Towards holistic performance-based conceptual design of Arctic cargo ships

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ABSTRACT: We present an extension of an earlier presented framework for use in the conceptual design of Arctic cargo ships. To enable a holistic approach, the framework integrates a wide range of performance assessment tools and methods namely (a) Discrete Event Simulation (DES) based Monte Carlo simulations, (b) system thinking, and (c) empirical data analysis. The thinking behind the framework is demonstrated by discussing how it could be applied to assess the design impact of four specific technologies: (1) a 'Biomimetic anti-icing coating', (2) a 'Safe Arctic bridge' using augmented reality (AR) technology for improved situation awareness,(3) a 'Arctic voyage planning tool' using Big data analysis, and (4) the use of low flash point fuels' in the Arctic.

1 INTRODUCTION

1.1 *Background*

The design of Arctic ships is challenging. This is because Arctic maritime operating conditions are harsh and demand consideration of the effects of sea ice, icebergs, extreme temperatures, polar lows, and seasonal darkness. Engineering idealisation of these phenomena is challenging as their occurrence is highly stochastic. The performance of ice-going ships is also often dependent on the availability of icebreakers (IBs), making it necessary to extend the design boundaries beyond the individual ship, i.e., to consider a ship as system of systems. (Bergström, et al., 2016a) presents a design framework that deals with these challenges by making use of a combination of system thinking and by treating an Arctic cargo ship as a component of a wider Arctic Maritime Transport System (AMTS). They also present a Discrete Event Simulation (DES) based on the Monte Carlo approach. The later enables simulation of data supporting a well-informed design process. Specifically, their framework allows for:

1. The determination of the required fleet size (number of ships), ship size (ship cargo carrying capacity), and ship speed (specified by the so-called *hv*-curve that determines the speed of a ship as a function of the ice thickness) for a specific transport task.
2. The simulation of scenarios in support of the design process. Examples are: (a) a ship's exposure to various ice conditions, and (b) the temporal distribution between a ship's various operating modes (e.g. operation in open water, independent operation in ice, and IB-assisted operation). Such data may also be used to assess ship (or fleet) fuel consumption, IB tariffs, and level of ice loading.

This framework does not consider accidental events (e.g. collisions, groundings, contacts), specific technologies or 'active' operational measures that might influence how a ship is operated. To this end, this paper outlines an extended version of the design framework presented by (Bergström, et al., 2016a) that addresses these limitations. To open the way toward future research, the paper also discusses how goal based thinking could be applied to assess the design impact of specific technologies. The technologies considered are:

1. A biomimetic anti-icing coating.
2. A 'Safe Arctic bridge' using augmented reality (AR) technology for improved situation awareness.
3. An 'Arctic voyage planning tool' using Big data analytics.
4. The use of Low Flash Point Fuels (LFPFs) such as methanol in the Arctic.

These technologies, together with the design framework, are developed as a part of the EU-funded

Horizon 2020 research project SEDNA – Safe maritime operations under extreme conditions: the Arctic case (SEDNA, 2017). The overall aim of the SEDNA project is to develop an innovative and integrated risk-based approach to safe Arctic navigation, ship design and operation.

1.2 *Design regulations for Arctic ships*

Traditionally, the design of Arctic ships has been regulated by main stream IMO statutory instruments (e.g. SOLAS, MARPOL). Certification is supplemented by Flag State ice class rules mitigating Arctic specific risks. To harmonise the regulations, on January 1st, 2017, the International Code for Ships Operating in Polar Waters (Polar Code), was introduced by (IMO, 2015) on all ships operating in the Arctic or Antarctica. This Code incorporates performance based safety by active (operational decision driven) and passive (de-sign orientated) risk control measures. The goal-based approach is ratified via a framework that brings together design requirements and functional requirements (FRs) to meet those. In accordance with Figure 1, compliance with the FRs can be achieved either by meeting a set of prescriptive regulations (traditional regulations that prescribe a specific solution) associated with the FR(s), or by carrying out a safety performance assessment demonstrating that the FR(s) are met. The latter case results in a so-called alternative or equivalent design. In accordance with regulation 4 – "Alternative design and arrangement" of SOLAS Chapter XIV (IMO, 2014d), where alternative or equivalent designs or arrangements are proposed they are to be justified by the following IMO Guidelines:

- "Guidelines for the approval of alternative and equivalents as provided for in various IMO instruments", MSC.1/Circ.1455 (IMO, 2013a).
- "Guidelines on alternative design and arrangements for SOLAS chapters II-1 and III, MSC.1/Circ.1212 (IMO, 2006a).
- "Guidelines on alternative design and arrangements for fire safety", MSC/Circ.1002 (IMO, 2001).

