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Benjamin Lagemann

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NTNU
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Thesis for the degree of
Philosophiae Doctor
Faculty of Engineering
Department of Marine Technology

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Benjamin Lagemann

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Trondheim, May 2023

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Abstract

Human-induced climate change is one of the significant challenges of our time. In order to help limiting global warming, the International Maritime Organization has set out stepwise greenhouse gas emission reduction ambitions for the maritime industry. Other stakeholders exercise pressure to increase the maritime ambition level. Therefore, shipowners and designers today expect emission reduction requirements to tighten over time, but the precise level is currently uncertain.

Against this background, the objective of this thesis has been defined as to “enhance conceptual ship design methodology to cater for greenhouse gas emission reduction ambitions along a ship’s operational lifetime”. The research objective is divided into two research questions. First, how to effectively explore and synthesize low-emission conceptual ship designs? Second, what is an effective method for selecting among alternative ship fuels and power systems under lifetime uncertainty and considering flexibility? For each research question, a working hypothesis is formulated, tested and evaluated through a method called ’validation square’.

The results of this research are disseminated in six main and four supporting papers. From these papers, three main contributions are identified:

C1 The coupling of a set-based approach with modular system-based ship design, a systems architectural model and discrete-event simulation for a case-dependent evaluation of conceptual designs

C2 A method for the selection of the optimal ship fuel and power systems considering flexibility throughout the lifetime

C3 An extension of the deterministic selection method (C2) that concurrently considers uncertainty through multiple stochastic scenarios

Contribution 1 describes a ship synthesis model, and addresses primarily structural and behavioral complexity aspects. By structural complexity it is meant the multitude of possible systems, such as different hull concepts or different energy storage options, that can be combined in different ways. The behavioral complexity is related to the non-trivial system behavior that emerges from the different combinations of subsystem options. The set-based approach denotes an exploration and evaluation of such different options before commitment to one concept. Contribution 2 addresses the selection of fuels and power systems under an assumed certain lifetime scenario. Within this lifetime

scenario, fuel costs and carbon prices are changing over time and fuel switches and retrofits are considered as flexibility options. Contribution 3 builds upon the developed selection method under certainty, but additionally considers uncertainty with respect to fuel costs and carbon prices through the sampling of multiple scenarios. The bi-objective nature of the developed stochastic programming method shows the effect of different cost-versus-emission compromises on the selection of ship fuel and power system.

Preface

This thesis is submitted for the partial fulfillment of the requirements for the Degree of Philosophiae Doctor (PhD) in Engineering at the Norwegian University of Science and Technology (NTNU). The work was carried out between August 2019 and March 2023 at the Department of Marine Technology, Faculty of Engineering, NTNU, Trondheim. Professor Stein Ove Erikstad has been the main supervisor. Professor Sverre Steen and Professor Bjørn Egil Asbjørnslett have co-supervised the research.

The project has received funding from the Research Council of Norway through the center for research-driven innovation (SFI) Smart Maritime, project number 237917.

The target audience of this thesis includes researchers and practitioners in the field of ship design sharing an interest in reducing greenhouse gas emissions.

Acknowledgments

I would like to say thank you to a number of people that have accompanied, guided, and supported me throughout the last three and a half years. First of all, I extend my gratitude to my supervisor Prof. Stein Ove Erikstad. In addition to the countless things you taught me, thank you for believing in me at times when I was tumbling, and doubting me when I felt too confident. I would also like to thank my co-supervisors, Prof. Sverre Steen and Prof. Bjørn Egil Asbjørnslett for critical discussions and valuable advice whenever needed. This thesis would not be the same without the support from Prof. Per Olaf Brett. My sincere thanks for your advice, critique and encouragement from the first day we met, I always appreciate your feedback. I would also like to express my gratitude to Prof. Kjetil Fagerholt for introducing me to the world of stochastic programming.

Being part of the SFI Smart Maritime, I enjoyed many interesting discussions with colleagues and partners within our research center. A special thanks to the researchers at SINTEF Ocean, in particular Dr. Elizabeth Lindstad, Agathe Rialland, Trond Johnsen, Jon Dæhlen and Dr. Endre Sandvik for welcoming and including me into your projects.

I was also fortunate to collaborate with and learn from numerous people outside of Norway. Thanks to Tobias Seidenberg for initiating a fruitful collaboration. Dr. Jose Jorge Garcia Agis, thank you for sharing first-hand experiences as a practitioner and scholar of ship design. Prof. Jeroen Pruyn and Jesper Zwaginga, thank you for a great time and collaboration in Delft. Not the least, a huge thanks to Prof. Harilaos N. Psaraftis and Dr. Sotiria Lagouvardou for your support, discussions and enriching perspectives.

I would like to thank the many colleagues and friends at the Department of Marine Technology, particularly Dr. Dražen Polić, Diederik van Binsbergen, Astrid Vamråk Solheim, Dr. Prateek Gupta, Ehsan Esmailian, Dr. Jarle Kramer and Svein Aanond Aanondsen. A special thanks also to Ann-Johanne Bjørgen for nimbly digging out the hindmost publication from the archives. Also, I would like to acknowledge the excellent support from the entire administrative staff at the department. Over the past years, I have had the chance to co-supervise several master thesis projects and would like to thank the students Ola Skåre, Anne Sophie Ness, Dorthe Alida Slotvik, Anna Sophia Hüllein, William Hyggen Viken and Finn Lorange. I learned a lot from and with you.

Last but not the least, I would like to say thank you to my family and friends. You have witnessed the ups and downs I have been going through and I am grateful for your continuous and unconditional support that kept me going.

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Main Paper 2
System alternatives for modular, zero-emission high-speed ferries
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SNAME International Conference on Fast Sea Transportation; Rhode Island, USA

Main Paper 3
Optimal ship lifetime fuel and power system selection*)*
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Sotiria Lagouvardou, Benjamin Lagemann, Harilaos N. Psaraftis, Elizabeth Lindstad, Stein Ove Erikstad
Submitted to Nature Energy

Nomenclature

ABD	Accelerated Business Development
AMMPT	Approach, methodology, method, procedure, technique; a taxonomy for design
CEM	Concept exploration model
CFD	Computational fluid dynamics
CII	Carbon Intensity Indicator
CN	Customer need
CO_2	Carbon dioxide
DBB	Design Building Block
DP	Design parameter
DSM	Design structure matrix
EEXI	Energy Effciency Existing Ship Index
FEM	Finite element method
FR	Functional requirement
GHG	Greenhouse gas
HoQ	House of Quality
IMDC	International Marine Design Conference
IMO	International Maritime Organization
KPI	Key performance indicator
LCA	Life cycle analysis
LNG	Liquified natural gas
MBSE	Model-based systems engineering
MEKO	Mehrzweck Kombination; German for "multipurpose combination"

MGO	Marine gas oil
NTNU	Norges teknisk-naturvitenskapelige universitet, Norwegian for "Norwegian University of Science and Technology"
OR	Operations research
RFLP	Requirements-functional-logical-physical; a model of design as a mapping over these four different domains
RoRo	Roll-on/roll-off
RQ	Research question
SBSD	System-based ship design
SES	Surface effect ship
SFI	Senter for forskningsdrevet innovasjon; Norwegian for "center for research-driven innovation"
SWATH	Small waterplane area twin hull
UML	Unified Modeling Language
VLSFO	Very low sulfur fuel oil
WH	Working hypothesis

1 Introduction

> *"Climate change is the defining issue of our time - and we are at a defining moment."*
>
> *- António Guterres (2018)*

When ordering a ship today, how should it be conceptually designed in order to be sustainably operated throughout its foreseen lifetime? - Given the current slump on new orders (Ulstein International AS 2022) and significant uncertainty around greenhouse gas (GHG) reduction requirements (IMO 2018; European Commission 2019) as well greenhouse gas-reducing solutions (Bouman et al. 2017), the introductory question aims to describe the situation that ship designers, shipowners and ship operators are facing with respect to effective decision-making. This thesis investigates how ship design methodology can be enhanced to better address the decisions to be made for reaching lower GHG emissions over the ship's lifetime. The following section will elaborate more on the background of emission reduction ambitions and its relation to ship design.

1.1 Background

International shipping's greenhouse gas (GHG) emissions are not attributed to single countries and thus international shipping is excluded from the Paris Agreement (United Nations 2015). Instead, the responsibility to help limiting global warming has been delegated to the International Maritime Organization (IMO), which has set out high-level GHG emission reduction ambitions. Those IMO (2018) ambitions that are measurable at specific dates, defined against 2008 emission levels, are: Reduce the annual carbon dioxide (CO_2) emissions per unit transport work by at least 40% by 2030; pursue efforts to reduce the annual CO_2 emissions per unit transport work by at least 70% by 2050; and reduce the total annual CO_2 emissions from shipping by at least 50% by 2050.

The translation of these high-level ambitions into concrete requirements is a continually ongoing process as formulated by IMO MEPC 76/15/Add.2. That document defines, among others, an Energy Efficiency Existing Ship index (EEXI) as a measure for a ship's theoretical GHG emission efficiency, as well as a Carbon Intensity Indicator (CII), which indicates the GHG emission efficiency under actual operation. The threshold for both these measures is planned to be lowered continually. Other stakeholders, such as the European Commission (2019) and European Community Shipowners' Association (2020), are pushing for more stringent reduction targets. The political negotiations at IMO level possess their own complexity (Psaraftis and Kontovas 2010, 2020) and their outcome may therefore be described as uncertain. To comprehend the general level of uncertainty, it is also important to acknowledge the "cumulative nature of CO_2 emissions" (Gilbert et al. 2014, page 455), meaning that the failure to reduce GHG emissions today leads to higher reduction requirements tomorrow under a given maximum temperature target.

For a shipowner, this background translates into significant uncertainty. Not only is there uncertainty with respect to concrete per-ship requirements over time, but also uncertainty around the high-level emission reduction requirements and ambitions this regulation was based on. Will the cumulative nature of GHG emissions require tighter reduction goals in the future, in order to make up for the gap (DNV 2021a) between the initially envisaged and the actually observed emission trajectory? Will the ambitions of the initial IMO (2018) strategy be revised? How will the discussions and negotiations around marked-based measures (Lagouvardou, Psaraftis, and Zis 2020) play out? These questions illustrate the high level of general uncertainty expressed by shipowners, operators and designers during regular gatherings of the center for research-driven innovation (SFI) Smart Maritime, the research center I have been part of.

In addition to the aforementioned general uncertainties, further uncertainties are linked to specific GHG abatement options. Such specific uncertainties, for example, hinge around cost and availability of feedstocks for alternative fuels (Brynolf et al. 2018). Recently, this has manifested in bunker prices for natural gas beyond most predictions (e.g., DNV GL 2019b; Lloyd's Register and UMAS 2020). Other solution-specific uncertainties can be associated with the development of new technology, for instance a new generation of nuclear propulsion systems for merchant ships (Houtkoop et al. 2022). Erikstad and Rehn (2015) categorize different types of uncertainties as physical, regulatory, economic and technological uncertainties. These uncertainties, along with examples for the present situation, are sketched in in Figure 1.1.

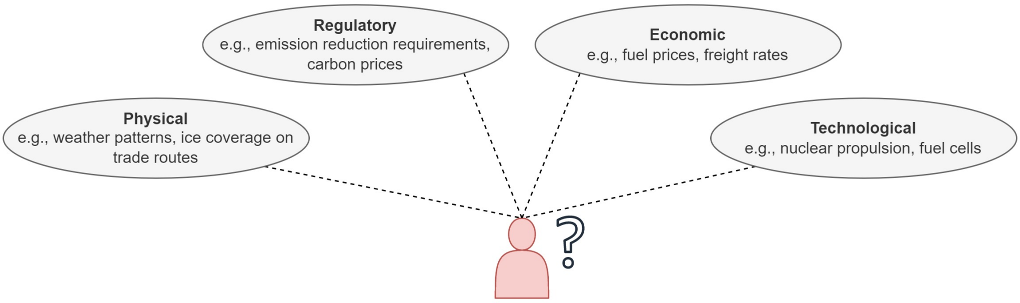


Figure 1.1: Uncertainties affecting the decision-making problem

Besides uncertainties, many GHG abatement options come with an increase in complexity: Examples are hybrid machinery propulsion (DNV GL 2019a) or the aero- and hydrodynamic inter-dependencies for wind propulsion (Thies and Fakiolas 2022). As ships have diverse missions and operating profiles (Stopford 2009), a technical 'one-size-fits-all' solution is unlikely (Calleya 2014).

The freedom for making decisions decreases throughout the ship design process (Mistree et al. 1990). The initial, conceptual design phase generally provides the largest freedom and thus biggest leverage when it comes to affecting the performance of a ship (Erikstad 1996; Papanikolaou 2014; Andrews 2018b). The starting point for this thesis can thus be described by the following statement: Given that the conceptual design phase provides the largest leverage over a ship's performance, how can the existing uncertainties and complexities with respect to GHG emission abatement be meaningfully addressed within this particular design phase?

1.2 Research objective

The starting point provides a research opportunity within the field of ship design methodology. This opportunity, grounded in the concrete problem of GHG emission reductions, must be incorporated into the research objective. For this thesis, the research objective has thus been defined as:

"Enhance conceptual ship design methodology to cater for GHG emission reduction ambitions along a ship's operational lifetime."

As indicated in Figure 1.2, the term "concept ship design" denotes the early ship design phase as a precursor to the basic ship design phase. During this concept phase, where the overall conceptual solution (size, speed, propulsion system etc.) is to be decided, the ideas and thinking are still fluid and premature. Hence, the possibility to influence the design and its performance - among others emission levels - are largest at this stage (Erikstad 1996;

Papanikolaou 2014; Andrews 2018b). The term “GHG emission reduction ambitions” in the research objective shall comprise hard, statutory requirements (such as CII or EEXI, IMO MEPC 76/15/Add.2), ambitions (e.g., IMO 2018 or European Commission 2019) as well as other stakeholders’ expectations, such as shipowners, investors, banks, charterers or the general public. Each stakeholder may have different expectations with respect to emission reductions, of which some may be looser and some stricter (Andrews 2011; Papanikolaou et al. 2009; Ulstein and Brett 2015). Notably, these expectations and complementary requirements will change over time (e.g., CII). This change over time is, therefore, an explicit part of the objective. Over 90% of the GHG emissions ships emit today, occur during the operational lifetime (Chatzinikolaou and Ventikos 2014). This research, therefore, targets specifically the operational phase as opposed to ship production or scrapping.

