the size and shape of an ice ridge.

The average slope (α) and the average ridge density (ρ) are known to be area and season specific. In this specific case, we assume in accordance with (Riska, 2010) that the average slope angle α is 25°, and in accordance with (Arpiainen & Kiili, 2006) that the average ridge density ρ is 2 /km.

Arctic design model 4

Because Arctic design model 3 only considers average ice characteristics, it fails to account for individual ice features such as large ridges that might stop or significantly slow down a ship. In this model, we address this issue by further increasing the model fidelity to make the model able to consider the effect of large individual ridges. To this aim, we model the ice cover and the ship's progress through the ice in accordance with Figure 8. This means that each leg is split up in a number of sub-legs

corresponding to the distance between two consecutive ridges, i.e., the ridge spacing (s_n) , so that the total leg distance equals the sum of the sub-leg distances $\sum s_n$. In accordance with (Hibler, et al., 1972), we assume that the ridge spacing follows a negative exponential distribution determined in accordance with Eq. 5.

$$p_d(x) = \rho e^{-\rho x} \tag{5}$$

, where ρ is the average ridge density [ridges/km]. We further assume that the feasible range of ridge spacing is 0.125 - 1.5 km corresponding to a ridge density range of 0.67 - 8 ridges /km. For an assumed statistical average ρ value 2.3 ridges/ km, this results in a sample average ridge spacing of approx. 0.5 km corresponding to a ridge density of 2 ridges/km as determined by (Arpiainen & Kiili, 2006). It should be noted that, in accordance with the applied distribution, the ridge density is below 4 ridges/km in 74% of the cases, which slightly differ from (Romanov, 1995), according to which the ridge density in the Arctic Basin is equal or below 4 /km in 88 % of the cases.

The sail eight of individual ridges are determined in accordance with (Leppäranta, 2011) assuming that the sail height is exponentially distributed above a specific cut-off height so that the total sail height is determined as $H_{s_cutt_off}+H_{s_above_cutt_off}$ where the probability density function of $H_{s_above_cutt_off}$ follows Eq. 6.

$$p(x) = \frac{1}{H_{s_avg} - H_{s_cutt_off}} e^{-\frac{1}{H_{s_avg} - H_{s_cutt_off}} x}, H_{s_avg} \ge H_{cut_off}$$
(6)

The keel draft H_R of individual ridges is determined based on the sail height assuming that the ratio H_R/H_S is uniformly distributed between 4 and 5 (Leppäranta, 2011). Assuming that the maximum feasible ridge sail height is 5 m, this results in a maximum ridge keel draft of 25 m, which is in line with (Romanov, 1995).

When a ship penetrates a large ridge, its resistance generally exceeds its trust meaning that it must penetrate the ridge using its momentum. A ship's ridge penetration capability is defined in terms of the maximum ridge size that the ship can penetrate with a single ram without losing all its momentum, i.e., without stopping. If a conventional ship encounters a ridge exceeding its ridge penetration capability, once it has got stopped, it has either to wait for IB assistance, or to try to penetrate the ridge by ramming it multiple times. A DAT, on the other hand, is able to penetrate large ridges independently at continuous speed without multiple ramming (Forsén, et al., 1998). This is achieved by using the ship's azimuth thrusters to disintegrate large ridges by flushing (Niini, et al., 2012). Based on (Valkonen & Riska, 2014), we assume that the ships are able to penetrate large ridges in this manner, in the following referred to as ice milling, at a constant speed of around 0.5 kn.



Figure 8: Parameters used for the modelling of a ship's progress in ice.

In accordance with Figure 8, if the keel draft (H_r) of either of the ridges defining a specific sub-leg exceed the ridge penetration capability of the ship, the sub-leg is further divided into two partial distances x_{na} and x_{nb} out of which either represent the distance covered by the large ridge corresponding to $\frac{H_r}{\tan \alpha}$ and other represent the remaining distance. In case both of the ridges defining a sub-leg exceed the ridge penetration capability of the ship, the sub-leg is divided into three partial distances x_{na} , x_{nb} , and x_{nc} out of which x_{na} and x_{nc} represent the distances covered by the two large ridges respectively and x_{nb} represent the intermediate distance. Distances covered by large ridges are completed at the speed associated with ice milling, i.e., at 0.5 knots, whereas the other distances are completed at a speed determined based on the prevailing H_{ea} and the ship's h-v curve.

Arctic design model 5

According to (Riska, 2010), snow on the top of the ice does not significantly increase the structural loading, but might increase the ice resistance of a ship. In this model, we account for this effect by converting the snow cover into equivalent ice thickness in accordance with Eq. 7.

$$H_{eq} = \left(c - 2\frac{1}{\tan\alpha}\rho H_{r_{avg}}\right)t + \frac{1}{\tan\alpha}\rho H_{r_{avg}}^2 + H_{snow}k_{snow},\tag{7}$$

where H_{snow} = snow cover depth and k_{snow} = 0.33. In accordance with (Romanov, 1995), in the Arctic Basin, the average snow depth H_{snow} occurring on level ice can be considered normally distributed with a mean value of 18 cm and a standard deviation of 7.2 cm. In the present study, we assume that this also applies for the route in question. In addition, we assume that the maximum average snow thickness is 30 cm.

Arctic design model 6

In order to determine the average ice exposure of the ships as well as the required fleet size, it is necessary to consider intermediate ice conditions, i.e., how the ice conditions develop throughout the year. This is challenging because the available data on intermediate ice conditions is very limited as ice data generally relates to the annual peak ice conditions. Several sources including (Løset, et al., 1998) indicates that the ridge density increases throughout an ice season. However, the available ridge density appears to represent an average value and fails thereby to describe how the ridge density develops throughout an ice season. On the upside, as stated in section 3.1, intermediate level ice thickness and coverage data is available. In this model, we model the intermediate ice conditions directly based the available data. Because the available data is month specific, this means that we assume that the ice conditions change once per month in accordance with the dashed line of Figure 9. Because we do not have access to intermediate ice ridging data, we assume that the average ridge density is constant throughout the ice season.

Arctic design model 7

It is well known that sea ice conditions are constantly changing, sometimes very fast. Thus, assuming that the ice conditions change monthly might lead to misleading results. In accordance with ice thickness growth studies presented by for instance (Høyland, 2009), ice thickness growth appears, for limited growth ranges, to be linear with respect to time. Thus, in this model, we assume that ice conditions develop linearly from one month to another. Based on this assumption, we convert the given month-specific conditions into day-specific ones by the means of linear interpolation. The resulting day-specific ice conditions are compared to the corresponding month-specific ice conditions in Figure 9.