A general principle is that any alternative design should be at least as safe as a design determined by prescriptive rules (see Figure 1). It should be noted that alternative solutions are only possible with respect to SOLAS regulations .To date the IMO has not agreed on any similar goal-based approaches with respect to MARPOL regulations or on any environmental risk metrics (Skjong, et al., 2007). The MARPOL code includes a method to quantify a ship's accidental oil outflow performance (IMO, 2006). However, as pointed out by (Papanikolaou, 2009), this metric is not related to any actual environmental risk.

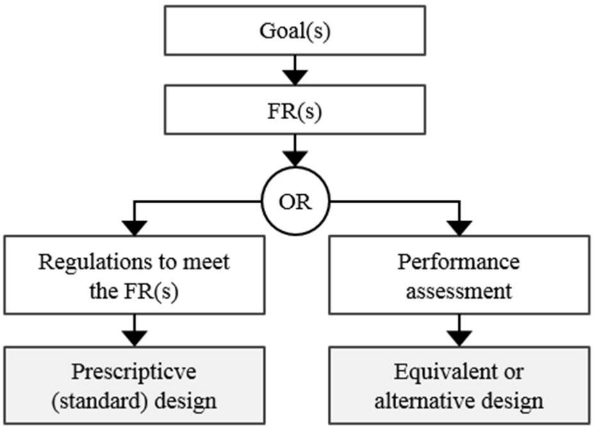

Figure 1: Approval principle of the Polar Code.

1.3 *Design methods*

We can distinguish between two different types of ship design approaches namely: (a) prescriptive-based design (PBD) in which a design is determined following prescriptive design regulations, and (b) goal-based design (GBD) in which a design is determined following goal-based regulations.

PBD facilitates a time and resource efficient design process by clear-cut and easily applied design rules. However, PBD has two fundamental weaknesses: (a) prescriptive rules might act as design constraints that limit the feasible solution space, and (b) the efficiency of the solution depends on the efficiency of the rules. For instance when applying the Polar Class, the efficiency of the solution might suffer due to the following reasons (Kim & Amdahl, 2015) (LR, 2014):

1. The rules are semi-empirically determined and might therefore be inefficient when applied on new or innovative designs,
2. The rules do not consider the probabilistic nature of ice loading, meaning that a ship operating briefly in some specific ice condition is assumed to be exposed to the same level of ice-loading as a ship operating extensively in the same ice conditions.
3. The rules are not determined with respect to any clearly communicated goal(s), i.e., in terms of application the rules do not result in any specific known level of performance.

GBD offer solutions to the weaknesses of PBD. First, by applying goal-based regulations, GBD expands the feasible design space, enabling new and innovative solutions (Papanikolaou, 2009). In addition, GBD enhances the 'safety culture' in terms of engineering practice. This is because it challenges the designer to assess design in terms of 'performance' and cost-efficiency. Notwithstanding, the implementation of goal-based regulations implies weaknesses in terms of time and resource allocation, they may lead to risks in terms of technical assurance and may suggest complications in terms of Intellectual Property Rights (IPR) (Papanikolaou, 2009). Recently, (Bergström, et al., 2016b) identified that with reference to application of goal-based rules and the Polar Code, there is a lack of unified performacne measures, criteria and perfromacne assessment tools or methods.