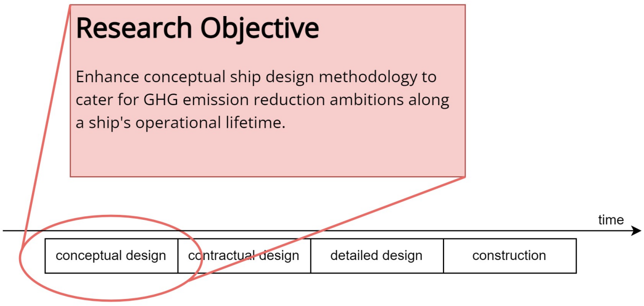


Figure 1.2: Research objective

Having described the research objective, the following section formulates and discusses specific research questions.

1.3 Research questions

The research objective is an enhancement of ship design methodology. This objective permits research in many possible directions. In order narrow down the general objective, two specific research questions (RQs) have been defined for this thesis. The research questions directing this research work are:

RQ1 How to effectively explore and synthesize low-emission conceptual ship designs?

RQ2 What is an effective method for selecting among alternative ship fuels and power systems under lifetime uncertainty and considering flexibility?

These research questions provide direction by focusing on a subset of the problems and decisions to made in the conceptual design phase. The grounding of the research questions in the research objective is illustrated in Figure 1.3.

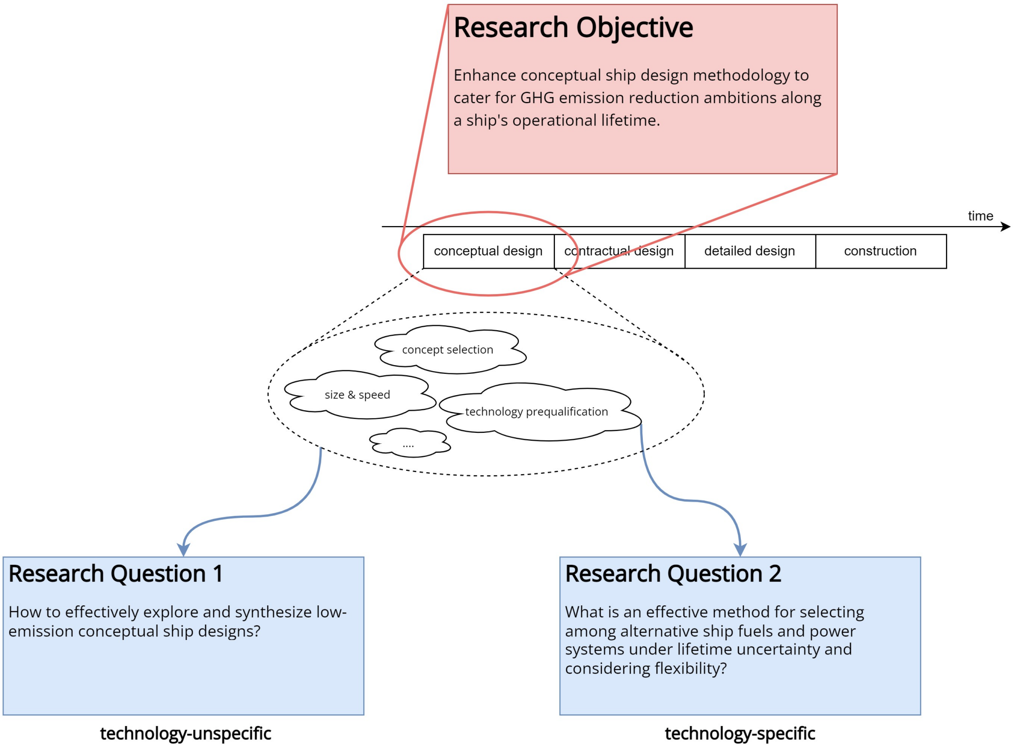
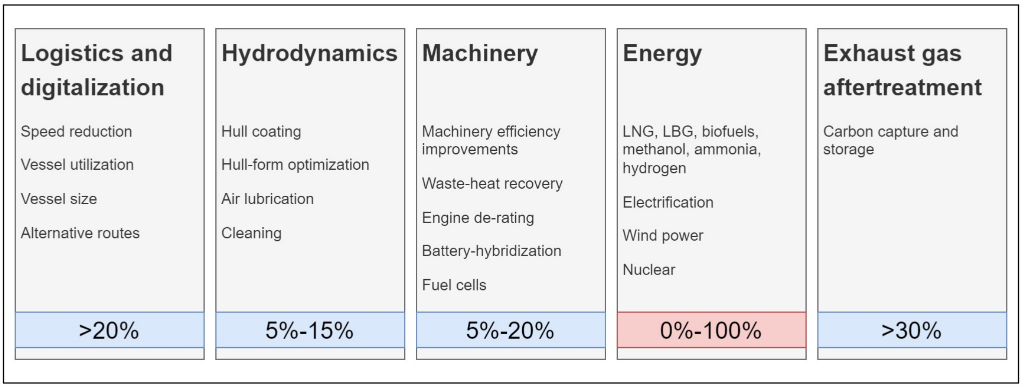


Figure 1.3: Research questions

RQ1 is technology-unspecific and aims to address structural and behavioral aspects of complexity (Rhodes and Ross 2010; Gaspar et al. 2012). The structural complexity aspects are related to the number of connections and possible combinations of subsystems and the behavioral complexity aspects are linked to the resulting, often non-linear, performance of the system assembly. RQ2 is technology-specific in the sense that it focuses on alternative fuels and comprises explicitly the contextual and temporal aspects of complexity as well as uncertainty. Alternative fuels have been selected as a technological option as they are estimated to have the highest GHG emission abatement potential on a long-term perspective (Balcombe et al. 2019; Faber et al. 2020). The high GHG emission abatement potential in comparison to other options, such as hydrodynamics, is underpinned by DNV (2022) and reflected in Figure 1.4.



Logistics and digitalization	Hydrodynamics	Machinery	Energy	Exhaust gas aftertreatment
Speed reduction	Hull coating	Machinery efficiency improvements	LNG, LBG, biofuels, methanol, ammonia, hydrogen	Carbon capture and storage
Vessel utilization	Hull-form optimization	Waste-heat recovery	Electrification	
Vessel size	Air lubrication	Engine de-rating	Wind power	
Alternative routes	Cleaning	Battery-hybridization	Nuclear	
		Fuel cells		
>20%	5%-15%	5%-20%	0%-100%	>30%

Figure 1.4: GHG emission abatement options in shipping, redrawn and adapted from DNV (2022)

Alike the other aforementioned studies, the group ’energy’, with alternative fuel options as a subset, is estimated to provide up to 100% GHG emission abatement potential. The figure, however, also indicates that no GHG emission reduction effect may be achieved, which highlights the importance of thorough and holistic analyses. The figure also implies a certain amount of uncertainty associated with the GHG abatement effect. This uncertainty is present on an aggregate level - individual options within the group ’energy’ have different GHG abatement effects - but also for individual options the effect may be uncertain to some extent. The source of uncertainty may be contextual (e.g, how and where in the world the fuel is produced), technical (e.g., required amount of pilot fuel is uncertain) or others. RQ2 focuses specifically on the uncertainty related fuel production costs and carbon prices. Technical uncertainties, such as combustion properties or safety challenges, are not part of this research question.

1.4 Scope and limitations

This thesis focuses on GHG emission reductions that can be achieved through conceptual design. With conventional technologies, over 90% of ship GHG emissions are estimated to occur during the operational phase (Chatzinikolaou and Ventikos 2014). The remaining ones may be attributed to the production or scrapping process. This research, therefore, targets specifically the GHG emissions stemming from the operational phase, as opposed to ship production or scrapping phase. As this thesis aims to contribute to the body of knowledge on conceptual ship design, it makes use of screening methods for life cycle analyses (LCAs) in contrast to full LCAs as defined by *EN ISO 14040:2006*. The perspective of this thesis, i.e., the abatement of GHG emissions occurring in the operational phase through enhanced conceptual design, is illustrated in Figure 1.5.

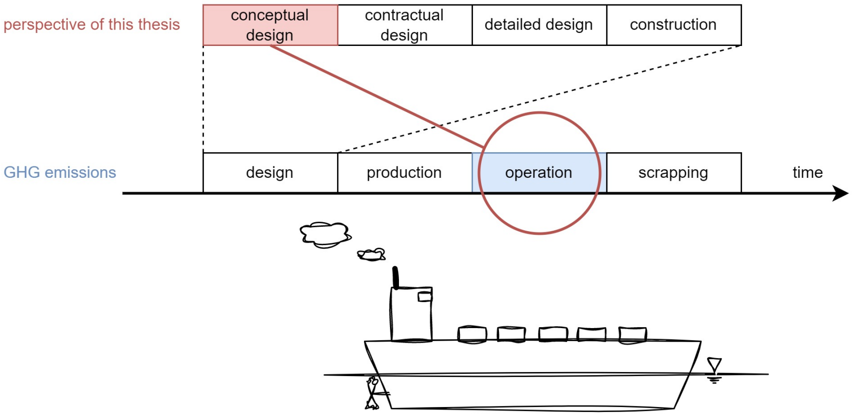


Figure 1.5: Scope of this thesis with respect the ship life cycle according to Ang et al. (2018)

One design option to significantly reduce GHG emissions from the operational phase is the application of onboard nuclear propulsion (Houtkoop et al. 2022). For this thesis, however, the onboard application of nuclear technology has been defined as beyond the scope. Thus, while some of the presented methods may be applicable to nuclear technology as well, this technology group has explicitly not been part of this research work.

1.5 Positioning of this research within the SFI Smart Maritime

This research work has been conducted as part of the SFI Smart Maritime, which was established in 2015. The center gathers major Norwegian industrial and academic stakeholders and strives for “improved energy efficiency and reduced harmful emissions from the maritime sector” (Rialland and Einang 2018).

Figure 1.6 depicts the work package structure within the SFI Smart Maritime. This research work has been part of work package 4, ’Ship system integration and validation’. As design traverses many other disciplines, collaboration with other work packages has evolved over time.

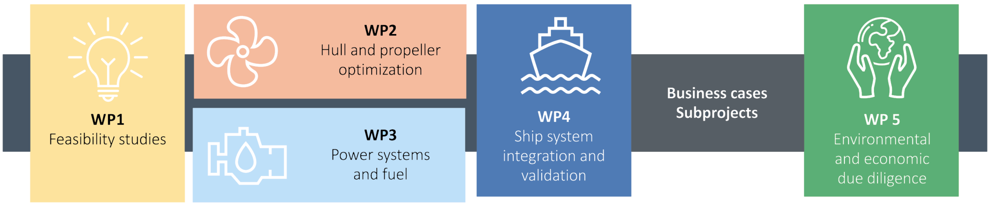


Figure 1.6: Work packages within the SFI Smart Maritime, reprinted from Rialland and Einang (2018)

The research results up to May 2022 of the SFI Smart Maritime have been summarized and disseminated to its industry partners in the center's "Sea map to Green Shipping" (Gamlem 2022), which collates the results into the four steps "reorientation, logistics, energy use and efficiency, alternative fuels" as a systematic, stepwise approach towards low-emission shipping.

1.6 Thesis structure

The thesis structure is depicted in Figure 1.7. Chapter 2 reviews relevant literature for this thesis, both from a design and technology perspective. Chapter 3 outlines how the theoretical elements are connected to the research problem and formulates working hypotheses. Chapter 4 describes the research methodology for this thesis. Being a paper-based thesis, as opposed to a monograph type of thesis, the analysis and results are summarized in Chapter 5. Chapter 6 discusses the main findings and contributions of this research work and evaluates the working hypotheses. Chapter 7 finally presents the conclusions of this thesis and outlines its limitations.

Figure 1.7: Thesis structure

2 Literature Review

> *"In order to design a ship, one first needs to design a ship."*
>
> *- A. C. Habben Jansen (2020)*

This chapter describes the literature examined for this research work. It shall both explain the theoretical foundations as well as outline the context into which this thesis shall be placed. The chapter is organized as follows: Section 2.1 describes how the topic of this thesis (conceptual ship design) relates to the broader field of ship design and engineering design in general. Section 2.2 reviews different elements of conceptual ship design methodologies. These elements describe basic building blocks on different levels that can be assembled into more comprehensive conceptual ship design methodologies. A selection of notable examples of such assemblies, i.e., more complete conceptual ship design methodologies, is presented in Section 2.3. Section 2.4 briefly reviews relevant GHG emission abatement options for ships, and alternative fuels in particular.

Figure 2.1 shows a histogram plot of the examined literature. The literature collection has followed the snowball principle, i.e., starting from the International Marine Design Conference (IMDC) state-of-the-art reports on design methodology (Andrews et al. 1997, 2006, 2009; Papanikolaou et al. 2009; Andrews and Erikstad 2015; Andrews et al. 2018) and branching out to adjacent and ensuing publications. The literature has covered both the design process and the design product, i.e., technical design options for GHG emission abatement. In total, over 600 publications have been examined during this research project. More than half of these are referenced directly in this thesis, not accounting for the references of the appended papers.