Comparison of models

In order to assess how the level of model fidelity affects the estimated transit time, we apply Arctic design model 1-5 for the estimation of the transit time for leg 3 for the three different ice conditions

specified in Table 1. The outcome of the analysis, which is presented in Figure 10, indicate that the estimated transit time increase significantly with the increase of the level of model fidelity. Assuming that all the models are correct, this leads us to the conclusion that it is motivated to apply the highest model fidelity, i.e., Arctic design model 5.



Figure 9: Month- vs. day-specific ice conditions.

In order to assess how the level of model fidelity affects the estimated required fleet parameters and ice class, we apply Arctic design model 6-7 for the determination of those design parameters. The outcome of the analysis, which is presented in Figure 11, indicates that the use of month-specific ice conditions result in a more conservative estimation of the transport reliability. For instance, for a desired transport reliability of 100 %, the use of month-specific ice conditions resulted in fleet size requirement of 16 x 170,000 m³ ships, whereas the use of day-specific ice conditions resulted in a fleet size requirement of 15 x 170,000 m³ ships. This deviation is explained by the fact that when using month-specific ice conditions, the duration of the peak ice conditions is longer than when using day-specific ice conditions.

Table 1: Analysed ice scenarios

Ice condition scenario	1	2	3
Level ice thickness (t)	0.83 m	1.18 m	1.34 m
Ice coverage (c)	100 %	100 %	100 %
Average ridge sail height range $(H_{s avg})$	[0.83, 0.92], m	[1.18, 1.31] m	[1.34, 1.49] m
Average ridge keel draft range $(H_{r avg})$	[3.3, 4.6],m	[4.7, 6.6], m	[5.2, 7.5] m
Average ridge density (ρ)	2 /km	2 /km	2 /km
Ridge density range (ρ)	[0.67, 8] 1/km	[0.67, 8] 1/km	[0.67, 8] 1/km
Average ridge slope angle	25°	25°	25°
Average snow depth range (H_{snow})	[0, 30] cm	[0, 30] cm	[0, 30] cm



Figure 10: Effect of model fidelity on the estimated transit time. M1-5 refers to Arctic design model 1-5.



Figure 11: Effect of model fidelity (a) on the estimated required fleet size, and (b) on the estimated ice loading. M6-7 refers to Arctic design model 6-7.

The use of month-specific ice conditions resulted in an average exposure to thick (>120 cm) first-year ice of 2,920 NM/year, whereas the use of day-specific ice conditions resulted in a slightly lower exposure of 2,730 NM. The corresponding 100-year maximum ice loading, determined in accordance with Eq. 1 in terms of the 100-year maximum nominal pressure as a function of the design area, is presented in Figure 11. As shown in the figure, the slight deviation in the ice exposures as determined by Arctic design model 6-7 did not result in any significant deviation in the calculated ice loading. To assess if the prescribed ice class PC 4 provides a sufficient level of ice strengthening, the calculated pressure curves are compared with the design loads of PC 3-7. In accordance with the figure, the calculated pressure stays within the design load range of PC 4 for design areas larger than approx. 0.62 m². Thus, if we in accordance with (Taylor, et al., 2009) assume that the minimum design area of interest is around 0.6 m², we can conclude that PC 4 generally provides a sufficient level of ice-strengthening.

The resulting ice loading was determined in accordance with Eq.1 assuming an impact frequency of 10/NM, and *C* and *D* values of 0.38 and -0.79 respectively. The applied *C* and *D* values, which were determined based on (Taylor, et al., 2009), correspond to ice loads measured in April 1983 in the northern Chukchi Sea. These values were applied in the lack of corresponding values determined specifically for the south Kara Sea or the Pechora Sea.

3.3 Sensitivity analysis

Identification of uncertainties

In terms of month-specific average level ice thicknesses, our default values are determined in accordance with (Østreng, 1999). An alternative set of data is provided by (Arpiainen & Kiili, 2006). However, the data presented by the two sources is not directly comparable. (Østreng, 1999) assumes that the same level ice thickness value applies for the whole area covered by leg 3 (south Kara Sea), whereas (Arpiainen & Kiili, 2006) divides that area into two parts: the centre and the western Kara Sea. In order to make the data comparable, we assume that the data provided by (Østreng, 1999) for the south Kara Sea corresponds to the average of the data provided by (Arpiainen & Kiili, 2006). Based on this assumption, the level ice thickness values provided by the two sources for leg 2 and leg 3 are compared in Figure 12. In accordance with the figure, the average level ice thickness values presented by (Østreng, 1999) are higher than those presented by (Arpiainen & Kiili, 2006). For instance, for leg

3, (Østreng, 1999) proposes and average of 1.34 m, whereas the data provided by (Arpiainen & Kiili, 2006) results in an average of 1.15 m.

Our default month-specific average ice coverage values are determined based on (Riska, 1995). An alternative set of ice coverage values are determined by (Arpiainen & Kiili, 2006). Like in the case of the level ice thickness values, the data provided by the two sources are not directly comparable. In order to make the data provided by the two sources comparable, we assume that the data provided by (Riska, 1995) for the Pechora Sea corresponds to the data provided by (Arpiainen & Kiili, 2006) for the Kara Gate, and that the data provided by (Riska, 1995) for the western Kara Sea corresponds to the average of the data provided by (Arpiainen & Kiili, 2006) for the average of the data provided by (Arpiainen & Kiili, 2006) for the western and centre Kara Sea. Based on this assumption, the average ice coverage values provided by the two sources are compared in Figure 12. In accordance with the figure, (Arpiainen & Kiili, 2006) indicate that the maximum average ice coverage value is 98 %, whereas (Riska, 1995) indicate that that value is nine tenths or 90 %.

We assume a default average ridge density (ρ_{avg}) of 2.2 ridges/km for the whole route (Romanov, 1995). Alternative values are presented by (Arpiainen & Kiili, 2006), according to which the average ridge density might reach 3 ridges/km in the area covered by leg 3, and 8 ridges/km in the area covered by leg 2. An example of how the different determinations of ρ_{avg} might affect the occurrence of randomly determined ridge densities is presented in Figure 12. It should be pointed out that none of the sources indicate how the ridge density develops throughout the ice season.

For the average ridge slope, we assume as default value of 25° (Riska, 1995). An alternative value of 30° is proposed by (Leppäranta, 2011). Corresponding ridge shapes are compared in Figure 12. It should be pointed out that neither of the applied sources indicate how the average slope develops throughout the season, nor do they suggest any measure of variability.