2 DESIGN FRAMEWORK OUTLINE

2.1 *System terminology*

We divide an Arctic Maritime Transport System (AMTS) into a hierarchy of subsystems, where each subsystem serves a specific function towards its overall objectives. Each system is defined in terms of a set of design variables that are precise characteristics of this 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 design variable. The uncontrollable conditions under which a system operates are defined in terms of design parameters, including environmental, operational, technical, and financial parameters. Parameters that are stochastic or subject to uncertainty are determined in terms of value distributions (Bergström, et al., 2016b). The feasible design space is limited by design constraints consisting of either physical limit values (bounds) determined in the form space, or of mandatory FRs determined in the function space (Bergström, et al., 2016b). Various types of constraints include operational, technical and regulatory constraints (Bergström, et al., 2016b). The performance of the system is assessed by using a performance assessment model. A performance assessment model is typically subject to some degree of uncertainty, that as per (Bergström, et al., 2016b) may be defined as internal uncertainty.

2.2 *Design process*

The design framework applies a design process as outlined in Figure 2. In the following sections we describe the contents of each step.

2.2.1 *Design context*

The design process starts by determining the design context specifying the primary function of the ship or maritime system being designed as well as its operating conditions, described in terms of a set of design parameters.

2.2.2 *Concepts of operations and preliminary designs*

Based on the design context, a set of preliminary designs, each determined in terms of a set of preliminary design variables, representing various concepts of operations (CONOPS). CONOPS is a performance variable that considers operational strategies and questions how design objectives can be met. A CONOPS for an Arctic ship might for instance include the following (Bergström, et al., 2016b):

1. An Ice Mitigation Strategy (IMS) describing how the AMTS will deal with sea ice (e.g. independent or IB assisted operation).
2. A strategy on how to compose the fleet (e.g. via the use of large or small vessels).
3. A strategy on how to balance the transport demand and capacity under different operation (e.g. ice) conditions (e.g. reserve speed or reserve payload capacity).

2.2.3 *DES-based Monte Carlo simulations*

The operational performance of each preliminary design is assessed probabilistically using DES-Monte Carlo simulation as described by (Bergström, et al., 2016a). Inputs for the DES model may be (a) empirical data, (b) design tools, and (c) models encompassing the impact of specific ship technologies. Applied empirical data might include accident data, full-scale ice load measurements, operating data (e.g. port turn-around times), and financial data (e.g. fuel costs, IB tariffs). Applied design tools include for instance a model for to the calculation of the equivalent ice thickness (Riska, 2010). Models on how to consider specific technologies are still under development in the SEDNA project.

Upon completion of DES data analytics are processed and each design is adjusted and re-simulated until a sufficient level of transport capacity is obtained. In addition to transport capacity, data streams include information on the ship ice exposure (e.g. average distance travelled in various ice conditions per ice-year) and the temporal distribution between various operating modes (e.g. operation in open water, independent operation in ice, and IB-assisted operation). These data may be used to assess a ship’s (or a fleet’s) fuel consumption and IB assistance related costs. SEDNA aims to produce models and approaches that also enable the processing of empirical accident data in the simulation. Those may result in risks associated with accidental events (e.g. grounding, collision, contact).

2.2.4 *Design elaboration*

Using the obtained design data, each AMTS design is further elaborated by division into a hierarchy of subsystems. This approach helps to assess the performance of a specific subsystem functions against the original objectives of the AMTS. Based on