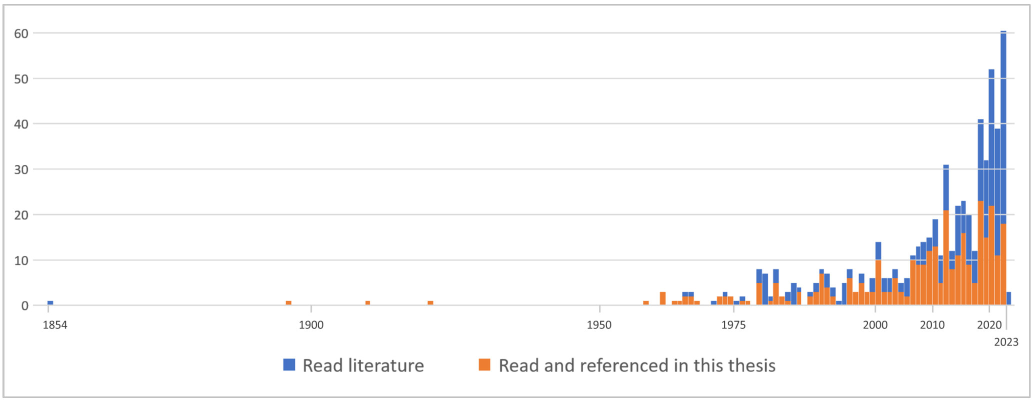


Figure 2.1: Histogram plot of the read literature

Design traverses many disciplines, and as such many of the references presented herein come from or cover other research fields such as economics or optimization. The literature could thus have been categorized and presented according to discipline. I have chosen the present structure, in order to outline the literature's relation to design as the central theme within this thesis.

2.1 What is design?

"Everyone designs who devises courses of action aimed at changing existing situations into preferred ones" (Simon 1996, page 111). Designing thus involves decision-making (Mistree et al. 1990) and therefore belongs to the sciences of the artificial as opposed to the natural sciences (Simon 1996). By no means does this mean that the natural sciences are useless for design, rather the opposite seems true as many artificial systems, in particular engineered ones, are analyzed by means of the natural sciences. However, design is fundamentally different from analysis in the way that it represents an abductive activity, rather than a deductive one. While analysis is concerned with deducting facts from existing objects, abduction aims towards creating objects with given facts, e.g., given performances (Coyne et al. 1990).

Design shall result in a specification of the artifact (Goel and Pirolli 1989). Subsequent production processes are generally not seen as part of the design phase, especially not for physically large and complex systems such as ships. While for less complex systems, the designer may obtain direct feedback from construction and operation (Jones 1992), this feedback is not necessarily present in the design of physically large and complex systems (Meek 1982). Nevertheless, design should normally relate to the aspects of efficient production and life-long maintenance (Papanikolaou et al. 2009).

While it is hard to define ’design’ in a precise, concise and at the same time complete way, the concept of ’design methodology’ can seem even more blurry and therefore needs clarification (Love 2000; Andrews 2012b). Alternative definitions are provided in literature by Finkelstein and Finkelstein (1983), Cross (1986), Andreasen (1991), and Andrews (2012b). In this research, I will use the definition of Cross (1986, page 410) as design methodology being “the study of the principles, practices and procedures of design in a rather broad and general sense. Its central concern is with how designing both is and might be conducted”. Essentially, this definition conveys three facets of design methodology: First, the science of design; second, the descriptive study of design procedures; and third, the prescriptive (or normative) study of design procedures. Figure 2.2 sketches the relations between the three facets articulated in Cross’ definition.

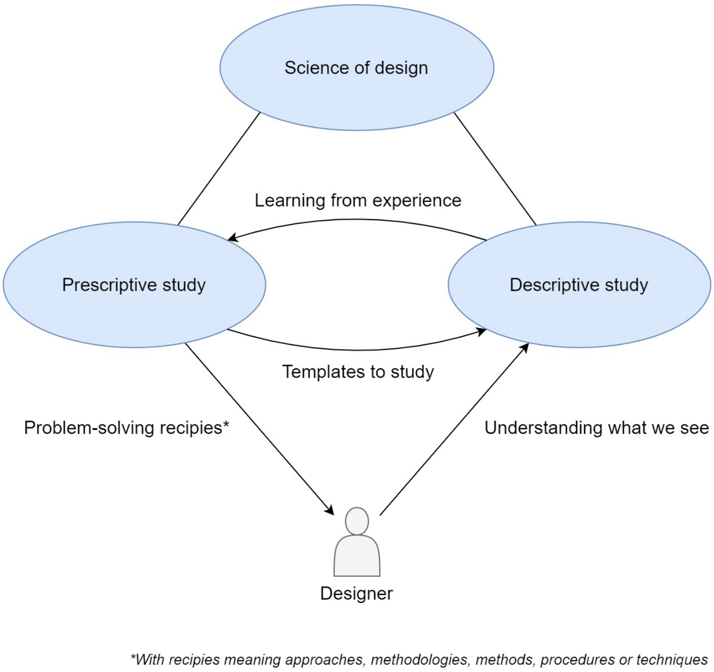


Figure 2.2: Facets of design methodology

While the three facets are closely related, it is important to acknowledge and distinguish between these three different meanings: The first facet implies a rather broad view on design methodology. It characterizes design methodology as a scientific discipline without being explicit on the content of this discipline. The following two facets are narrower and describe different stances on the study of design. The second, descriptive facet relates to the study of how design is actually done in practice. This facet is often employed as the perspective for empirical studies of the design process, such as protocol analysis (Akin 1979; Goel and Pirolli 1989; Dorst 1997). The third facet of design methodology relates to how design ought to be done and therefore conveys a prescriptive meaning. This facet is addressed by Wolff (2000, page 3), stating “the goal of a design methodology is not to formalize the design process and thus restricting the inherent creativity of designers. On the contrary, the goal is to support creativity by providing a framework aiding warship [and merchant vessel] designers in structuring the design problem, reasoning towards solutions and making valid decisions in a world full of uncertainties, subjective value judgments and sometimes even emotions”. This claim is supported by Pahl et al. (2007, page 9) asserting that “design methodology should [...] encourage creativity, and at the same time drive home the need for objective evaluation of the results”.

All three facets are generally relevant for this thesis: This research is positioned within the discipline of (ship) design. The following two sections will briefly summarize the characteristics of the ship design process from a descriptive standpoint. The third, prescriptive facet of design methodology will be the one most frequently used within this thesis. Not the least, this facet is implied in the research objective, which aims for a prescriptive enhancement of design methodology.

2.1.1 Ship design

The ship design process is commonly divided into sequential phases. While both division and terminologies dependent on country and tradition (Mistree et al. 1990; McDonald 2010; Papanikolaou 2014; Rehn 2018), all divisions follow the general pattern from coarse to detailed. Figure 2.3 depicts four different design phases. The conceptual design phase is located in the beginning of the process, where the design freedom is still large and the total knowledge about the design is low. The aim of research into conceptual design methodology is generally to increase the available knowledge in the beginning, such that decisions can be made when there is still enough freedom of change. If decisions need to be made without sufficient knowledge, there is a risk these need to be revised which often incurs large costs.

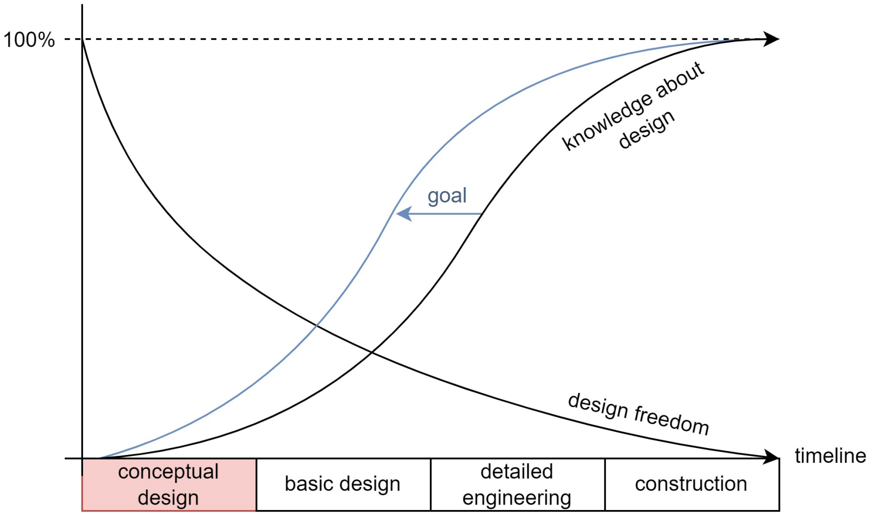


Figure 2.3: Development of knowledge about the design and design freedom throughout the process according to Mistree et al. (1990)

Within the conceptual design phase, Andrews (1998) further distinguishes between concept exploration, concept studies and concept design as steps from divergence towards convergence. Alike the entire design process, this suggests a gradual procedure from broad exploration towards a narrower definition of the solution. For the scope of this thesis, the term 'conceptual ship design phase' shall denote the initial design phase, starting with requirements definition and resulting in one or several feasible principle solutions with a high-level solution architecture.

2.1.2 Conceptual ship design

The amount of resources spent within the conceptual design phase generally varies depending on the degree of novelty of the solution (Andrews 1986), as elaborated on in Table 2.1. While a 'second batch' design might only require few adjustments from a previous design, 'radical technology', such as the introduction of active air cushions to support the hull, requires significantly more resources in the conceptual design phase. As a general rule, increasing novelty requires more time spent in the conceptual phase.

Table 2.1: Degrees of novelty in ship design, adapted from Andrews (1986)

Category	**Description**	**Degree of novelty**
Second batch	Very small deviation only from original design	↓ Increasing
Evolutionary	Adapting an existing design	
Historical	Making use of historical design data and relations	
Simple synthesis	Rough synthesis and balancing required	
Broader synthesis	Traditional solution with locally radical changes, e.g., new equipment	
Radical configuration	Using current technology in radically new way, e.g., small waterplane area twin hull (SWATH)	
Radical technology	Employing radically new technology, e.g., surface effect ship (SES) at time of introduction	

Rhodes and Ross (2010) suggest to distinguish between five aspects of complexities in systems design. These are: structural (many interrelationships), behavioral (non-trivial system performance), contextual (external circumstances), temporal (changes over time) and perceptual (multiple stakeholders' perceptions) complexity aspects. The five complexity aspects taxonomy, outlined in Figure 2.4, has proved to be relevant for conceptual ship design (Gaspar 2013). As for this thesis, the taxonomy may help to categorize different types of complexities, and thereby facilitate a more structured discussion.

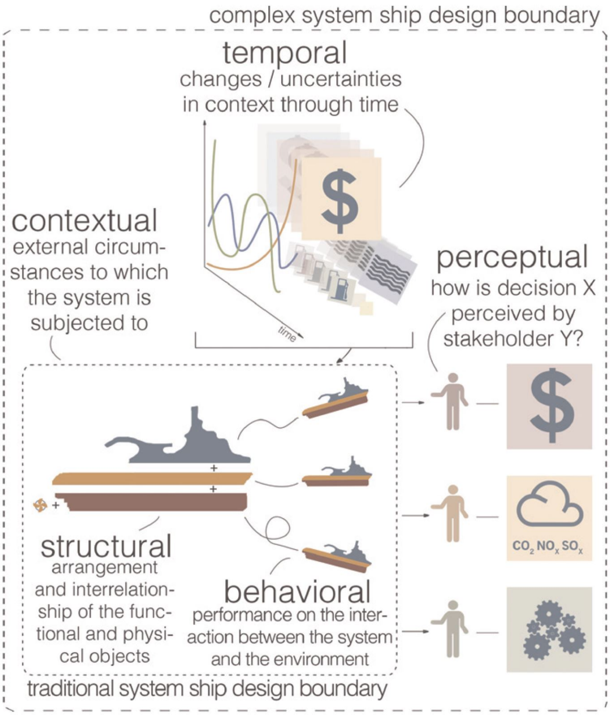


Figure 2.4: Five aspects of complexities in ship design, reprinted from Gaspar et al. (2012)

The five complexity aspects are part of the reason why the conceptual design phase is often characterized as ill-structured (in contrast to well-structured, Simon 1973; Pettersen et al. 2018) or wicked (Rittel and Webber 1973; Andrews 2018b). Andrews (2018b) highlights the importance of identifying design drivers in the conceptual phase, which potentially relate to (a combination of) these complexity aspects.

In addition, the conceptual design phase often involves ’requirements elucidation’ (Simon 1996; Andrews 2003b, 2011), i.e., the working out of requirements in the presence of feasible technical solutions. Requirements elucidation requires understanding the consequences of alternative requirements before they can be settled. At times, requirements may be conflicting and thus the better design solution needs to be defined from all stakeholders’ perspectives (Ulstein and Brett 2015).

2.2 Elements of design methodologies

First, what is meant by ’elements of design methodologies’ and why is this concept applied here? Ship design methodologies are not necessarily mutually exclusive (Habben Jansen 2020). Instead, there may be a significant overlap between design methodologies in many cases, see for instance Ulstein and Brett (2012) for a comparison of 29 different methodologies. The term ’elements of ship design methodologies’ shall denote fundamental concepts which are often used in different ways within various methodologies.

Andiappan and Wan (2020) suggest a framework for ordering terms ranging from ’approach’ to ’technique’ (AMMPT framework: Approach, Methodology, Method, Procedure, Technique). Their framework, developed within the field of process systems engineering, is depicted in Figure 2.5. Andiappan and Wan’s definitions generally coincide closely with terms used in the marine domain. Therefore, I will use this framework within this thesis, together with the definitions shown in Table 2.2.

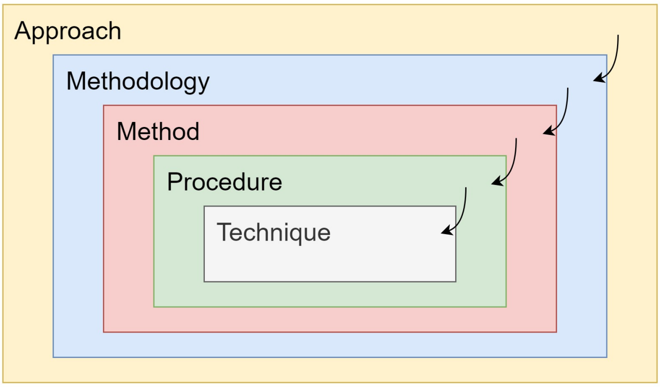


Figure 2.5: AMMPT framework, redrawn from Andiappan and Wan (2020)

The framework suggests a hierarchical order for the five terms. Table 2.2 provides a definition for each term within the framework, along with examples from marine design: The LOGBASED methodology (Brett et al. 2006b), for instance represents a business-centric approach to ship design. Within the methodology, ship voyage simulation (Sandvik 2019) could be applied as a method for performance analysis. The simulation might make use of a semi-empiricial procedure (e.g., Holtrop and Mennen 1982) for the calculation of calm water resistance, which itself could draw upon of one out of several techniques for the estimation of the longitudinal center of buoyancy (Papanikolaou 2014).