For the determination of the average ridge sail height H_{s_avg} , as default we assume in accordance with (Romanov, 1995) that the average sail height can be determined based on the level ice thickness assuming that the t/H_{s_avg} is normally distributed with an average of 0.91 and a standard deviation of 0.14 (for the southwestern Kara Sea). In order to avoid unrealistic values, we limit the feasible range of the ratio to [0.9,1]. We have not found any alternative measure of variability for the ratio t/H_{s_avg} . However, some sources determine H_{s_avg} as a standalone value independent of other ice characteristics. For instance, according to (Leppäranta, 2011), representative values for H_{s_avg} in the Arctic are 1.2 – 1.4 m. Examples of how the chosen definition of H_{s_avg} might influence obtained ridge keel draft values is presented in Figure 12.

As default, we determine the average ridge keel draft H_{r_avg} based on the average ridge sail height H_{s_avg} assuming, in accordance with (ISO, 2010), that the ratio H_R/H_S is between 4 and 5. However, according to (Riska, 1995), the ratio in question typically varies between 5 and 7. Because none of the sources determine any specific distribution, we assume that the ratio is uniformly distributed.

As default, we determine H_{eq} in accordance with Eq. 7. Alterative definitions include Eq. 8 determined based on (Leppäranta, 1980) and Eq. 9 determined based on (CNIIMF, 2014).

$$H_{eq} = tc + \frac{1}{\tan \alpha} H_{r_{\alpha} v g}^{2} \rho + k_{\text{snow}} H_{\text{snow}}$$

$$H_{eq} = tc + 0.25 i t + \Delta H_{snow}$$
(8)
(9)

, where i = the amount of ice hummocking (in balls), $\Delta H_{snow} = k_{snow} * H_{snow}$, $H_{snow} =$ depth of snow cover, $k_s = 0.33$ for $H_{snow} < 0.5$ m and 0.50 for $H_{snow} \ge 0.5$ m.



Figure 12: Visualization of analysed design uncertainties with respect to the assumed (a) average month-specific level ice thickness, (b) average month-specific ice coverage, (c) ridge density, (d) slope angle, (e) method for determining ridge sail height, (f) definition of H_{eq}

The definition given by Eq. 8 differ from the definition by Eq. 7 in that it does not deduct level ice overlapping ridges, leading to a higher H_{eq} estimate. The definition by Eq. 9 differ from the other H_{eq} definitions in that it quantifies the amount of ridging on a so-called ball scale, which is a relative scale used in Russian maritime and ice related science (Heideman, 1996). When applied on ice ridging, the scale relates to the percentage of an ice cover that consist of ridged ice so that one ball represents 20 % area coverage (Heideman, 1996). Thus, if for instance the amount of ridging in an area is estimated at 2 ball, this means that 40 % of the ice cover in that area consists of ridged ice. This approach is suitable for the modelling of average ridging. However, because it does not consider the size of individual ridges, nor the distance between consecutive ridges, it is not compatible with our high fidelity ice model, i.e.,

Arctic design model 5. Also, it should be noted that Eq. 9 limits the value of the H_{eq} to 125 % of the prevailing level ice thickness. Using Eq. 7 and Eq. 8, significantly higher values can be obtained. A comparison between H_{eq} values calculated in accordance with Eq. 7 and Eq. 8 is presented in Figure 12.

Due to climate change, ice conditions in the Arctic are expected to decrease. However, there is large uncertainty in terms of the magnitude and rate of the decrease. Studies on climate change generally describe sea ice conditions development trends in terms of variations in the total extent (km²) of Arctic sea ice. However, because we are not in the position to link such variations to variations in the average ice thickness along our route, we choose to determine random future ice scenarios in accordance with Figure 13 for two different scenarios: 1. The ice conditions remain statistically unchanged, 2. The average annual maximum level ice thickness decreases by 1.5 % per year.



Figure 13: Considered ice condition development trends: (a) statistically unchanged ice conditions, (b) decreasing ice conditions.

Assessment of the effect of the identified uncertainties

The first part of the sensitivity analysis is carried out by analysing how sensitive the estimated 100-year maximum transit time is to variations in the definition of various parameters. Analysed variations are determined based on the above identified uncertainties in accordance with Table 2. In order to make the calculated maximum values comparable, i.e., in order to single out the effect of the definition of an individual ice parameter, the stochastic parameter values are determined using a default random seed, meaning that the same random numbers are generated in each run.

The outcome of the analysis, which is presented in Figure 14, indicates that the estimated 100-year maximum transit time is sensitive to numerous potential uncertainties. In accordance with the figure, the estimated transit time was found to be the most sensitive to the variations in the definition of the H_R/H_S ratio, with definition 2 resulting in a 37 % higher 100-year maximum that definition 1. Variations in the definition of H_{eq} was found to have the second largest impact, tightly followed by variations in the assumed average month-specific ice thickness. Variations in the definition of the

average ridge sail height was found to have the smallest impact. Nevertheless, the more conservative definition resulted in a 4 % higher maximum transit time.

Factor	Definition 1 (default)	Definition 2
t_{avg}	1.34 m	1.15 m
$C_{av,g}$	90 %	98 %
ρ^{-}	2 /km (leg 2-3)	8 /km (leg 2), 3 /km (leg3)
α	25°	30°
H_R/H_S	Unif(4,5)	Unif(5,7)
H_S	$\frac{t}{H_s} = N(0.91, 0.14^2)$	Unif (1.2,1.4)
H_{eq}	According to Eq. 7	According to Eq. 8
tavg-trend	No trend	1.5 % decrease per year

Table 2: Analysed parameter variations with respect to transit time



Figure 14: Sensitivity of the estimated 100-year maximum one-way transit times to variations in various parameter definitions (default random seed). Definition 1-2 are determined in accordance with Table 2.

The second part of the sensitivity analysis consist of analysing how sensitive the estimated 100-year maximum ice loading, determined in terms of the 100-year maximum nominal pressure as a function of the design area, is to uncertainties in related design parameters. In accordance with Eq. 1, a ship's estimated maximum ice loading depends on the ship's annual ice exposure (x), the impact frequency (f), and the empirically determined C and D values. In our simulation model, the simulated ice exposure depends primarily on the modelling of the level ice thickness along the route. Thus, we analyse the sensitivity of the calculated ice loading to the assumed average month-specific average level ice thickness values, as well as to possible ice condition development trends. In addition, we analyse the sensitivity of the calculated ice loading to variations in the f, C, and D values. An exact description of the analysed parameter variations is provided in Table 3.