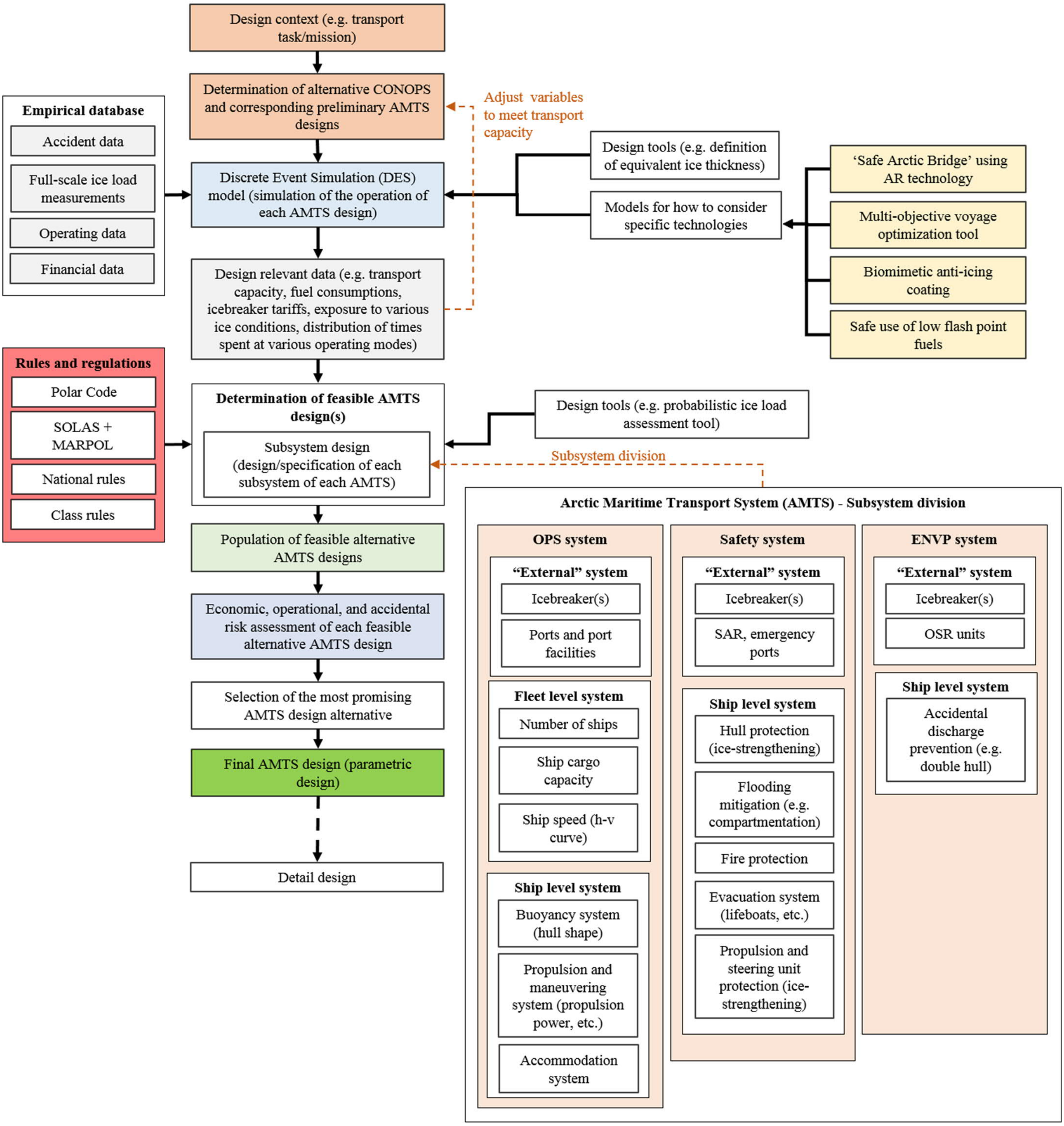

Figure 2: Design process and framework overview.

(Bergström, et al., 2016a), we propose to use the subsystem division presented in Figure 2. Accordingly an AMTS is divided into three main systems namely: (a) an OPS related to transport tasks, (b) a safety system managing safety risks (e.g. risk to human life), and (c) an environmental protection (ENVP) system managing environmental risks (e.g. spill of cargo).

The OPS system consists of : (a) external systems such as IBs and port facilities, (b) fleet-level subsystems determined in terms of the number of cargo ships, the cargo capacity and speed (*hv*-curve) of each ship, and (c) ship-level systems (e.g. the hull buoyancy system, propulsion and manoeuvring systems, accommodation system). Design criteria for the OPS system are determined based on the mission of the AMTS as determined by the owner.

The safety system consists of (a) external systems such as IBs and search and rescue (SAR) resources, and (b) of ship-level systems such as a hull protection system protecting a ship from ice-loading, a flooding mitigation system mitigating the consequences of a potential flooding, a fire protection system preventing and mitigating on-board fires, an evacuation system and a propulsion and steering unit ice-loading protection system that protects the propulsion and steering unit(s) from ice-loading.