Table 2.2: Definitions used in this thesis within the AMMPT framework

Classification	Definition	Example
Approach	"the basic philosophy or belief concerning a given subject matter" (Andiappan and Wan 2020)	Business-centric approach
Methodology	"a framework or system of methods applied to a particular class of tasks" (Finkelstein and Finkelstein 1983)	LOGBASED methodology (Brett et al. 2006b)
Method	instructions that can be followed like a recipe (based on Andiappan and Wan 2020)	Ship voyage simulation (Sandvik 2019)
Procedure	"a sequence of techniques" (Andiappan and Wan 2020)	Holtrop and Mennen (1982) procedure for calm water resistance
Technique	"specific activities practiced by users that can be observed and measured" (Andiappan and Wan 2020)	Empirical relations for the estimation of longitudinal center of buoyancy (Papanikolaou 2014)

The term 'elements of design methodologies' is not part of the suggested framework: Although the 'elements' shall denote fundamental aspects of design methodologies, they can in many cases be used on different levels, i.e., as a methodology or a technique. For example, optimization can be employed as a governing methodology (e.g., Papanikolaou 2010) or simply as a minor technique within a procedure. The elements examined in the following can thus be combined and crossed on different levels. The AMMPT framework may help relating to these levels in a more precise way.

There would have been several alternative ways to structure the literature review, e.g., according to adjunct disciplines, chronologically, or by research group. I have chosen 'elements of design methodologies' as these can be seen as essential building blocks for any complete and prescriptive design methodology. The focus on these elements shall equip the reader with an overview of existing literature and the 'toolbox' described therein. Section 2.3 describes examples of prescriptive design methodologies in existing literature, which draw upon the described elements. It should be noted that the order of elements discussed in the following section does not imply any priority. Instead, the order is simply chosen to facilitate a coherent text. The more basic concepts, such as the design spiral, are therefore discussed before more advanced elements, e.g., set-based design.

2.2.1 Design spiral

The design spiral by Evans (1959), depicted in Figure 2.6, is arguably one of the earliest and perhaps most widely known model in ship design methodology. The available tools certainly have an influence on design methodologies (Nowacki 2009), and as such it should be acknowledged that the spiral was developed at a time when computers were not used in daily business in ship design (Andrews 2010). The spiral indicates an iterative design strategy, traversing aspects such as, stability, machinery and arrangement with each iteration.

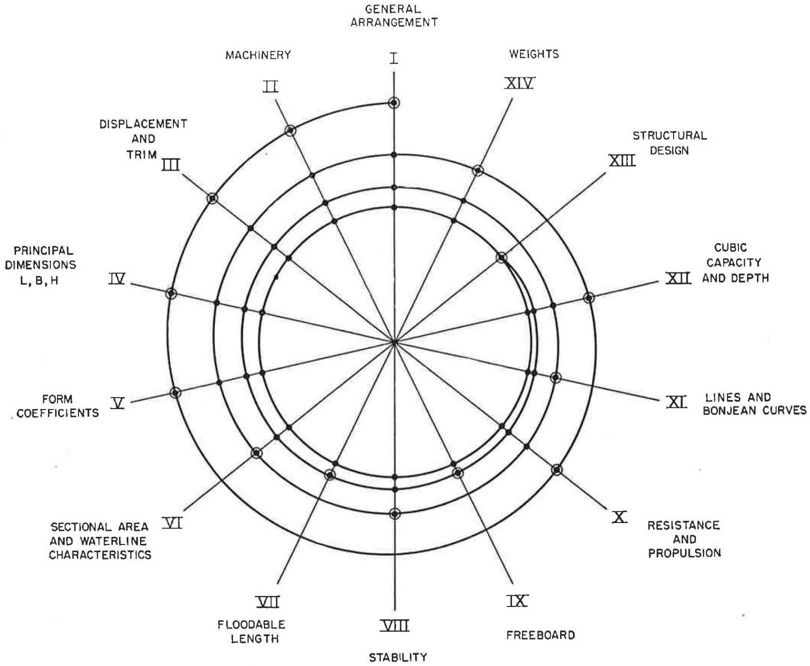


Figure 2.6: Ship design spiral, reprinted from Evans (1959)

The design spiral was meant to provide a heuristic design strategy, relying on estimations and iterations in order to arrive at a feasible, balanced solution. Over time, different versions of the design spiral were developed. Notable variants are Andrews' (1981) three-dimensional spiral and Rawson's (1986) enhancement with additional spikes.

The influence of the design spiral as a prescriptive design methodology declined over time. Today, it is more used to highlight the sequential, iterative nature of design (Nowacki 2009) and the need for balancing out a specific design (Pawling, Percival, and Andrews 2017). Mistree et al. (1990) have presented a frustum of a cone, pictured in Figure 2.7, to indicate that knowledge on the spiral's spikes must be developed as the design proceeds.

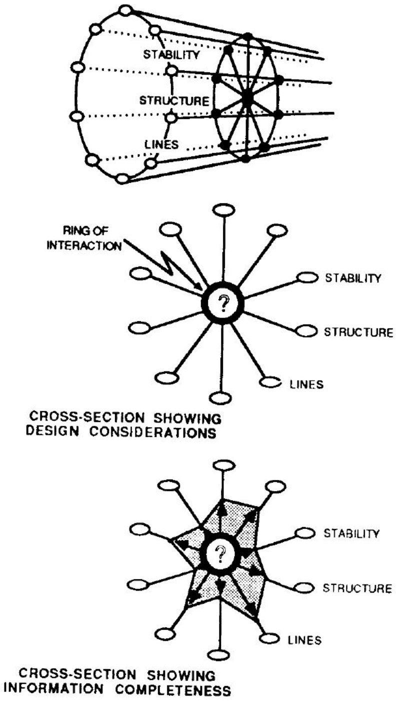


Figure 2.7: Frustum of a cone, reprinted from Mistree et al. (1990)

The frustum of a cone suggests that all aspects, such as stability, powering etc., represented by the spikes, need to be addressed in the design process, but not necessarily in any prescribed sequence. Instead, and not the least due to the development of computer tools, these aspects are addressed increasingly simultaneously and with more capable tools. The importance of addressing these individual aspects is also underlined by the development of design-for-X methods (Papanikolaou et al. 2009) and holistic design (Papanikolaou 2010, 2019).

2.2.2 Parametric design

A parametric approach to design relies on relationships between characteristic parameters. Often, these relationships are established empirically (Yoshikawa and Koyama 1982) or from previous designs (Parsons 2003). Many useful empirical relationships can be found in publications such as Watson and Gilfillan (1977) or Papanikolaou (2014). As an alternative to mathematical equations, MacCallum (1982) and van Hees (1997) represent such parameter relationships as a network. Figure 2.8 displays such a parameter network for a deadweight carrier[1].

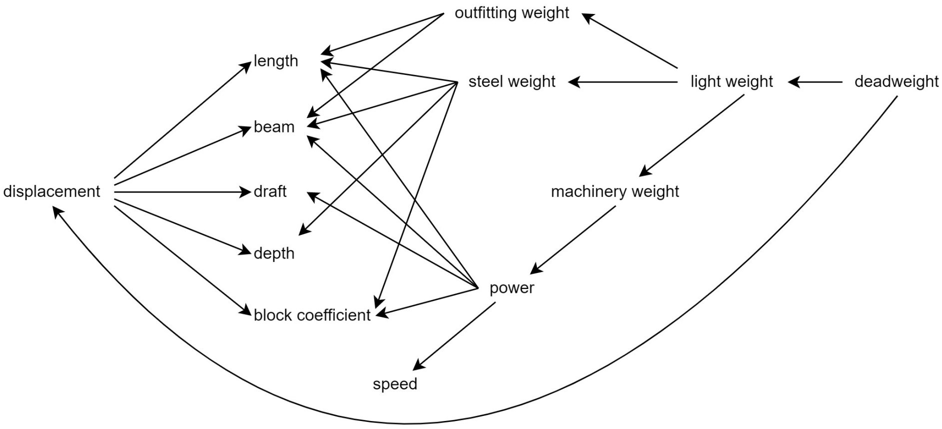


Figure 2.8: Network of parameter relationships for a deadweight carrier, redrawn from MacCallum (1982)

It should be noted that "each different concept for each set of functional objectives is likely to have a different set of significant parameters with different inter-relationships" (MacCallum 1982, page 1). For instance, relationships applicable to a monohull cargo ship, are likely not equally applicable to a passenger high-speed ferry.

Parametric design is often combined with optimization (Section 2.2.7 elaborates on optimization in more more detail). The usefulness of this combination has been embraced, for instance, by Benford (1966, 1967), using a parameterized ship model to identify the optimal size and speed, or Mandel and Leopold (1966). While these early applications are based heavily on (semi-)empirical data, parametric optimization today is used increasingly in combination with simulation.

Concept exploration models (CEMs) can be seen as an alternative development to optimization approaches. Well-known examples are Eames and Drummond (1976) or Nethercote and Schmitke (1982) for SWATH vessels. CEMs typically promote higher interactivity than optimization, as they leave important decisions to the designer. That being said, many CEMs make use of optimization subroutines for decisions which can be more easily automated, such as the dimensioning of structural profiles under a given spacing.

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[1] The dimensions of a deadweight carrier are linked through a weight equation, as opposed to volume or constraints such as stability or lock restrictions (Watson and Gilfillan 1977). Bulk carriers are typically examples of deadweight carriers.

In addition to optimization and CEMs, a parametric design strategy is often applied in the context of knowledge-based design (e.g., Wolff 2000). The following section describes knowledge-based design in more detail.

2.2.3 Knowledge-based design

Knowledge-based design is based on the concept of an "inference engine" (Yoshikawa and Koyama 1982), which shall help to map desired requirements and performances to ultimately solution parameters. Coyne et al. (1990) draw parallels to language structures, depicted in Table 2.3. According to this parallel, designs (sentences) are configured by the assembly of parts (words) according to certain rules (grammar). The resulting designs (sentences) can be analyzed and mapped to their specific performance (interpreting their meaning).

Table 2.3: Parallels between language structures and design according to Coyne et al. (1990)

Category	**Symbol**	**Language**	**Design**
Vocabulary	V	Words	Parts
Syntax	K	Grammar	Actions for configuration
Utterances	D	Sentences	Designs
Semantics	I	Meaning	Interpretation of designs as performances

Acknowledging the partially iterative definition of requirements (Andrews 2003b, 2011), Coyne et al. (1990) do not propose knowledge-based design systems as a complete replacement for the human designer. Instead, knowledge-based design systems are meant as a supportive tool for concept exploration, which separates design knowledge from control. The designer may then use the inference engine to obtain new facts, which he or she can exercise control over.

Examples for the application of knowledge-based design systems to marine design are ShipX (Erikstad 1996) and Quaestor (van Hees 1997; van der Nat 1999). Both models make use of (semi-)empirical parameter relations and serve as concept exploration platforms. Van Oers et al. (2008) present a coupling of a knowledge-based model (Quaestor) with geometric information (Rhinoceros).

Despite successful applications, knowledge-based design systems are not seen as a panacea or even replacement for marine designers. The ill-structured nature of design problems appears to be barrier. Another one is the vast amount of knowledge required from different domains. Simon's (1973) requirements of practically manageable information and a predefined "problem space" thus represent challenges in practice.

2.2.4 Axiomatic design

Suh (1990) describes design as a mapping from customer needs (CNs) to functional requirements (FRs in the functional domain) and further to design parameters (DPs in the form domain, see Figure 2.9). Axiomatic design primarily focuses on the mapping from FRs to DPs, much in line with Yoshikawa's (1979) function-attribute mapping.

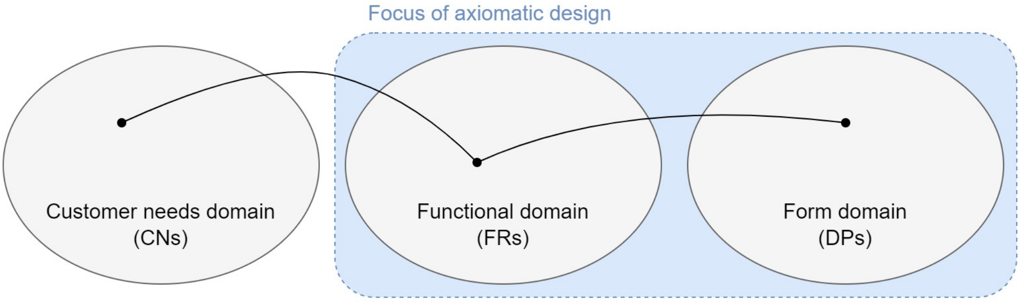

Figure 2.9: Design as a mapping between domains

As for the mapping from FRs to DPs, Suh (1990) establishes two design axioms:

1. The independence axiom: Maintain the independence of FRs.
2. The information axiom: Minimize the information content.

The first axiom can be put differently as: For an acceptable design the FRs are satisfied, whereas for an ideal design the FRs are independently satisfied. The ideal of independence is supported by Alexander (1964).

A mapping between FRs and DPs can be visualized by the House of Quality (HoQ). The 'roof' of the HoQ can be seen as a symmetric design structure matrix (DSM, Eppinger and Browning 2012). In contrast to the HoQ, which maps between FRs and DPs, a DSM visualizes relations between DPs, which can help achieving greater independence between DPs or subsystems.

Applications of axiomatic design to ship design are described by Whitcomb and Szatkowski (2000a,b). Figure 2.10 illustrates their proposed mapping between FRs and DPs.