Table 3: Analysed parameter variations with respect to ice loading. * Values determined based on Taylor et al. (2009) corresponding to ice loads measured in March 1983 on the northern Bering Sea.

Factor	Definition 1 (default)	Definition 2
t_{avg}	According to Østreng (2009)	According to Arpiainen and Kiili (2006)
tavg-trend	No trend	1.5 % decrease per year
f	10 /NM	15 /NM
<i>C</i> , <i>D</i>	0.38, -0.79	0.28*, -0.62*

The outcome of the analysis, which is presented in Figure 15, indicates that the estimated maximum ice loading is the most sensitive the definition of the C and D values. It is also relatively sensitive to possible long-term ice conditions development trends. On the upside, it appears insensitive to minor variations in the impact frequency and the assumed average level ice thickness.



Figure 15: Sensitivity analysis of the estimated ice loading with regards to (a) the assumed average tvalues, (b) the assumed ice condition development trend, (c) the assumed impact frequency, (d) the applied *C* and *D* values

Figure 15 also shows design area specific design loads for PC 3-7. For all analysed sets of parameter values, for design areas larger than approx. 0.65 m^2 , the calculated ice pressures stay within the design load range of PC 4. Thus, if we in accordance with (Taylor, et al., 2009) assume that the minimum design area of interest is approx. 0.6 m^2 , these findings indicate that PC 4 generally provides a sufficient level of ice-strengthening. Only by replacing the default (definition 1) *C* and *D* values, determined based on ice loads measured in the north Chukchi Sea in April 1983, with C and D values determined based on ice loads measured in the north Bering Sea in March 1983 (definition 2), the obtained ice pressure curve drops below the design load range of PC 4, indicating that PC 3 would be sufficient.

Uncertainty mitigation

The above presented outcome of the sensitivity analysis indicates that the estimated transit time is sensitive to numerous possible uncertainties. Naturally, any uncertainty in the estimated transit time is translated into uncertainty regarding the required fleet characteristics (e.g. fleet size, ship size, and ship speed) to meet the transport demand. Thus, in the following we demonstrate what effect such uncertainties could have on decision making concerning the determination of fleet characteristics, and how such uncertainties could be mitigated.
In the present design case, we identify four main uncertainty mitigation approaches:

- 1. Mitigation by reserve ship speed. This requires that the ships are fitted with reserve propulsion power that can be utilized to mitigate the effect of higher than expected ice resistance.
- 2. Mitigation by reserve ships. This requires access to reserve ships that can be used to compensate for a loss in transport capacity per ship caused by slower than expected ship speed.
- 3. Mitigation by flexible contracting. This requires a contract that allows the operator to ship the cargo to a more nearby destination port for instance in the case of unusually difficult ice conditions.
- 4. Mitigation by reserve port-based storage capacity. This requires a reserve storage capacity that allows a temporary shortage in the transport capacity caused by for instance lower than expected ship speed.

In the present study we focus on the two first mitigation strategies, i.e., mitigation by ship speed as well as mitigation by reserve ships. The merits of the third and fourth strategies are already analysed by (Bergström, et al., 2016a). In accordance with that study, for an AMTS similar the one of the present case study, the merits of mitigation by flexible contracting was found to be in-efficient, whereas mitigation by reserve port-based storage capacity was found to be efficient.

The outcome of the analysis of various uncertainty mitigation approaches is presented in Figure 16. If we assume that the ice data provided (Arpiainen & Kiili, 2006) is correct, we conclude that a fleet of 14 ships is sufficient. If we instead choose to believe in the ice data provided by (Østreng, 1999), we conclude that 15 ships are required. Alternatively, the ice-going capability of the ships, defined as the maximum ice thickness is which the ships can maintain a speed of 2 knots, has to be increased by approx. 5 % from 2.1 m to 2.2 m.



Figure 16: Analysis of various uncertainty mitigation alternatives.

Likewise, if we choose to believe that the ice conditions will decrease in accordance with the assumed trend, we conclude that a fleet of 13 ships is sufficient. If we instead choose to believe that the ice

conditions will remain statistically unchanged, we conclude that the required fleet size is 15 ships Alternatively, the ice-going capability of the ships would have to be increased by approx. 12 %.

In the above analysis, we assume that all ships operate independently at all time and have the same icegoing capability. If the ships would operate in convoys of two ships, half of the ships could have a lower ice-going capability as they could be assisted by another ship with a higher ice-going capability. This would mean that it would be sufficient to fit half of the ships with a power reserve. In order to assess the merits of such convoy operations, we carried out an analysis in which ships operate in convoys of two ships that follow each other at a time distance of 15 minutes. The outcome of the analysis, presented in Figure 17, indicates that convoy operation has a significant effect on the required fleet size. Specifically, the simulation results indicate that convoy operations result in longer maximum periods between port visits. In addition, because the ships operate in pairs, for instance a prolonged port turn-around time of one of the ships affects both of them. Thus, based on the above findings we conclude that convoy operation is not suitable for the transport of LNG requiring frequent port visits.



Figure 17: Fleet size requirements for convoy vs. non-convoy operation.

4 Case study B

4.1 Introduction

This case study deals with the design of an AMTS for the transport of stainless steel from Tornio (Finland) to Terneuzen (the Netherlands) following the approx. 1,454 NM route presented in Figure 19. In winter, segments of the route, in particular the most northern ones crossing the Gulf of Bothnia, are generally ice infested. In these areas, the annual maximum ice thickness is typically 50- 80 cm thick, but might exceed 100 cm.

In accordance with (Ship2shore.it, 2010), we assume that the annual transport demand is 600,000 tonnes of steel. In addition, in order to limited the required cargo storage capacity, we assume that continuous year-round operation is required. The steel is to be transported in specially designed containers, each with a maximum payload of 40 t (Langh Cargo Solutions, 2016). Thus, in order to meet the transport demand, a total of 15,000 loaded TEU is to be transported annually.

The design task is to determine the required fleet parameter in terms of the number of ships, as well as the capacity and speed (h-v curve) of each ship, to meet the transport task in accordance with all relevant regulations. Naturally, the range of feasible solutions is limited by both physical and regulatory design constraints. With regards to physical design constraints, we assume that the maximum feasible ship size is limited by the 7.6 m draft limitation set by the port of Tornio (Ports.com, 2016). As a simplification, we assume that this draft limitation limits the maximum feasible ships capacity to that of m/s Hjördis,

which at 14 t homogenous load per TEU has a capacity of 320 TEU equalling a total payload of 4,480 t (Langhship, 2016).