The ENVP system consists of (a) external systems such as IBs and Oil Spill Response (OSR) units, and of (b) ship-level systems, such as an accidental discharge prevention system, preventing or limiting accidental discharges of harmful substances such as oil. Design criteria both for the safety and ENVP systems are set by existing rules and regulations (e.g. SOLAS, MARPOL, the Polar Code, national rules, and classification rules).

2.3 *Challenges of Subsystem design*

(Bergström, et al., 2016b) provide an overview of design tools for the design of Arctic ships. This work focused on the 'fitness for purpose' of safety and ENVP systems and concluded that there are established approaches in terms of flooding mitigation (SOLAS probabilistic damage stability) fire protection (e.g. fire simulations etc.) and evacuation (e.g. evacuation simulations). On the other hand, for the hull protection systems, they identified that there are no 'well-proven' performance assessment methods or performance based acceptance criteria (Bergström, et al., 2016b). To address this situation, based on (Bergström, et al., 2016b), we propose the validation and implementation of the probabilistic ice load assessment tool presented by (Jordaan, et al., 1993). The tool makes it possible to assess a ship's probabilistic ice loading based on its simulated ice exposure over multiple years of service (an outcome of the DES-based Monte Carlo simulations). As per (Bergström, et al., 2016b) the return period for ice loads should correspond to the plastic limit states of the hull structure. However, this performance measure has not yet been adopted. Since the accuracy of this approach has not yet been validated the SEDNA consortium aims to validate the method by using full-scale data from (ARCDEV, 1998). Other limitations of the method that should be assessed include: (a) the applicability of tools and methods beyond a ship's bow area, and (b) the extension of the theoretical basis toward the calculation of the 'cumulative' effects of ice-loads resulting from exposure to various types of ice conditions (e.g. medium-thick first-year ice plus thick-first-year ice). Until these limitations have been addressed, the level of hull ice strengthening must be determined in accordance with an appropriate IACS Polar Class standard (IACS, 2016a).

Similar to the hull, there are no performance methods, measures or criteria for the propulsion and steering of unit protection systems (Bergström, et al., 2016b). For example, it is believed that to assess the ice-loading acting on a ship's propeller an ice-propeller model is needed. However, as pointed out by (Bergström, et al., 2016b), since existing ice-propeller models are too simplified to provide a sufficient level of accuracy, the validation of any new high-fidelity model would require additional full-scale ice propeller load measurements. Until then, established design rules including those determined by (IACS, 2016a) should be used.

With regards to the design of the ENVP systems, as a first step towards goal-based design, the maritime industry must agree on metrics for environmental risk. Subsequently methods enabling the assessment of those metrics must be developed. This is outside the scope of the SEDNA project, and thus something that will be addressed in the future. Meanwhile, the ENVP system must be designed in accordance with existing prescriptive regulations outlined by MARPOL and other regulations.

2.3.1 *Performance assessment and design selection*

Once each subsystem of each AMTS design is designed in accordance with relevant design criteria, a population of feasible competing AMTS designs is derived. A holistic safety and economic assessment is then carried out for each design. The economic assessment is carried out based on a combination of empirical data (e.g. IB tariffs, fuel prices, time charter costs) and simulated data (e.g. the temporal distribution between a ship's various operating modes). The operational performance of the various AMTS designs is assessed based on simulated data in terms of design robustness (e.g. how sensitive is performance to changes in the operating conditions), and transport reliability (e.g. the likelihood of failing to meet a transport task during a random operating year). Methods for carrying out the safety risk assessment (risk of accidental events) are still under development within the SEDNA project. The intention is to carry out the safety assessment using both empirical accident data, and simulated data, such as data on a ship's exposure to various operating conditions and areas. The applied method could be similar to the Bayesian Network based method presented by (Valdez Banda, et al., 2016).

Based on the outcomes of the economic, operational, and accidental risk assessments, the overall most promising design alternative may be selected. The selected design consisting of a set of design variables (parametric design) may subsequently be used as input for subsequent (detail) design stages.