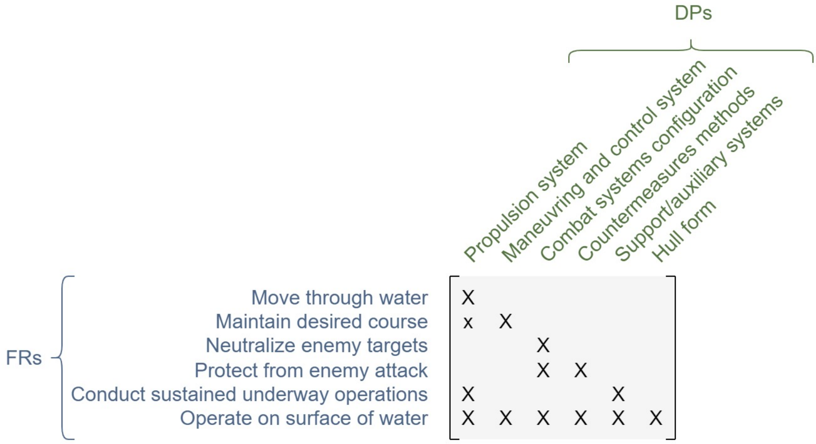

Figure 2.10: Mapping from FRs to DPs, redrawn and adapted from Whitcomb and Szatkowski (2000a)

Inherent circular dependencies (see also subsection 2.2.1 on the design spiral) obscure a fully uncoupled mapping. Nevertheless, near decoupling, indicated through the triangular form of the matrix, can be achieved to avoid excessive iterations and thus speed up the design process.

Further design methodologies relying on functional decomposition are illustrated by, for example, Nordin (2016) and Andrews and Dicks (1997). Both aim for independence or at least a decoupling of system inter-dependencies and strive for solution-neutral FRs.

Axiomatic mappings are not only useful in design, but can also help to unveil so-called “latent capabilities” during operations (Pettersen 2018), i.e., unintended but useful capabilities. By definition, latent capabilities cannot be designed for.

2.2.5 Set-based design

Set-based design uses elimination of infeasible solutions to narrow down and subsequently understand the design space (Ward and Seering 1989). According to Sobek, Ward, and Liker (1999), set-based design is based on the three principles “mapping the design space”, “integrate by intersection” and “establish feasibility before commitment”. Ward et al. (1995) describe how a concurrent set-based design strategy is applied at Toyota. By working concurrently on specification sets, also called “interval specifications”, teams can work on different subsystems independently. Final decisions are thus delayed to a point when trade-offs and implications are better understood (McKenney, Buckley, and Singer 2012). While a point-based design strategy in practice often requires what Goel and Pirolli (1989) identify as a “Limited Commitment Mode Control Strategy with Nested

Evaluation Cycles”, i.e., a preliminary commitment to a decision for tractability reasons, a set-based strategy avoids preliminary commitment until better knowledge is available. The final commitment, as described by Ward et al. (1995) for the case of Toyota, is much stronger because it can be backed by numbers and understood trade-offs.

The application of set-based strategies in marine design, as opposed to point-based strategies such as the design spiral, is discussed by Singer, Doerry, and Buckley (2009). Elements of set-based design, however, can already be traced in earlier publications, e.g., Mandel and Chryssostomidis (1972). Moreover, many of the CEMs, discussed under parametric or knowledge-based design in this thesis, incorporate a set-based design approach. When used properly, set-based design can facilitate the requirements elucidation process (Bernstein 1998; Andrews 2013) and as such benefits a systematic approach to marine design (Woodward, Benford, and Nowacki 1968).

Negotiating trade-offs between goals is often done by means of Pareto fronts (Pareto 1896). Visualizing and analyzing Pareto fronts generally becomes difficult with an increasing number of objectives. Vasudevan (2008) presents methods to better address such multi-dimensional problems. With three or more objectives, identifying trends in the Pareto front is still challenging. Also, non-numerate considerations are generally difficult to incorporate (van Oers, Stapersma, and Hopman 2012; van Oers et al. 2018). By non-numerate it is meant aspects which escape a straight-forward quantification, such as ship arrangement.

2.2.6 Simulation in design

Simon (1996) characterizes simulation as an imitation of a system within imitated environments and raises the question: “How can simulation even tell us anything we do not already know?” (Simon 1996, page 14). His answer is that simulation can help discovering what premises imply. While the premises, that is, the simulated entities and the environment, need to be stated explicitly by the simulation engineer, the computer will work out the implications. Rather than being a design strategy, simulation thus represents a method enhancing the designer’s analysis capabilities. Design can be described as an abductive step from function to form, while simulation facilitates deduction of function (or performance) from a given form, see Figure 2.11. Garcia Agis (2020) characterizes simulation as useful for reducing and controlling uncertainty in the ship design phase.

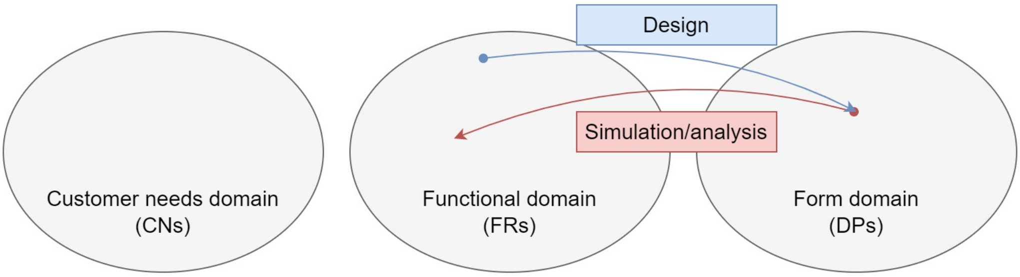

Figure 2.11: Deductive reasoning in simulation in relation to design abductive reasoning in design

Applications of simulation-based design in the marine domain are manifold and cover aspects such as fluid dynamics, structural analysis, hydrostatics or vulnerability analyses, among others (Stapersma and van Oers 2006). Erikstad et al. (2015) describe a virtual test bench for ship configuration with adjunct simulation of operations. Sandvik, Gutsch, and Asbjørnslett (2018) make use of voyage simulation for predicting a design's fuel consumption and GHG emissions. Fonseca et al. (2018) present and open and collaborative simulation framework for marine systems.

By investigating the specific example of personnel movement, Andrews and Pawling (2009) note that simulation in general can increase the believability of solutions and reveal unseen design drivers. Also, simulation can facilitate a dialogue with, for example, an operator and thereby trigger useful feedback.

Most importantly for this thesis, a simulation investigates only one design description at a time. In order to explore a larger design space, simulation must therefore be complemented with other elements, such as set-based design or optimization. The advantage of simulation is its capability to account for numerous interactions and thus enable deductive analysis of complex problems.

2.2.7 Optimization in design

Optimization in design requires translating the design problem into a mathematical model, which is formulated according to strict formal requirements. By adhering to such strict mathematical requirements, the problem can be solved arithmetically within a finite time frame. According to Papalambros and Wilde (2000), optimization models generally require the formulation of variables $\mathbf{x}$ with bounds, objective(s) $f(\mathbf{x})$ and constraints (requirements) in the form of $\mathbf{g}(\mathbf{x}) \leq \mathbf{0}$ and $\mathbf{h}(\mathbf{x}) = \mathbf{0}$. Having formulated the problem mathematically, different categories of problems are traditionally solved by distinct disciplines:

1. If the model requires a numerical solution of coupled differential equations for $\mathbf{g}(\mathbf{x})$ and $\mathbf{h}(\mathbf{x})$, this is often called simulation.
2. If $\mathbf{g}(\mathbf{x})$ and $\mathbf{h}(\mathbf{x})$ are algebraic equations, mathematical programming is applied, either linear or non-linear.
3. In case $\mathbf{g}(\mathbf{x})$ and $\mathbf{h}(\mathbf{x})$ are integrals, control theory applies.

When designing complex systems, the global optimum may be difficult or even impossible to locate. In such cases, partial optimization can lead to at least satisficing solutions (Simon 1996). Mathematically optimal solutions should be checked for robustness in order to work well for the actual real-world problem (Ackoff 1979; Whitfield, Hills, and Coates 1999). Such post-optimum analysis may be based on derivatives (sensitivity analysis) or larger variations of fixed parameters (parametric studies).

Operations Research (OR) holds many relevant tools for design problems. Many of these address the operational phase, e.g., the vehicle routing problem (Laporte 2007). Fu (2002) describes different combinations of OR with simulation and Christiansen et al. (2007) common problems and solutions for maritime transport. Stochastic programming is often used when uncertainty needs to be addressed (see Higle 2005 for an overview and King and Wallace 2012 for a more thorough introduction). Section 2.2.8 will address design under uncertainty in more depth.

Optimization has been applied to marine design problems early on (e.g., Benford 1966, 1967). Mandel and Leopold (1966) denote three important choices relevant to any optimization approach: The optimization technique, the optimization criterion and the choice of the mathematical model. Marine design optimization models have been developed for different system levels, all being potentially relevant for conceptual ship design. Examples on a strategic fleet renewal problem are Fagerholt et al. (2010), Pantuso, Fagerholt, and Wallace (2016), and Ormevik, Erikstad, and Fagerholt (2020). Medbøen et al. (2020) also describe a coupling of a fleet optimization with a weather-dependent simulation. The ship design and deployment model for non-transport vessels developed by Erikstad, Solem, and Fagerholt (2011) optimizes ship/fleet configurations towards future contract scenarios. Balland, Erikstad, and Fagerholt (2012) formulate an optimization model for emissions to air. Baldi (2016) distinguishes between a data-based optimization approach (same author) and a model-based, e.g., Solem et al. (2015) on machinery optimization. Gu (2018) develops several OR models for maritime emission problems. As an alternative to stochastic programming (e.g., Balland et al. 2013), Niese and Singer (2013) present an optimization model based on Markov chains to provide decision support for ballast water treatment systems. The core model is extended by Niese, Kana, and Singer (2015) and Kana and Harrison (2017) towards GHG emission abatement options, including different fuel options.

Many of these references make use of algebraic expressions, and thus fall into category (2) according to Papalambros and Wilde (2000), sometimes coupled with simulation. Notable marine design examples for category (1) optimization models (simulation) are holistic ship design (Papanikolaou 2019) and the open simulation platform (Smogeli et al. 2020) for category (3).

2.2.8 Design under future uncertainty

We always design for the future and the future is inherently uncertain. Uncertainty fundamentally impacts business (Knight 1921) and with “a commercial ship [being] an investment that earns its returns as a socially useful instrument of transport” (Benford 1965, page 36), future uncertainty affects ship design.

Different categories can be drawn between uncertainty and absolute certainty (e.g., Knight 1921; Dove and LaBarge 2014; Köhn 2017). Uncertainty may also be subdivided into economic, technological, regulatory and physical (Erikstad and Rehn 2015). Without embarking on various definitions of uncertainty, what is most important for the context of this thesis is that the future is unknowable (Köhn 2017). This is underpinned by Taleb (2010) noting that even experts’ predictions on future socioeconomic development have often been proved wrong empirically, because they miss out unforeseen events that turn out to be decisive. Not the least in the low-emission shipping landscape, the fact that the future is unknowable requires appropriate methods for effective treatment (Garcia Agis, Brett, and Erikstad 2020; Zwaginga and Pruyn 2022).

Decision-making under uncertainty involves psychological aspects (Tversky and Kahneman 1974). Future uncertainty can translate into both risks and opportunities, each with specific mitigation and exploitation options, respectively (McManus and Hastings 2007). Garcia Agis (2020) outlines and investigates several strategies to handle uncertainty in design. The preference for specific decision options generally depends on the decision maker as well as the framing of decisions (Kahneman and Tversky 1984). Compared to a risk-neutral standpoint, prospect theory (Kahneman and Tversky 1979) can explain many apparent inconsistencies. The concept of bounded rationality may explain others (Simon 1996).

Methods that account for future uncertainty generally rely on scenarios[2]. Scenarios may be created in different ways, from intuition over heuristics to statistics (Schoemaker 1995), see Figure 2.12.

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[2] According to IPCC (2007, page 951) a scenario is “a plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships”

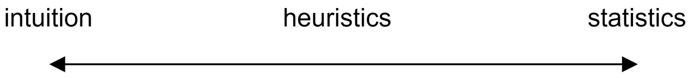

Figure 2.12: Ways to generate scenarios, according to Schoemaker (1995)

Kroneberg (2000) and Rosentrater (2010) motivate for scenario thinking as shifting focus from the most likely future towards satisfactory outcomes under fundamentally different circumstances. A similar narrative approach is proposed by “fictional economics” (Köhn 2017). While scenario thinking can help to account for a broad range of possible circumstances, it is still susceptible to the narrative fallacy (Taleb 2010): That is, a believable narrative can make a scenario seem more likely than it actually is. This phenomenon has been reported in empirical psychological studies (Kahneman 2011).

Detached, statistic methods for generating scenarios can be found in the opposite end of the spectrum shown in Figure 2.12. While these are less prone to the narrative fallacy, they still can only consider known unknowns. Some methods within this category, such as Monte Carlo simulation, require probability distributions. Even though these may be derived empirically from historic data, Köhn (2017) argues that these could at best be seen as measures of belief. The implicit assumption is that the future resembles the past statistically. In general, statistic methods allow for more mathematical rigor. Both Taleb (2010) and Köhn (2017) however warn that the mere availability of a method does not justify their appropriateness for a problem.

Ross and Rhodes (2008) and Gaspar, Erikstad, and Ross (2012) describe the use of epoch-era analysis, a technique for narrative scenario generation and exploration, for handling temporal complexity and thus future uncertainty. While interactive stakeholder involvement is one aspect supported by epoch-era analysis, the reduction of futures into recombineable epochs and lastly eras facilitates a modular thinking towards constructing scenarios. Based on epoch-era analysis, Gaspar et al. (2015) present a model for different emission control scenarios. Rader, Ross, and Rhodes (2010) find that the preference for either narrative (epoch-era analysis) and statistic (Monte Carlo simulation) methods “must be directed by the nature of uncertainty specific to the problem” and therefore depends on factors such as availability of probability distributions, number of dependent scenario parameters and the like. Similar conclusions are reported by Zwaginga and Pruyn (2022). For fleet renewal problems, Pantuso, Fagerholt, and Wallace (2015) show that good estimates on stochastic properties such as mean value and standard deviation are more important than the exact probability distribution for an overall robustness. As a critique of statistic scenario generation methods, Köhn (2017, page 189) claims “the future is unknowable in the present and uncontrollable. Yet it is not random, as most of modern economics assumes". From a design standpoint, the question seems to be whether *treating* the future as random can help to better account for the inherent uncertainty. Literature has shown some support for this hypothesis.