In accordance with (Sjöfartsverket, 2016), in order to enable year-round operations, the ships need to be built in accordance with an ice class standard that is equivalent to or higher than the Finnish-Swedish ice class 1A. In the present study, we assume in accordance with (Trafi, 2010a) that the Finnish-Swedish ice classes 1A and IA Super roughly correspond to the IACS ice classes PC 7 and PC 6 respectively. Based on this assumption, we apply the probabilistic design load method presented in section 2.1 to access whether the minimum required ice class 1A is sufficient for the ships considering their simulated ice exposure.



Figure 18: Example ice chart (SMHI, 2016).

As a part of the design of an AMTS, it is necessary to determine an ice mitigation strategy describing how the system will deal with sea ice (Bergström, et al., 2016b). In the present case, because the ships will operate mostly in open water, and because the IB fee is determined based on the gross tonnage and ice class of a ship, and not based on whether or not it requires IB assistance, we decide that the ships are to be of type ice-strengthened ships. This means that the ice navigation of the ships is primarily limited to operation in brash ice channels prepared by an IB. As a result, the ships can be fitted with a bulbous bow for good open water performance.

In contrary to Arctic seas, historical ice conditions in the Baltic Sea are well documented in terms of ice charts, an example of which is presented in Figure 18. Such ice charts, provided by for instance (SMHI, 2016), describe the ice conditions in terms of ice type (e.g. fast ice, close ice), level ice thickness range, as well as the occurrence of for instance ridged ice. In addition to the ice charts, there are numerous studies determining various probabilistic characteristics of sea ice characteristics (e.g. ridging) in the Baltic Sea.

As a simplification when modelling the ice conditions, we assume that the route can be divided into legs along which the ice conditions are assumed statistically constant (e.g. meaning that the level ice thickness and coverage is assumed constant). By studying ice charts provided by (SMHI, 2016), aiming to identify typical ice condition patterns in terms of where and when different types of ice conditions typically occur, we decided to divide the route into 8 such legs in accordance with Figure 19. The occurrence of ice is assumed to be possible along leg 1-7, which are 20-90 NM long. The other half of the route, represented by leg 8, is assumed permanently ice free.

In order to assess the turnaround times of the ships, it is necessary to determine their open water speed, brash ice speed, IB waiting times, and port turnaround times. In accordance with the reference ship MS Hjördis, we determine that the open water speed of the ships is 16 knots. The Finnish-Swedish ice class 1A notification, in turn, requires a ship to be able to maintain a minimum speed of 5 knots in up to 1.0 thick brash ice (Trafi, 2010b). Based on these speed requirements, we determine that the required speed of the ships in accordance with the *h*-*v* curve presented in Figure 20.



Figure 19: Route and legs of case study B.



Figure 20: Required *h*-*v* curve (IB assisted operation).

In accordance with (BIM, 2015), the goal of the Finnish maritime authorities is that the average waiting time for IB assistance should not exceed 4 hours and that most ships should not have to wait at all. Based on this goal, we assume that the IB waiting time is distributed in accordance with the triangular distribution presented by Eq. 10, resulting in a sample mean waiting time of approx. 4 hours.

$$T_{IB \text{ waiting } time} \sim Tri(0, 0.25, 12) hr$$
(10)

The port turnaround time include time for manoeuvring, mooring, and unloading/loading. Based on a sample of real-life port turnaround times of feeder container ships published by the (Port of Helsinki,

2016), we assume that the port turnaround times of the ships are distributed in accordance with the triangular distribution presented by Eq. 11.

 $T_{port_turnaround} \sim Tri(8,12,16) hr$ (11)

4.2 Analysis of the required level of model fidelity

Following the example of the previous case study, we divide the analysis of the required level of model fidelity into two parts. In the first part, we analyse the required level of model fidelity for the estimation of the ship's transit times. This is carried out by estimating the transit time for the one-way route (distance 1,454 NM) for three different ice scenarios using 4 different design models. The three different ice scenarios are determined in terms of level ice thickness (t) and ice coverage (c) ranges in accordance with Figure 21. Both the t-and c- values are assumed to be distributed in accordance with a triangular distribution where the maximum, minimum, and mean values correspond to the maximum, minimum, and mean of their value range. In the second part, we analyse the required model fidelity for the estimation of the required ice class of the ships as well as of the required fleet size. This is carried out by estimating the required ice class and fleet and ship size using two different design models. In the following we present the applied design models representing different levels of model fidelity.

Baltic design model 1

In this model, we determine the ice conditions in terms of an equivalent ice thickness (H_{eq}) determined solely based on the level ice thickness (t) and the ice coverage (c) in accordance with Eq. 12.

$$H_{eq} = tc \tag{12}$$

Baltic design model 2

In this design model, we increase the model fidelity by considering average ice ridging in accordance with Eq. 13.

$$H_{eq} = tc + \rho_{avg} H_{eq \ per \ ridge} \tag{13}$$

, where t=level ice thickness, c=ice coverage, ρ =ridge density (ridges/km), and $H_{eq_per_ridge}$ = equivalent ice thickness contribution per ridge (m/ridge).

Eq. 13 is determined in accordance with (Leppäranta, 1981b) based on the assumption that the average ridge sail height in the Baltic Sea is nearly constant and that the volume of ridged ice therefore can be estimated based on the number of ridges per km. In accordance with (Leppäranta, 2011), on the Baltic Sea one ridge contributes on average 2.2 cm \pm 27 % to the equivalent ice thickness. Thus, in the present study we assume that the contribution per ridge ($H_{eq_per_ridge}$) is distributed in accordance with a triangular distribution with a mean value of 2.2 cm, a minimum value of 1.61 cm, and a maximum value of 2.79 cm. The average ridge density (ρ_{avg}) is determined in accordance with (Riska, 1995) as 6.8 ridges/km. Based on these assumption, ice ridging in the Baltic Sea contributes to H_{eq} by 11-19 cm. An example of how ice ridging might contribute to H_{eq} is shown in Figure 22. Naturally, this simplified averaging approach for the modelling of ice ridging fails to consider local variations in ridge density and size, something that is considered in the higher fidelity models presented in the following.



Figure 21: Level ice thickness and ice coverage ranges of the analysed ice scenarios 1-3.



Figure 22: H_{eq} with and without the consideration of average ice ridging.