3 DESCRIPTION OF CONSIDERED TECHNOLOGIES AND DISCUSSION ON THEIR POSSIBLE DESIGN IMPACTS

3.1 *'Biomimetic anti-icing coating'*

Icing related risks are significant for most Arctic ships. For relatively small ships (e.g. fishing vessels), icing is a serious safety issue as it might complicate ship stability. In larger ships icing may affect the function of deck equipment (e.g. radar antennas and lifeboat release systems), deck mobility. It may also lead to human factor safety concerns (e.g. hazards due to slippery surfaces).

Icing on ships can be managed either by de-icing measures removing already formed ice or by anti-icing measures preventing the formation of ice. Anti-icing measures can be further divided into active and passive anti-icing measures. A commonly applied de-icing measure is to manually remove ice by using hammers, a laborious and potentially dangerous job. The icing rate depends on multiple factors including (a) the air and water temperatures, (b) wind and ship speed, and (c) the angle between a ship's bearings and the wind and wave direction. Whereas active anti-icing measures include adjusting ship speed and bearing (route) (Blackmore & Lozowski, 1994), passive anti-icing measures may include the use of anti-icing coatings.

Anti-icing coating technology is not new. The technology has been applied on aircrafts and wind turbines. However, the fitness for purpose in terms of maritime applications may differ in terms of cost expectations ,toughness requirements and ship segment/design or location of the application. In SEDNA project we develop two different types of anti-icing coatings: (a) a low-cost, tough coating for application on the superstructure and other large areas, and (b) a transparent coating for lifeboat surfaces and windows. In the latter case, costs may be of less importance due to the smaller areas to be covered and the higher importance of safety.

Both coatings are biomimetic in nature, because their anti-icing properties is achieved by mimicking a penguin's coat (Choy, 2018).The anti-icing coating developed within SEDNA project could replace traditional anti-icing measures by reducing the speed of a ship or by adjusting her bearing and hence lead to enhanced transport capacity and more cost-efficient design. It could also make manual de-icing redundant, and therefore lead to reduction in terms of crew size and required accommodation capacity. Finally, it could affect the required icing allowance. The later would impact future stability regulations.

Figure 3: Example of how AR technology could be applied for an improved situation awareness in Arctic ship operations. ®Amalie Albert

3.2 *'Safe Arctic bridge'*

Navigation in ice-infested waters relates to a number of unique navigation challenges. For example the distance from and movements of nearby ships (e.g. an IB) may change quickly if nearby ships suddenly get stuck in ice. The curvature of an ice channel and local variations in the ice cover (avoidance of large ridges) may also be significant challenges in term of operations. Arctic environmental phenomena such as fog, seasonal darkness, and sun glare present an additional challenge in terms of visibility. Solutions to many of these challenges may emerge by suitable understanding of human behaviour and implementation of principles of ergonomics. In addition we propose applying augmented reality (AR) technology in order to improve arctic bridge systems. AR is a technology that might improve situational awareness and decision-making of a crew by bringing in elements of the virtual world into the real world. Aviation and automobile industries have already successfully applied various implementation of AR technologies in practice in order to support situational awareness (Melzer, 2012). In addition, research within the maritime domain have outlined its potential in supporting the maritime domain (Vasiljević, et al., 2011).

This technology has the potential to improve safety by limiting the need to look away from the outside view and as such significantly reduce operators head down time and directly associate data with the real world setting. In addition, the technology is expected to improve the human-system interface by providing a mechanism to successfully manage large and varied information layers that crews are exposed to (e.g. by an improved possibility to present versatile information at the same time, and by enabling a very large total screen area). The increased versatility in displaying information anywhere in the world increase the potential for effectively integrating new categories of applications that may support users working in the arctic. An example of how AR could be applied in Arctic ship operations is presented in Figure 3.

Facilitating AR for use in the Arctic could provide several operational advantages. For example, the system could be useful on an Arctic ship escorted by an IB in an ice channel, or for operations in areas where icebergs occur. Technology applications could potentially extend the permitted/safe range of operating conditions for specific manoeuvres (e.g. entering and leaving port, docking), or impact upon on the layout of the bridge/superstructure. In addition, the improved situational awareness provided by the ‘Safe Arctic bridge’ could help to identify ice features such as growlers and large ice ridges, that may help to minimise ice exposure. This could reduce the required level of ice-strengthening.