So far, different techniques for thinking about the future have been examined. The following subsections will deal with -ilities, i.e., system lifecyle properties.

2.2.8.1 -Ilities

McManus et al. (2007, page 2) define -ilities as "system properties that specify the degree to which systems are able to maintain or even improve function in the presence of change". -Ilities are thus meant to deliver value robustness. By value robustness, it is meant the "the ability of a system to continue to deliver stakeholder value in the face of changing contexts and needs" (Ross and Rhodes 2008), throughout an uncertain future. According to Fricke and Schulz (2005), this is especially relevant for systems with a long life time, such as ships.

Ross, Rhodes, and Hastings (2008) present a taxonomy for the concept of changeability. They categorize different ways to achieve system changeability according to change agent, change mechanism and change effect. Change agents can be internal or external. Change mechanisms are specific paths or implementations for change, each associated with a specific cost. Change effects are none (termed 'robust'), parameter level (termed 'scalable') or parameter sets (termed 'modifiable').

In order to investigate relations between -ilities, De Weck, Ross, and Rhodes (2012) conduct an expert survey and a means-ends-analysis. Four expert groups were asked to sketch means-ends hierarchies for -ilities. Figure 2.13 depicts the aggregate results of the means-ends-analysis across the four groups.

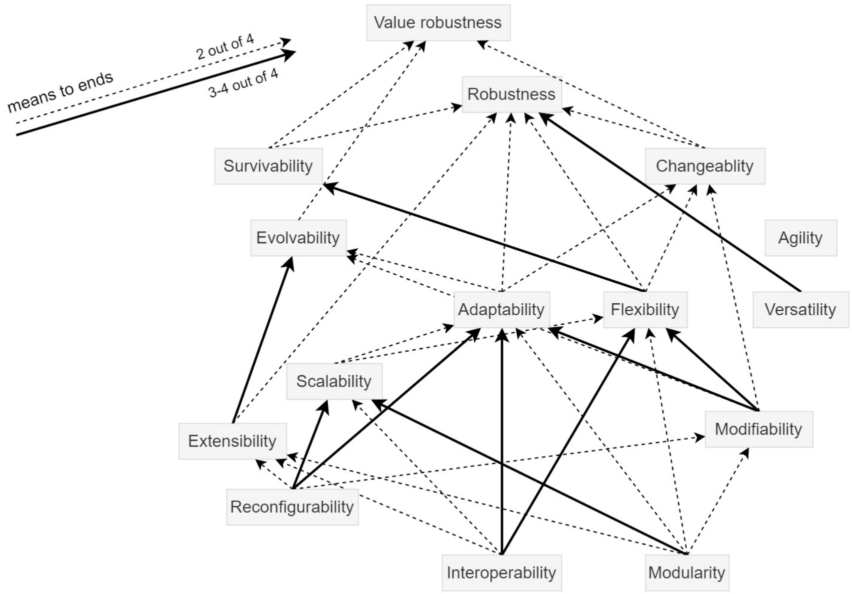

Figure 2.13: Means-ends analysis of -ilities, redrawn from De Weck, Ross, and Rhodes (2012)

The analysis shows that certain properties, e.g., modularity, are often seen as contributors to others, for example, flexibility. Ultimately, all -ilities are thought to contribute to changeability which in turn shall ensure value robustness.

Gaspar, Hagen, and Erikstad (2016) show that value robustness is dependent on the stakeholder and different stakeholders might at times have conflicting perspectives. They use epoch-era analysis to arrive at "satisfying solutions" from all perspectives. Similarly, Rehn et al. (2018) investigate trade-offs between versatility and retrofittability for offshore vessels, by coupling epoch-era analysis with Monte Carlo simulation. Their findings indicate that retrofittability can have significant value compared to versatility.

2.2.8.2 Flexibility

Based on the premise that the correctness of precise deterministic forecasts cannot be assured, De Neufville and Scholtes (2019, page 10) write that "flexibility provides a twofold advantage: it limits possible losses and increases possible gains". As such, flexibility is one strategy to mitigate or even exploit uncertainty. However, flexibility often comes at a cost, and thus the appropriate level of flexibility becomes a classical trade-off decision. Knight and Singer (2012) distinguish between "on" options (e.g., possibility of selling) and "in" options (e.g., possibility of physical extension). De Neufville and Scholtes' book provides engineering methods that can be used for identification and evaluation of "in" options specifically. Many of these methods build upon real options analysis. Knight and Singer (2014) suggest to complement real options analysis with prospect theory. Moreover, for non-revenue-making assets such as military vessels, game theory has shown to be a suitable extension (Knight 2014).

Early marine examples of flexibility are described by Buxton and Stephenson (2001) for merchant vessels and Andrews (2001) for military ships. More recently, agility has received increasing attention, which can for example enable quick market switches (Sødal, Koekebakker, and Aadland 2008; Christensen et al. 2018) in response to volatile external circumstances. While the precise value of agility can generally only be quantified for known future scenarios, agility can also be of value under unknown future scenarios (Dove and LaBarge 2014).

As illustrated by the means-ends-analysis in Figure 2.13, flexibility can be achieved in different ways. One such way is modularity (Parker and Singer 2012), which shall be examined in the next subsection.

2.2.8.3 Modularity

Erikstad (2019) characterizes modules as relatively self-sufficient components, which can be recombined into a larger system. Wolff (2000) recognizes three distinct types of modules in ship design: design modules, building modules and operational modules. Design modules only exist on paper and do not necessarily need to map into physical modules. Design modules may be close to Goel and Pirolli's (1989) idea of "solution decomposition into leaky modules" for the purpose of handling the design process complexity by hiding internal complexity behind a simplified interface (Simon 1996). Moreover, design modules facilitate reuse and thus can potentially help to reduce resource expenditures in the design process (Brett et al. 2022). Building modules and operational modules, on the other hand, represent modules that exist physically. Building modules are commonly used in production, for instance in block assembly. Operational modules denote systems with fixed interfaces, that are designed to be easily exchangeable during the service life.

Being relatively self-sufficient, the modules generally strongly rely on interfaces, which make the "inner environment" (Simon 1996) accessible from the outside. Modules can often be mapped to specific functions, and therefore the concept is related to axiomatic design. A one-to-one mapping of functions to modules is not uncommon and, in line with axiomatic design, can ease the individual modules' design process by reducing dependencies (Ulrich 1995). Ulrich (1995) identifies three distinct types of interfaces: slot, bus and sectional interfaces. Salvador, Forza, and Rungtusanatham (2002) suggest combinatorial modularity as an additional interface type. These four different types of modularity a depicted in Figure 2.14.

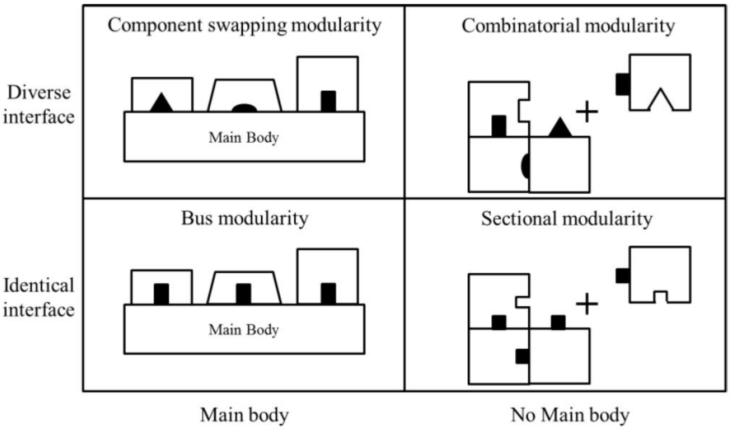

Figure 2.14: Types of modularity, reprinted from Choi (2018)

Product platforms intend to capitalize on the recombineability of modules (Simpson, Maier, and Mistree 2001). Erikstad (2009) describes platform examples from the Norwegian industry, based on either a functional or physical system breakdown. Simpson (2004) moreover distinguishes between top-down platform design, i.e., a strategic decision to develop customized products based on a common platform, and bottom-up platform design. The latter is applied in order to standardize and consolidate a product family. Kalligeros et al. (2006) describe how a design structure matrix may be used for product platform identification. Again, this illustrates the strong link between modularity and axiomatic design.

Marine examples of modularity are often found in naval design, in many cases with mission modules that can be exchanged to adapt to different needs (Hornhaver 1995; Scott 2004; Volkert, Jackson, and Whitfield 2010). Abbott et al. (2003) describe an evolutionary acquisition strategy enabled through defined module interfaces. Blohm+Voss' MEKO concept (MEKO being the German abbreviation for multipurpose combination) describes a modular approach to outfitting strategy (Warship Technology 2006). Schank et al. (2016) find that space availability is often more important than adherence to a exactly specified interface. The concept of modularity has not been without critique due to serious doubts about mission effectiveness in some cases (Warship Technology 2016).

For civil vessels, block assembly production and containerization are obvious examples of modularity that resemble building and operational modules respectively. Regarding modularity as a strategy to mitigate or exploit uncertainty, Choi, Erikstad, and Chung (2018) employ component swapping modularity for mission flexibility to handle uncertainty in the case of an offshore vessel. Similar to evolutionary acquisition for naval vessels, Choi, Erikstad, and Chung (2018) note that - once the module slots are defined - additional, today unforeseen modules can be developed along the vessel's lifetime. Thus, uncertainty can be exploited rather than merely mitigating its effects. Making use of the concept of design modules within a product platform, Brathaug, Holan, and Erikstad (2008) present a configuration-based approach to conceptual ship design.

Jolliff (1974, page 27) states that "most disadvantages associated with modularity either require one-time expenditures of resources, or they are only potential penalties which can be minimized by proper design or proper application of modular concepts". However, it is documented that integral architectures can exhibit greater global performance characteristics (Ulrich 1995). Modular design generally reduces structural complexity due to weaker subsystem dependencies (Simon 1996; Göpfert 1998; Choi 2018). Since complex systems, such as ships, are seldom designed by one individual, the organization's structure must follow the system interactions. Reduced interaction through modularity therefore can also simplify the organization's structure and improve concurrency in the design process (Göpfert 1998).

2.2.9 Systems design

Systems theory as a research field comprises many types of systems, e.g., social and biological, with different properties, such as complex or reflexive (Phillips 1972). Ship design, and thus this thesis, is concerned with the design of physically large and complex systems (Andrews 2012a). Simon (1962, page 468) gives a broad definition of a complex systems as "one made up of a large number of parts that interact in a nonsimple way". This is much in line with Kolmogorov's (1983) definition of complexity as the amount of required information to describe a system.

In systems theory, systemic thinking is seen as the 'bigger perspective' for the current system at hand (i.e., emerging behavior and relations to super-systems), while systematic thinking is seen as a breakdown of the current system into sub-systems and components (Kannengiesser and Gero 2022). Simon (1962, page 468) states that "in the face of complexity, an in-principle reductionist may be at the same time a pragmatic holist". This view is reassured by Papanikolaou (2010, page 1030): "[. . .] holism and reductionism should be regarded as complementary approaches, as they are both needed to satisfactorily address complex systems in practice". McKesson (2010) shows that complex systems are often usefully addressed by very simple models, as a first approximation.

Simon (1973) writes that the process of solving ill-structured problems is generally divided into smaller, almost well-structured subtasks. The final design is very dependent on how this division actually is done and therefore the solution style is influenced by the design process organization. As for ship design, the naval architect, being concerned with the ill-structured problem of designing a ship, needs to foresee the following well-structured problems sufficiently well and leave enough freedom for their solution. As a result, the design process may look more well-structured than before. However, it is still not possible to prove that the solution that is found is close to an optimal one due to the large amount of available knowledge and changing requirements.

The need for a systems perspective in marine design has been early recognized (Woodward, Benford, and Nowacki 1968). According to Rawson (1979), marine transportation involves at least eight major arenas the designer needs to deal with: economic, political, social, geographical, physical, organization, industrial and temporal. The interconnectedness of marine design with these arenas therefore warrants both systemic and systematic approaches. Hagen and Grimstad (2010) propose the extension of system boundaries, i.e., a systemic perspective, to avoid sub-optimal solutions and unlock significant emission reduction potential.

Kroes et al. (2008) compare 'systems engineering' and 'systems architecting' as the two most prominent approaches to the design of complex systems. They find that, historically, "engineers tend to interpret design problems reductively using quantitative criteria, and architects tend to interpret design problems expansively and to employ qualitative criteria" Kroes et al. (2008, page 4). Table 2.4 summarizes the differences between architecting and engineering paradigms in a slightly exaggerated way.

Table 2.4: Architecting versus engineering design, excerpt from Maier and Rechtin (2000, Table 1.1)

Characteristic	**Architecting**	**Engineering**
Situation/goals	Ill-structured	Understood
Goals	Satisfaction	Optimization
Methods	Heuristics Synthesis *Art* and science	Equations Analysis *Science* and art
Interfaces	Focus on 'misfits'	Completeness
System integrity maintained through	'Single mind'	Disciplined methodology and process
Management issues	Working for client Conceptualization and certification Confidentiality	Working for builder Meeting project requirements Profit versus cost

Ship design exhibits characteristics of both architecting and engineering. Therefore, the following two subsections will briefly discuss the most common systems design strategies 'systems engineering' and 'systems architecting'.

2.2.9.1 Systems engineering

Hubka and Eder (1988) suggest a view of machines to be seen as combination of principles. A technical system is thus as an abstraction of an existing machine. Generally, different views can be taken upon a technical system, depending on whether the focus is on functions, organs, components or similar. Alike Simon (1996), Hubka and Eder (1988) differentiate between 'external' and 'internal' properties and design characteristics.

Pahl et al. (2007) describe a systematic approach to engineering design, while acknowledging the importance of creativity, intuition and experience. They distinguish between generative and corrective working styles. While the latter one is based on experience and starting from existing solutions, the former is often chosen by novices and especially applicable to new problems. One such generative approach is the (re-)combination of working principles into new solution structures (Figure 2.15).