Baltic design model 3

According to (Leppäranta, 1981a), the ridge density in the Gulf of Bothnia vary between 2.1 and 22.1 ridges /km. In the present design model we aim to assess the influence of locally varying ice ridge densities by dividing the main legs into sub-legs, each with a distance of approx. 1 NM, for which the ice ridge density is determined individually, resulting in a varying H_{eq} values. In accordance with (Hibler, et al., 1972), ice ridge spacing, i.e., the distance between two subsequent ice ridges, can be assumed distributed in accordance with a negative exponential distribution as determined by Eq. 14.

$$p(x)dx = p_{avg}e^{-p_{avg}x}dx \tag{14}$$

From Eq. 14 follows that probability of finding x ridges in a segment of length L follows a Poisson distribution determined in accordance with Eq. 15 (Hibler, et al., 1972).

$$p(x) = \left[\frac{(Lp_{avg})^{x}}{x!}\right] e^{-Lp_{avg}}$$
(15)

An example of how H_{eq} might vary along a leg in accordance with Eq. 15 is presented in Figure 23.

In contrary to Arctic design model 4-7, this design model does not consider the size of individual ridges. Instead it considers the average amount of ice ridging found over a distance of 1 NM. In the present design case, based on the assumption that IBs operating on the Baltic Sea rarely get stopped by individual ridges, meaning that the transit time for an assisted distance is primarily dependent on the total ice volume in the area, we believe that this modelling approach is appropriate. We recognize that IBs operating on the Baltic Sea occasionally get stopped by individual large ice ridges. However, we assume that this is a rare event that is primarily relevant for safety considerations, e.g., for the assessment of the risk of a collision between IBs and assisted ships, and not for the assessment of the long-term transport capacity of the latter.



Figure 23: Example of H_{eq} -values along a segment of the route as determined with and without sublegs.

Baltic design model 4

In the archipelago immediately outside the port of Tornio, represented by Leg 1 (approx. 20 NM) stationary fast ice generally occurs. As a result, an ice channel with consolidated ice thicker than the surrounding ice might form. It is well known that such channels, in the following referred to as old ice channels, might cause a significant increase in ice resistance, but as pointed out by (Aker Arctic, 2006), there is a lack of knowledge both with regards to their formation and effects on ships. Anyhow, according to the same source, when operating in an old ice channel the speed of a typical 1A Super classed ship with IB assistance might drop to around 2 knots. In the present design model, in order to account for this effect, we assume that the speed of the ships operating in an old ice channel depends on the value of the surrounding H_{eq} in accordance with Figure 24.



Figure 24: Assumed effect of an old ice channel on ship speed.

Baltic design model 5

In order to estimate the ice exposure of the ships as well as to estimate their annual transport capacity, it is necessary not only to consider the annual peak ice conditions, but to also consider intermediate ice conditions. Given the rich availability of historical ice data provided by for instance (SMHI, 2016), it is possible to model past ice conditions, including intermediate ice conditions, with reasonably accuracy. However, the consideration of all available ice data would be very laborious. Thus, in the present model, as a simplification, we choose to only consider mid-month ice conditions, i.e., we assume that mid-month ice conditions represent the whole month. An example of the implementation of this simplification is shown by the dashed line of Figure 25.



Figure 25: Example of month- vs. day-specific ice conditions.

Design model 6

Sea ice conditions are in a continuous state of change. In the present model, in order to account for this fact, we assume that the ice conditions develop linearly. Based on this assumption, we convert the moth-specific ice conditions applied in design model 5 into day-specific ice conditions by the means of linear interpolation. An example of such gradually changing ice conditions is given by the continuous line of Figure 25.

Application and comparison of design models

A comparison of the transit times estimated by Baltic design model 1-4 is presented in Figure 26. In accordance with the figure, both the consideration of average ridging and the consideration of the effect of old ice channels do significantly affect the estimated transit time. The consideration of locally varying ridge densities, on the other hand, does not appear to have any significant impact on the result. As a result, we conclude that it is not motivated to divide the legs into sub-legs, but that all of the other design model features are justified.

In Figure 27 we present a comparison between Baltic design model 5-6 in terms of the estimated required fleet and ship size. In accordance with the figure, the outcome of the two models is similar. In both cases, the outcome indicates that a fleet of 4 ships each with a payload capacity of 4,219 tonnes is required to meet the transport demand in the 100-year operating conditions, i.e., the worst combination of operating conditions that is expected within a period of 100 years. This outcome agrees well with (Ship2shore.it, 2010), according to which a corresponding transport task is carried out by a fleet of four ships including MS Laura (6,535 dwt), MS Hjördis (6,526 dwt), and MS Marjatta (6,257 dwt), and MS Tingo (4,452 dwt).

The use of month-specific ice conditions (Baltic design model 5) resulted in an average exposure to medium thick (70-120 cm) first-year ice of 37 NM/year, whereas the use of day-specific ice conditions (Baltic design model 6) resulted in a slightly lower exposure of 25 NM. However, in accordance with Figure 27, presenting the 100-year maximum nominal pressure as a function of the design area as calculated in accordance with Eq. 1, this did not result in any significant difference in terms of the

estimated level of ice loading. By comparing the calculated ice pressure curves with the design loads of PC 5-7, also presented in Figure 27, we can conclude that for design areas above approx. 0.6 m2, which according to (Taylor, et al., 2009) typically is the minimum design area of interest, the calculated load curves stay within the design load range of PC 7. Thus, assuming that PC 7 equals the Finnish-Swedish ice class 1A, these findings indicate that there is no motivation to deviate from the prescribed ice class requirement.





The resulting ice loading was determined in accordance with Eq. 1 assuming an impact frequency of 10 /NM. The *C* and *D* values were determined in accordance with (Taylor, et al., 2009) as 0.28 and -0.62 respectively, corresponding to ice values measured in March 1983 in the northern Bering Sea. These values were applied in the lack of corresponding values determined specifically for the Bay of Bothnia / Baltic Sea.



Figure 27: Effect of model fidelity on (a) the estimated required fleet and ship size, and (b) on the estimated ice loading. M5-6 refers to Baltic design model 5-6.

Examples of ice conditions based on which the required ship size and ice class were determined are presented in Figure 28. The figure presents 25 randomly determined ice seasons determined based on ice data for the period 1992-2016. The 100-year conditions were simulated by determining four different 25-year periods based on the same ice data. However, because of the roughness the raw data, each randomly determined ice season is unique. This is verified by Figure 29, displaying variations in the simulated annual transport capacity of the AMTS for the simulated 100-years. It needs to be emphasized that the aim here is not to simulate 100-consecutive years, but to simulate 100 random operating for the assessment of the stochastic performance of the AMTS.