3.3 *‘Arctic voyage planning tool’*

When planning an Arctic voyage, the master might have to consider a multitude of factors including ice conditions (e.g. ice thickness, ice ridging, and ice compression), the risk of iceberg collision, the availability of IB support, ship draft and tide level variations, and currents. The choice of a suitable route relates with and impacts upon the operational risk profile of the vessel, voyage time, voyage costs, and emissions. Practically, the operator might wish to minimise either voyage time, ship wear (repair costs), fuel costs, or accidental risk. For example, if the priority is to minimise voyage time, the master will choose the quickest route and such action may require sailing through areas with difficult ice conditions leading to increased risks in terms of ship wear and fuel costs. On the other hand, if priority is to minimise ship wear and accidental risks, the master may chose a detour that minimises ice exposure. The later may result in a longer voyage time. Examples of potential efficiency gains that could be achieved by route optimization are presented by (Markström & Holm, 2013).

To help ship masters achieve their objectives, SEDNA consortium develops an Arctic voyage planning tool (see Figure 4). As such tool could impact

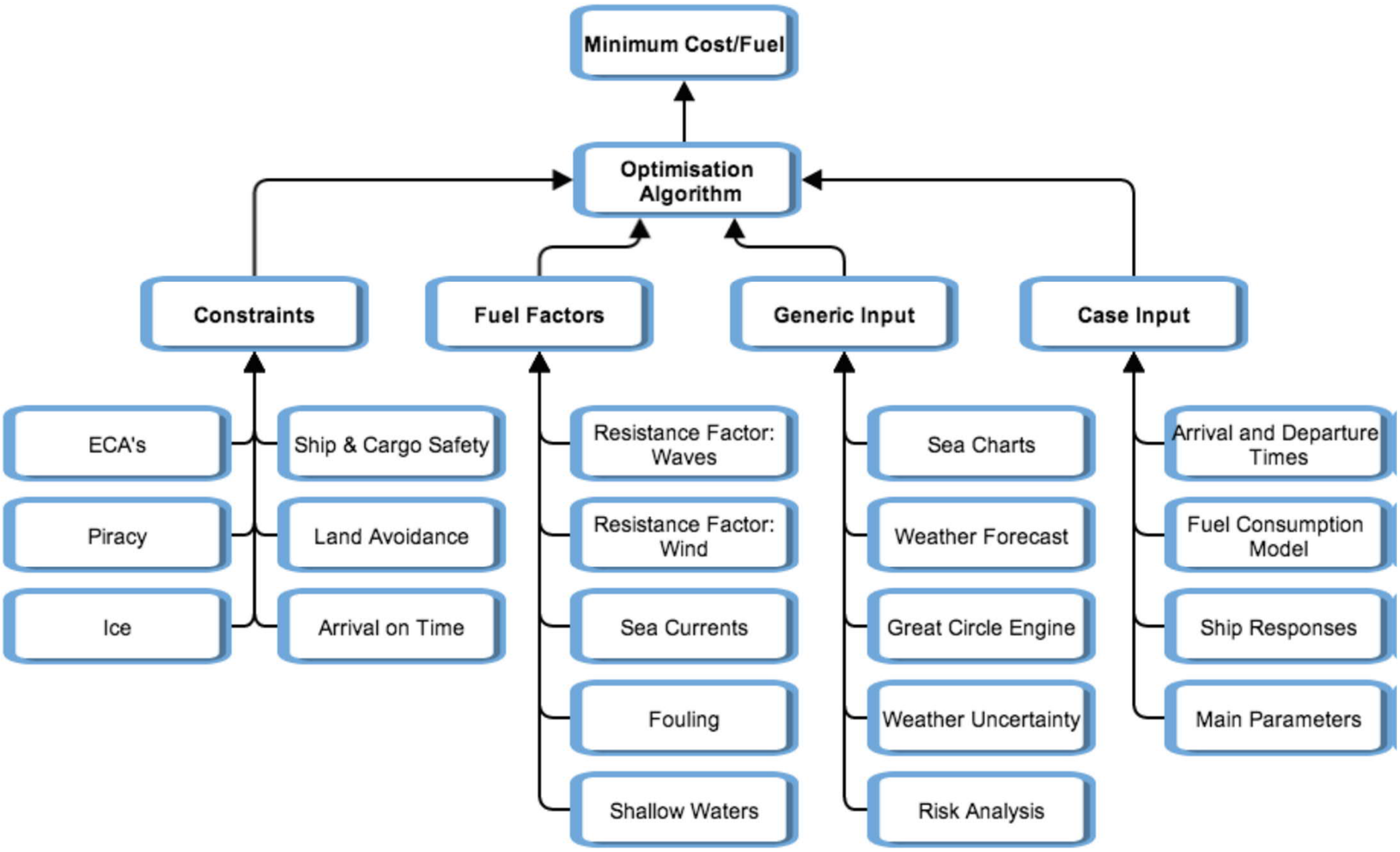

Figure 4: Overall structure of the Arctic voyage planning tool

upon the chosen ship speed, route, and ice exposure, it may affect the required ship/fleet size or propulsion power specifications for a transport task as well as ice strengthening requirements.

3.4 *'Safe use of low flash point fuels'*

The Arctic environment is sensitive to emissions and pollution. Using low flash point fuels (e.g. methanol) instead of conventional fuel oil such as Heavy Fuel Oil (HFO) may lead to reduction of exhaust emissions. Low Flash Fuels (LFPFs) dissolve in water, are biodegradable and hence reduce the risk of environmental damage due to accidental spills (Ellis & Tanneberger, 2015). Whereas similar benefits can be obtained by using Liquefied Natural Gas (LNG), LFPFs liquefy at room temperature and in this sense they may provide benefits over LNG in terms of fuel transportation and storage. The main risk in terms of using LFPFs on ships is that their flash point is below the minimum allowed safe flash point for marine fuels as specified by the IMO. This is why long-winded specialist approval is required.

To facilitate the use of LFPFs, the SEDNA project is developing generally acceptable procedures for 'Safe use of low flash point fuels' (LFPFs) in the Arctic.