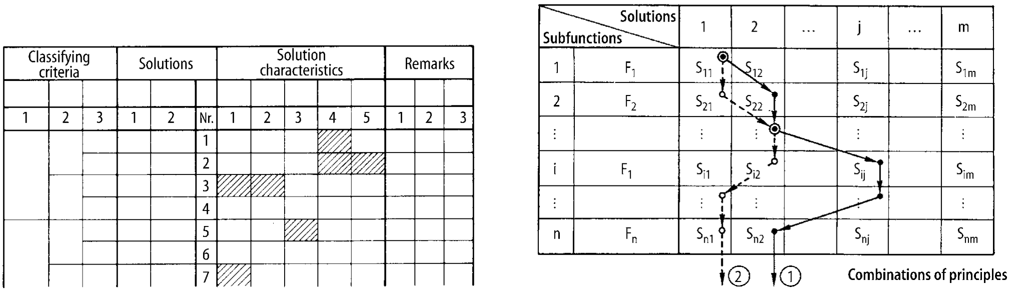

Figure 2.15: Design catalog (left) and combination solution principles (right), reprinted from Pahl et al. (2007)

Working principles are abstract solution principles and can be stored in design catalogs (left-hand side of Figure 2.15) to categorize their main properties and interfaces. The focus on interfaces enables reusing working principles as solution elements or modules in generative design tasks, illustrated on the right-hand side of Figure 2.15.

The systems engineering approach is commonly affiliated with a V-shaped diagram. The V-diagram indicates a systematic, top-down breakdown of the system to be designed with a following bottom-up recombination and evaluation. This approach has received critique for its indicative linearity. Esdras and Liscouet-Hanke (2015) draw a different model of the left side of the V diagram, depicted in Figure 2.16.

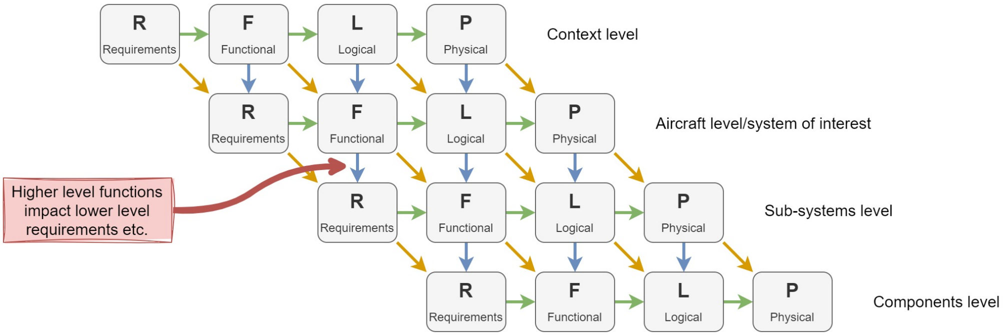

Figure 2.16: Mapping and breakdown from requirements to physical embodiment (RFLP model), redrawn and adapted from Esdras and Liscouet-Hanke (2015)

Their requirements-functional-logical-physical model (RFLP) suggests a mapping from requirements over functions to system form, with an additional step of logics between functions and system. The model moreover indicates the inter-relatedness of, e.g., functions on a lower level with logics on a higher level. That is, the top level system embodiment will impact the functional design on lower levels and vice versa.

Applied to marine design, the critique of the classical systems engineering approach, based on a V-diagram, is supported by van Griethuysen (2000, page 23): “As in the design of other mobile vehicles such as aircraft, for marine vehicles there is a very strong interaction between the system and sub-system design levels through mechanisms such as weight and size”. Similarly, Martin (2013) calls for caution when applying systems engineering methods in marine design, since they have often been developed for different problems. According to van Griethuysen (2000), the notion of systems engineering strengthens the cross-disciplinary nature of marine design, i.e., the integrative work that a naval architect must carry out.

Model-based systems engineering (MBSE) introduces the notion of one consistent computational model for the design of complex systems (Rauzy 2022). Naturally, this model is a simplification of the system, but a consistent one which enables the simulation of the systems behavior in different use cases. The system model is often communicated by means of diagram representations and modeling languages (Gausemeier et al. 2019). Diagrammatic representations, however, can only provide a partial view on the model and not communicate all aspects. Modeling languages are capable of providing more comprehensive descriptions of a model, and the computational model therefore takes precedence (Rauzy 2022).

2.2.9.2 Systems architecting

"The essence of architecting is structuring" (Rechtin 1991, page 1). More and more structuring is required with increasing system complexity, rendering the design of such systems more amenable to architecting design approaches. According to Maier and Rechtin (2000), large and complex architectures such as ships are usually the product of "a team of a single mind" or "a single vision". Rechtin (1991) moreover states that architecting is generally done for a client with a builder, while engineering is with an architect for a builder.

Being the client's advocate, one crucial task for a naval architect is to establish satisfactory criteria for acceptance and certification (Maier 1996; Maier and Rechtin 2000). These criteria and further requirements can only be established when it is "known that a feasible implementation exists whose characteristics represent a satisfactory compromise for the user" (Maier 1996, page 232). Thus, a strong emphasis is placed on negotiating requirements in the light of system feasibility, which corresponds to requirements elucidation (Andrews 2003b, 2011). Requirements elucidation requires a close dialog with the customer and and iterative approach, for which the systems architecting approach seems more capable than a streamlined systems engineering strategy (Andrews 2015). Together with the client, the architect also decides on strategic choices, e.g., single- versus multipurpose (Rechtin 1991).

In order to establish feasibility of a concept, it is necessary to identify crucial design drivers in the architecting process (Rechtin 1992; Andrews 2018b). Architecting, therefore, not only requires a divergent exploration approach together with a client, but also in-depth knowledge in certain domains to identify crucial design drivers: "Systems architects must necessarily know, or learn, a great deal about some details those that impinge on the overall system but need not, and probably should not pay much attention to the rest, which are best handled by the subsystem experts with whom the systems specialists work" (Rechtin 1992, page 67). In practice, this requires substantial experience, a dialog with subsystem specialists and a careful study of the system (Maier and Rechtin 2000). The architect is both integrator and specialist at the same time, as the search for design drivers requires both a holistic view and in-depth domain expertise (Rechtin 1991; Maier 1996).

Ill-structured problems tend to be solved by architects (Rechtin 1991), and as such architecting relies heavily on heuristics (Maier 1996). Heuristics can help avoiding misfits (Alexander 1964) and highlight the necessity of satisficing when optimization is nonviable due to the ill-structured nature of the problem (Archer 1967; Simon 1996). Rechtin (1991) and Maier and Rechtin (2000) provide general heuristics for system architects, while Andrews (2022) presents specific heuristics for naval architects.

Like in model-based systems engineering, models are central to systems architecting (Maier and Rechtin 2000). They shall support communication among stakeholders, maintain system integrity and support exploration and performance prediction, as well as provide acceptance criteria for certification.

In ship design, the architecting approach manifests itself not only in the spatial arrangement of systems (Andrews 1986), but also non-spatial aspects such as the topology of energy distributions systems (de Vos and Stapersma 2018; Brefort et al. 2018) or the relations between functions and components (Habben Jansen 2020). Ship design also features many cross-cutting decisions that can be summarized as choices of ’style’ (Pawling et al. 2014). Choices of style are a prerequisite for the deduction of form from function (Coyne et al. 1990). Beyond aesthetics (Andrews 2007), stylistic choices are often linked to system -ilities (Andrews 2018a).

While ship design is undoubtedly part of the engineering discipline, many of the choices made in the early design stages escape a streamlined systems engineering process (Andrews 2012a). The conceptual design phase may be therefore better described and mastered by an architecting strategy, in particular when aiming for creative and innovative solutions (Andrews 2003a). Conversely, further downstream in the design process, a systems engineering strategy may be more applicable.

2.2.10 Meta-design

In contrast to designing the physical artifact (the ship), meta-design addresses the design of the design process (Mistree et al. 1990). According to Mistree et al. (1991), “the principal role of an engineer, in the design of an artifact, is to make decisions”, and the idea of meta-design is to prepare for these decisions to be made in a structured way (Birmingham et al. 1997). As an empirical example, Garcia Agis, Brett, and Erikstad (2020) show that perceived uncertainty, for instance with respect to political or market conditions, significantly affects the decision-making effectiveness in ship design. Thus, there is empirical evidence for the need to structure the design process.

Erichsen (1989) addresses the project management in ship design on different levels, from how to organize a design team to change management during the design process. Another example of structured meta-design is the LOGBASED methodology (Brett et al. 2006a) depicted in Figure 2.17.

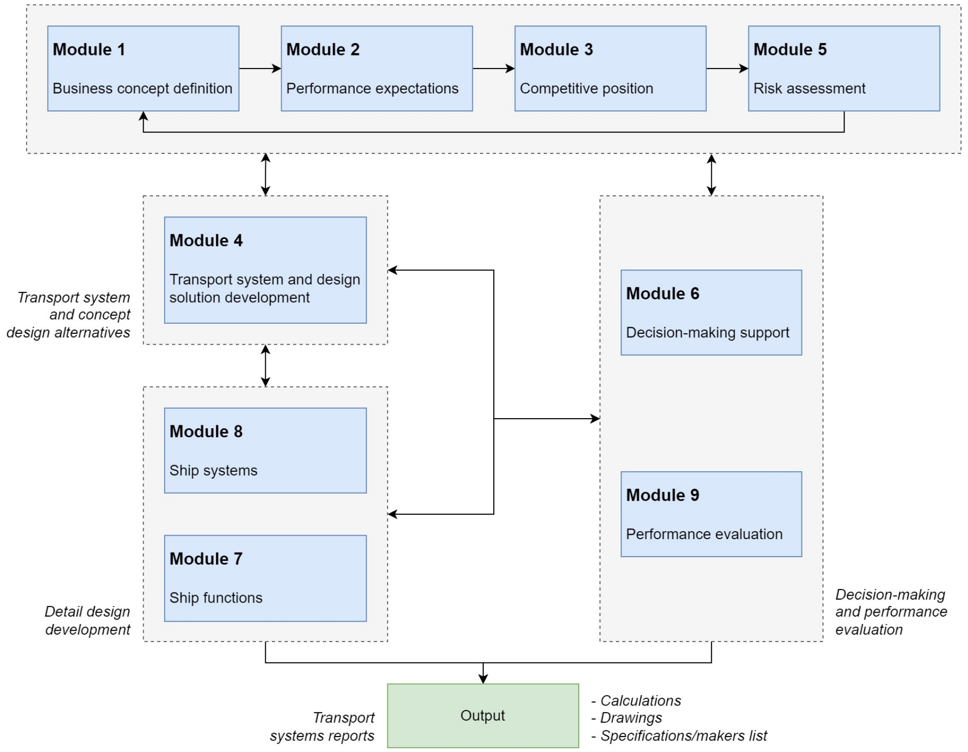

Figure 2.17: LOGBASED design methodology, redrawn and adapted from Brett et al. (2006a)

The LOGBASED methodology represents a semi-formalized procedure for 'requirements elucidation'. By going through the different modules, the stakeholders' requirements and expectations are captured in a systematic way. The original LOGBASED methodology has been further developed and enhanced, which is elaborated on in Section 2.3.4 on business-centric ship design. Central to this development has been the assumption that reaching a common understanding of the requirements and expectations is crucial for the concept design phase, as misalignments are much harder to resolve later in the process. The idea of reaching alignment of expectations through earlier and better stakeholder involvement has also been the basis for agile design approaches, such as the Scrum process (Schwaber 1995). Agile design approaches have gained increasing interest for the development of complex systems, though not necessarily physically large ones.

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The previous sections have reviewed different elements as basic ingredients of design methodologies. Each of these elements provides desirable characteristics for a design methodology, e.g., the generation of diverse functional architectures or the capability to address future uncertainty. These characteristics may be strengthened through a combination of elements, for example by analyzing a set of modular designs from a real options perspective. Table 2.5 summarizes the strengths and weaknesses of the reviewed methodological elements from the perspective of this thesis.

Table 2.5: Summary of the reviewed elements of design methodologies

Methodological element	**Strenghts relevant for this thesis**	**Weaknesses relevant for this thesis**	**Often combined with**
Design spiral (Section 2.2.1)	Multi-faceted, sequential process	Starts with and is biased by existing solution(s)	
Parametric design (Section 2.2.2)	Provides flexible numerical models to explore the design space	Exploration of diverse high-level systems can require very different parameters and relationships	Optimization, set-based design, simulation
Knowledge-based design (Section 2.2.3)	Automatic inference of design with knowledge from multiple disciplines	Requires explicit knowledge with strict formal requirements	Parametric design
Axiomatic design (Section 2.2.4)	Supports functional structures and promotes independence of subsystems	Difficult to apply effectively for systems with strong inter-dependencies	Parametric design, modularity
Set-based design (Section 2.2.5)	Supports exploration, requirements elucidation and pragmatic convergence	Exploration needs to be complemented with a design generator, potentially high computational effort required	Parametric design, simulation, future uncertainty
Simulation (Section 2.2.6)	Facilitates performance analysis under complexity and stochastic data	Represents an analysis technique	Parametric design, optimization, set-based design
Optimization (Section 2.2.7)	Promises optimal solutions and enforces explicit, objective performance measurement	Difficult to capture real, complex problems in mathematical models	Parametric design, simulation, future uncertainty
Future scenarios (Section 2.2.8)	Captures the fact that the future is uncertain	Narrative scenarios: susceptible to the ’narrative fallacy’; Stochastic scenarios: distributions can only represent expectations	Set-based design, optimization, simulation

Table 2.5: Summary of the reviewed elements of design methodologies (continued)

Methodological element	**Strenghts relevant for this thesis**	**Weaknesses relevant for this thesis**	**Often combined with**
-Ilities (Section 2.2.8.1)	Captures key system level aggregate performances	Requires extensive, often operational, models	Set-based design, optimization, future uncertainty
Flexibility (Section 2.2.8.2)	Captures the value of being able to change	Increased model complexity	Set-based design, optimization, future uncertainty
Modularity (Section 2.2.8.3)	Relevant for both product (to achieve flexibility) and process (partitioning into nearly-independent design modules)	Cost implications for product, decomposeability challenging in design process	Set-based design, optimization, future uncertainty
Systems engineering (Section 2.2.9.1)	Promotes a structured mapping from requirements to form	’Waterfall model’ does not aid requirements elucidation, susceptible to ignoring emerging design drivers	Parametric design
Systems architecture (Section 2.2.9.2)	Holistic approach promoting requirements elucidation and subsequent identification of design drivers	Few prescriptions on how to synthesize options	Set-based design
Meta-design (Section 2.2.10)	’Design the design process’ to effectively structure the decisions to be made	For bespoke products (ships), it is challenging to define one standardized process	

As indicated by the table, some elements are often applied in conjunction with others. Set-based design, for example, is often combined with parametric models to generate a set of design options. Such complementary combinations can help to come by the weaknesses of individual elements. It is important to note that such combinations may be constructed by employing the elements on different levels: Optimization may be used as a governing approach to design or merely as sub-procedure within, e.g., a set-based approach. The following section will further examine different combinations of the methodological elements that are documented in literature.