Figure 28: Example of simulated ice scenarios for mid-February. Each column related to the average H_{eq} along a specific leg.



Figure 29: Simulated variations in the annual transport capacity of the AMTS.

4.3 Sensitivity analysis

Identification of uncertainties

Historical ice data for the Baltic Sea is primarily presented in terms of ice charts provided by for instance (SMHI, 2016). The ice charts are based both on satellite pictures and local observations and can therefore be considered accurate. However, as already demonstrated in section 4.2, the data presented by the ice charts is not very precise. For instance, the prevailing level ice thickness is generally

determined in terms of thickness ranges where the upper limit value is more than 50 % larger than the lower limit value (e.g. the ice thickness is determined as 40-65 cm, 15-30 cm, or 20-35 cm). In addition, the ice thicknesses distribution within the specified thickness ranges is not known.

The ice charts determine where ice ridges and hummocked ice occur, but they do not specifically quantify the average ridge density or size. On the upside, ice ridging characteristics on the Baltic Sea, and how these should be modelled, are addressed by multiple studies. However, some of the studies have resulted in conflicting results. Among others, we have paid attention to conflicting definitions of H_{eq} . As default, we define H_{eq} in accordance with Eq. 13 determined based on (Leppäranta, 2011). Alternative definitions include Eq. 16 determined based on (Lensu, 2003), and Eq. 17 determined based on (Leppäranta, 1980).

$$H_{eq} = tc + \rho \gamma h_s^2 \tag{16}$$

$$H_{eq} = t c + \frac{1}{\tan \alpha} h_{r_{-}avg}^2 \rho + k_{\text{snow}} t_{\text{snow}}$$
(17)

, where t = level ice thickness (m), c = ice coverage, $\rho =$ the average ridge density (1/m), $h_{eq_ridge} =$ average h_{eq} -contribution per ridge, $\gamma =$ a ridge volume factor (≈ 0.129).

The average ridge density is another ice ridging related feature that has been defined differently by different studies. Our default average ridge density of 6.8 ridges/km is determined in accordance with (Leppäranta, 1981a). (Leppäranta, 1980), on the other hand, found that the mean ridge density in the Bothian Bay in March 1977 was 7.5 ridges/km, whereas (Aker Arctic, 2006) assumed ridge densities between 2 and 6 ridges/km for a route crossing the Bay of Bothnia. For the purpose of the present sensitivity analysis, we assume a lower average of 5 ridges/km.

Because the ships of the present case study are dependent on IB assistance, they need to wait for IB assistance whenever they encounter ice. Difficult ice conditions, or an increase in the number of ships in need of IB assistance (e.g. due to the upcoming EEDI regulations limiting the propulsion power of ships), might result in longer waiting times for IB assistance. In order to assess the effect of such a potential increase, we determine an alternative distribution for $T_{IB_waiting_time}$ in accordance with Eq. 18. Compared to our default distribution for $T_{IB_waiting_time}$ determined in accordance with Eq. 10, the mean waiting time is increased from 15 min to 30 min, and the maximum waiting time is increased from 12 hours to 18 hours.

$$T_{IB_waiting_time} \sim Tri(0, 0.5, 18) hr$$
(18)

In order to determine the sensitivity of the estimated transit time to various uncertainties, we calculate the maximum transit time for 2-3 different definitions of a number of design factors in accordance with Table 4. Differences between the various definitions are visualized in Figure 30.

Table 4: Analysed parameter uncertainties with regards to transit time

Factor	Def. 1 (default)	Def. 2	Def. 3
Level ice thickness range distribution	Triangular	Uniform	-
Ice coverage range distribution	Triangular	Uniform	-
Definition of Heq	Eq. 13	Eq. 16	Eq. 17
Average ridge density, ρ_{avg}	5	6.8	7.5
Ice condition trend	No trend	Decreasing	-
IB waiting time	Eq. 10	Eq. 18	-

The outcome of the sensitivity analysis with regards to transit time is presented in Figure 31. In accordance with the figure, the estimated transit time is the most sensitive to the variations in the definition of the distribution of $T_{IB_waiting_time}$ as well as in the definition of H_{eq} . Variations in the

choice of distribution for the level ice thickness and coverage ranges did not have any significant effect on the outcome.

It should be pointed out that we in the above study did not consider the effect of compressive ice, which might cause a ship both significant added resistance and ice loads (Riska, 1995). As demonstrated by (Haapala, 2013), in the case of severe compressive ice, even ships with the required ice class might struggle to follow an IB, in particular in the case of convoy operations. However, as pointed out by (Bergström, et al., 2016a), there are currently no methods for the quantification of the probability and intensity of compressive ice situations. On the upside, according to (Eriksson, et al., 2009), compressive ice conditions are generally local, i.e., limited to a relatively small area, and quite short lived lasting only a few hours. Thus, assuming that most voyages are not significantly affected by compressive ice, its effect on the long-term transport capacity of the present AMTS is likely limited.



Figure 30: Visualization of analysed design uncertainties with respect to (a) level ice thickness range distribution, (b) ice coverage range distribution, (c) definition of H_{eq} , (d) average ridge density, (e) IB waiting time. Definitions 1-3 are determined in accordance with Table 4.

In accordance with Eq. 1, a ship's estimated maximum ice loading depends on the ship's annual ice exposure (x), the impact frequency (f), and the empirically determined C and D values. In the present case study, the ice exposure depends primarily on how the level ice thickness is assumed to be distributed within the thickness ranges determined by the ice charts. Thus, we analyse the sensitivity of the calculated ice loading to variations in that distribution. In addition, we analyse the sensitivity of the calculated ice loading to variations in the f, C, and D values. An exact description of the analysed parameter variations is provided in Table 5.



Figure 31: Sensitivities to uncertainties affecting the estimated transit time. Definition 1-3 are determined in accordance with Table 4.

Table 5: Analysed parameter uncertainties with regards to ice loading. * Values determined based on Taylor et al. (2009) corresponding to ice loads measured in January in Antarctica.

Factor	Def. 1 (default)	Def. 2
Level ice thickness range distribution	Triangular	Uniform
Impact frequency, f	10 /NM	15/ NM
C, D	C=0.28, D=-0.62	C=0.18*, D=-0.71*

The outcome of the sensitivity to uncertainties with regards to ice loading is presented in Figure 32. In accordance with the figure, the estimated 100-year ice loading is sensitive to the applied C and D values. Variations in the assumed level ice thickness distribution and the impact frequency, on the other hand, appear to have a limited impact.