We believe that a shift from traditional ship fuels (e.g. Heavy Fuel Oil) to LFPFs would influence the implementation and usability of machinery and fuel systems in the maritime environment. The technology could also prove beneficial within the context of responding to expectations aligned with future environmental regulations at the Arctic Region Emission Control operating Areas (ECAs). Because of its combustion properties and costs, the optimal speed of an LFPF driven ship may differ from that of a ship operating by conventional technology. This may result in a different optimal speed ranges, and challenges with regards to the location of fuel tanks. Yet, LFPF operated machinery would likely require less maintenance (e.g. there would be no need for a scrubber), reducing maintenance costs, as well manning requirements. Combined, this would enable a more cost- and energy-efficient design.

4 DISCUSSION AND CONCLUSIONS

This paper outlines a framework for the holistic performance-based design of Arctic cargo ships. The framework is developed based on the assumption that there is potential for efficiency gains in Arctic shipping by applying such approach. Accordingly, the approach presented utilises systems thinking by treating an Arctic ship as a component of a wider maritime transport system. It is believed that the outlined framework suggests a tangible option for regulatory implementation. Yet, further research is necessary to extend its applicability. Important future re-search work of relevance that will be addressed by SEDNA project include (a) further development of ice-loading assessment methods and validation of ice load assessment tools, (b) development of goal based models that enable performance assessment of accidental events, (c) de-risking of emerging technologies for use by the Polar fleet.

5 ACKNOWLEDGMENTS

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6 ABBREVIATIONS

AMTS	Arctic Maritime Transport System
AR	Augmented Reality
CONOPS	Concept of Operations
DES	Discrete Event Simulation
ENVP	Environmental Protection
FR	Functional Requirements
GBD	Goal-Based Design
HFO	Heavy Fuel Oil
IACS	International Association of Classification Societies
IB	Icebreaker
IMO	International Maritime Organization
IMS	Ice Mitigation Strategy
LFPF	Low Flash Point Fuel
LNG	Liquefied Natural Gas
MARPOL	International Convention for the Prevention of Pollution from Ships
OPS	Operations
OSR	Oil Spill Response
SAR	Search and Rescue
SOLAS	International Convention for the Safety of Life at Sea

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