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

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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 full-scale ice load measurements), 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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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).

$$Risk = \sum (L_i C_i) \tag{1}$$

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%.
2. *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.