Figure 32: Sensitivity of the estimated ice loads variations in (a) the applied level ice thickness distribution, (b) the assumed impact frequency, and (c) the applied *C* and *D* values.

Uncertainty mitigation

The above assessment indicate that the estimated transit time is particularly sensitive to the definition of the IB waiting time ($T_{IB_waiting_time}$) and the definition of the equivalent ice thickness (H_{eq}). Naturally, any uncertainty in the estimated transit time translates into uncertainty in the estimated fleet parameters required to meet the transport task. In order to quantify these effects, we carried out an analysis aiming to determine how the relation between the transport reliability and the load carrying capacity per ship depends on the definition of the above highlighted factors. The outcome of the analysis, which is presented in Figure 33, indicate that that in both cases, the more conservative

definition increases the estimated required ship cargo capacity by approx. 2 % or 90 tonnes. Alternatively, the speed of the ship needs be increased by 0.5 knots.

5 Summary and conclusions

The level of model fidelity required to capture the behaviours of an AMTS relevant for its conceptual design is case specific. For case study A (the Arctic case), we conclude that it is motivated to use a high-fidelity model. Specifically, the model need to consider level ice thickness, ice coverage, the size of individual ice ridges, the distance between individual ice ridges, the effect of snow, and gradual day-specific developments in the ice conditions. For case study B (the Baltic case), we conclude that a somewhat lower model fidelity is sufficient. In this case, the model needs to consider level ice thickness, ice coverage, average ridging characteristics, and the effect of old ice channels. In contrary to the Arctic case, for the Baltic case the consideration of local variations in the ice ridging conditions does not appear motivated. In addition, in the Baltic case, is seems sufficient to consider month-specific ice conditions.



Figure 33: Analysis of various uncertainty mitigation alternatives. Definitions 1-3 are determined in accordance with Table 4.

In practise, the applied model fidelity is often determined or limited by the available information. This concerns for instance the choice of distributions. Generally, for any given parameter, the designer should choose a distribution that fits its actual distribution as well as possible. However, often the information available for the determination of a specific parameter distribution is very limited (e.g. the information might be limited to the expected maximum and minimum parameter value). For the modelling of such parameters, when there is insufficient data to support other specific distributions, we think that the application of highly simplified distributions is rational. This reasoning is supported by

(Pantuso, et al., 2017) who found that, for the stochastic modelling of maritime transport systems, it is the stochastic modelling that is important, and that the choice of distribution shape for individual parameters has little influence on the outcome. Thus, in the presented case studies, both triangular and uniform distributions were applied (e.g. for the modelling various sea ice characteristics, port turnaround times, and IB waiting times). Anyhow, an obvious weakness of the use of such simplified distribution is that they exclude extreme values found in other types of distributions (e.g. the normal distribution). Therefore, they need to be used with caution. In specific cases, it might be motivated to carry out design model analyses similar to the ones carried out in the present study to find out whether the use of a simplified distribution result in the failure to capture some important behaviour of the specific AMTS being designed. If so, measures need to be taken to accurately define a more realistic distribution.

By reviewing publically available sources looking for conflicting information, the study identified a wide range of uncertainties. The identified uncertainties can be divided into three groups: 1. Uncertainties in parameters describing the prevailing operating conditions, 2. Uncertainty in applied design tools and assumptions, 3. Uncertainty caused by potential long-term trends (e.g. climate change). Based on the conducted sensitivity analyses, we conclude that the sensitivity of the design outcome to the various identified uncertainties is case specific. For case study A, we conclude that the estimated required design characteristics with regards to transport capacity are relatively sensitive to all the analysed potential sources of uncertainty, and the most sensitive towards potential uncertainties in the assumed H_R/H_S -ratio, the applied definition of H_{eq} , and the assumed month- and leg-specific average level ice thickness. The estimated 100-year ice loading, in turn, is sensitive towards the assumed C, and D values, but appear relatively insensitive towards other possible uncertainties. For case study B, we conclude that the estimated required design characteristics with regards to transport capacity are sensitive to uncertainties both in the assumed IB waiting time and the definition of H_{eq} , but appear insensitive towards other possible uncertainties. As in case study A, the estimated 100-year maximum ice loading is sensitive towards uncertainties in the applied C, and D values, but appear robust towards other possible uncertainties. It should be pointed out that we do not take any position on whether any of the assumed uncertainties are real, and recognize that an individual designer might have access to additional information and knowledge reducing the uncertainty.



Figure 34: Variations in H_{eq} vs. relative variations in ship speed.

The conclusion that the estimated transport capacity of the AMTS of case study A is significant more sensitive to possible uncertainties than the AMTS of case study B line is probably explained by the fact that, due to more difficult ice conditions, as well as due to the speed requirement set by the FSIC rules, ships operating along the arctic route tend to operate within a lower range of their *h*-*v* curve than ships operating along the Baltic route. Consequently, as shown in Figure 34, any uncertainty in the assumed H_{eq} results in a larger relative uncertainty in ship speed, and consequently also in the transport capacity.

In both case studies, it proved feasible to mitigate uncertainties with regards to transport capacity by either reserve ship payload capacity, or by reserve ship speed. However, in case study A, based on the assumption that any increase in payload capacity requires an increase in fleet size, it appears to be more advantageous to mitigate uncertainty by reserve ship speed. With regards to the mitigation of uncertainty in terms of the estimated maximum ice loading, we do not see any obvious solution. On the upside, the estimated ice loading appears to be relatively insensitive to possible uncertainties, with the exception for those related to the applied C and D values. This highlight the need for the determination of C and D values for additional ice conditions, in particular for Baltic ice conditions.

The presented investigations are essentially numerical experiments. Given the large number of design variables and stochastic parameters that are considered, it is clear that a large number of simulation runs would be required to cover the complete space of possible simulation outcomes, for instance to carry out a formal design of experiments. However, due to the multitude of knowledge and data gaps, we are not convinced that such a time consuming undertaking is motivated. For instance, in the applied ice model, the maximum values of parameters describing individual ice characteristics (e.g. ice thickness, ridge density, and ridge size) are each limited in accordance with various ice studies. However, the theoretical extreme (worst possible) combination of those parameters is not well defined. Thus, future research on the interdependence of ice and other parameters is recommended. Meanwhile, the applied approach, in which the probabilistic performance of an AMTS is determined based on a limited number (100) of simulation runs appear sufficient to gain valuable insight into the stochastic performance of an AMTS.

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