2.3 Conceptual ship design methodologies

The preceding section examined different elements of design methodologies. This section will show these elements ’in action’, i.e., how they have been combined and applied as building blocks within complete, prescriptive conceptual ship design methodologies.

Ulstein and Brett (2012) compare and evaluate 29 of publications on ship design methodology. Since then, both ensuing and separate papers on ship design methodology have been published, raising the question what qualifies and what does not qualify as a complete design methodology. The demarcation applied in this thesis is that the candidate methodology

a) has been succesfully applied in practice;

b) is documented in multiple publications.

Demarcation a) is based on Kroes (2002), while demarcation b) is grounded in Andrews’ (2003) requirements that a design methodology is characterized by believable, coherent and open solutions, as well as being revelatory and fostering creativity. While individual publications do not necessarily comply with each of their requirements, many papers describe only parts of a design methodology, which is evolved over time and documented in multiple related publications. In order to satisfy Andrews’ (2003) requirements, the methodologies examined in the following sections are therefore seen as groups of closely related publications, often correlated with specific research groups.

2.3.1 System-based ship design

The system-based ship design (SBSD) methodology was first introduced for the design of passenger vessels by Levander (1991), and implemented into the SeaKey program. The methodology has received notable success in cruise ship design (Levander 2009), and has been generalized (Levander 2003) and applied to offshore vessel design as well (Erikstad and Levander 2012).

Compared to the design spiral, SBSD omits iterations by dividing the systems into payload and auxiliary systems, see Figure 2.18. Once a system breakdown is established, weights and volumes can be assigned in a similar way to design catalogs in engineering design. Many of such catalog data can be found in Levander (2012). This principle is not unlike the “equivalent design volume” in airplane design (Liscouet-Hanke and Huynh 2013) and based on empirical data. Within a given overall concept, e.g., choice of propulsion concept, SBSD provides a pragmatic approach to a transition from customer needs over function to form.

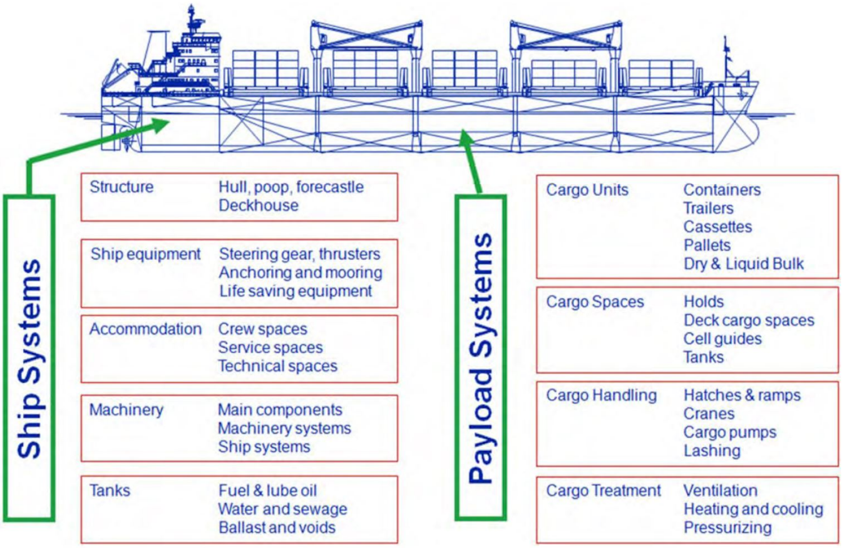

Figure 2.18: SBSD breakdown, reprinted from Levander (2012)

SBSD results in a system breakdown with weight and volume specifications, around which a hull needs to be wrapped. Even though the arrangement of systems is not prescribed, SBSD explicitly aims to ease such architectural considerations by enabling the designer to focus on the arrangement of items, as commonly done in architecture (Broadbent 1988). Systems are thus viewed as parameterized design modules. Vestbøstad (2011), see Figure 2.19, shows how SBSD can be crossed with architectural configuration and set-based design.

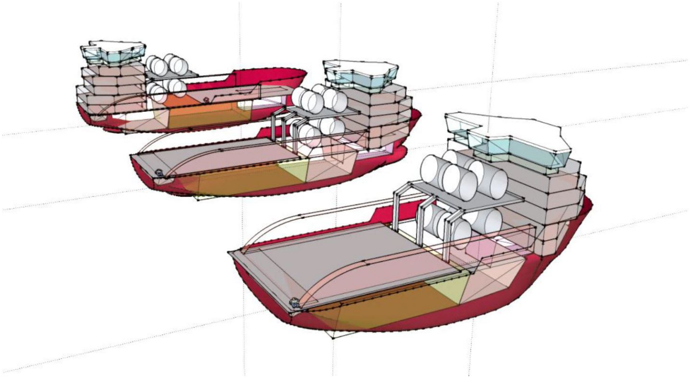

Figure 2.19: Three different arrangements for the same SBSD breakdown, reprinted from Vestbøstad (2011)

The figure illustrates three different arrangement options for the same vessel, that are based on the same system breakdown. Thus, by coupling the SBSD breakdown with templates for the arrangement, three-dimensional configurations may be readily explored.

2.3.2 Optimization-based ship design

The notion of holistic ship design has been introduced by Papanikolaou (2010). The concept of holism unites the previously scattered design-for-X methods (Papanikolaou et al. 2009). By stating the design problem with objectives, constraints and relations, the problem is transferred into an optimization problem, see Figure 2.20.

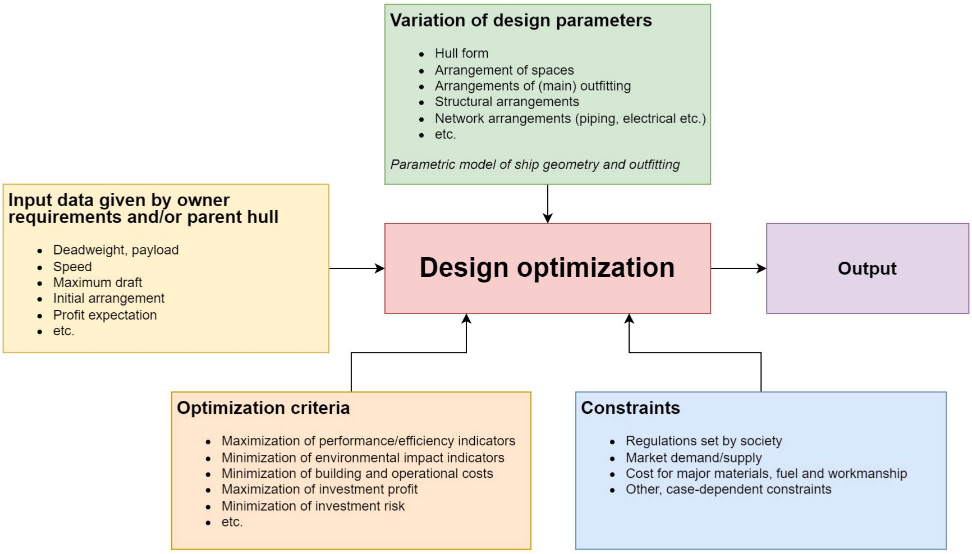

Figure 2.20: Holistic ship design optimization, redrawn from (Papanikolaou 2010)

The holistic design methodology has been applied to various designs, ranging from more conventional roll-on/roll-off (RoRo) ships (Papanikolaou 2010) to more unconventional high-speed ferries (Papanikolaou 2019; Skoupas, Zaraphonitis, and Papanikolaou 2019; Papanikolaou et al. 2020). Due to the methodology's frequent application with simulation (e.g., computational fluid dynamics, CFD or finite element method, FEM), a software ecosystem has been arranged around the holistic ship design methodology (Papanikolaou 2019). Parameterization is used to generate large design sets. The performance of these sets is often simplified through surrogate models in order to preserve the high accuracy of simulation results while enabling resource-efficient optimization. Notably, also the design of ships with low GHG emissions has been addressed, for instance through battery-electric high-speed ferries (Papanikolaou et al. 2020), and different life cycle performance analysis tools have been developed (Papanikolaou 2019).

2.3.3 Configuration-based ship design

Andrews (1986) advocates an architectural and arrangement-centered approach to ship design, in particular for complex service ships such as naval vessels. Andrews and Dicks (1997) describe how such a perspective can be implemented for surface vessels by means of the Design Building Block (DBB) methodology, see Figure 2.21. Andrews (1998) summarizes the theoretical considerations around the DBB methodology. The DBB methodology starts with a functional decomposition with the float, move, fight and infrastructure on the highest functional level. The purpose of this functional perspective is to foster creativity by not constraining the solution space unwillingly (Andrews 2003a). Combined with a three-dimensional architectural model, emergent design drivers can be revealed. For naval vessels, such drivers may emerge from the interaction between topside and a particular hull configuration (mono- versus multi-hull, Andrews and Dicks 1997). For merchant vessels, onboard logistics - people, vehicles or other materials - may be design drivers that emerge from the selection of a particular hull concept (Wijnolst and Wergeland 2009). By providing the capability to reveal such drivers, the DBB methodology strongly supports the crucial task of requirements elucidation (Andrews 2018b), i.e., the discussion of the overall desirable in the presence of feasible technical options.

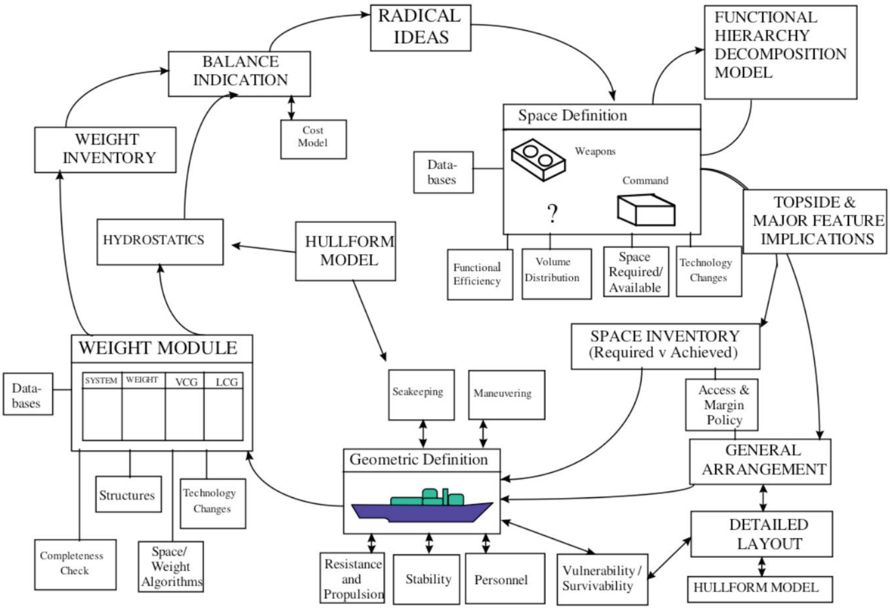

Figure 2.21: DBB methodology applied to surface vessel design, reprinted from Andrews and Dicks (1997)

The DBB approach has been applied to the design of both conventional and unconventional surface ships (Dicks 2000). Thus, it has proven to support innovation in ship design, while also revealing design drivers and discontinuities in the solution space (Pawling 2007). Pawling (2007) notes that the revelatory capability of the DBB approach is crucial in particular for problems requiring a high level of requirements elucidation. Andrews and Pawling (2003; 2008) thoroughly describe the individual steps and required decisions in the application of the DBB approach.

Andrews (2006) outlines the coupling of the DBB approach with simulation techniques. The example of evacuation and personnel movement simulation is made possible through the tight integration of the ship arrangement into the DBB methodology. Similarly, other simulations such as damage stability and progressive flooding simulations may favor an arrangement-centered design approach. Pawling and Andrews (2011) investigate the additional use of sketching for both thinking and idea generation as well as communication on different levels. While design state communication is generally well-supported by the DBB approach, sketching often is more intuitive and thus could ideally support the idea generation and exploration phase.

Andrews, McDonald, and Pawling (2010) present an extension of the DBB approach with a library-based exploration for hullforms, similar to a design catalog with different working principles. The approach is applied by McDonald, Andrews, and Pawling (2012) to rapidly synthesize and evaluate diverse configurations based on radically different hull forms, such as monohulls and trimarans. McDonald (2010) advocates for this approach being necessary for a full requirements elucidation without constraints on the solution space. The United States Littoral Combat Ship concept studies exemplify that, for the same requirements, radically different hull concepts can be selected by different designers (McDonald 2010).

Apart from the the library-based extension, the DBB methodology generally leaves most decisions to the designer and by default does not support the automatic generation of large design sets. Van Oers, Stapersma, and Hopman (2009) present a space allocation technique to efficiently generate a large and diverse set of candidate design options. By being able to pre-compute the performance of all design options, the designer can see the consequences of important architectural and arrangement decisions such as the placement of systems while elucidating negotiable requirements (van Oers 2011). Similar to McDonald (2010), the non-negotiable requirements such as 'float in upright position' are applied by default.

Large design sets under multiple and conflicting objectives generally result in Pareto sets of solutions. These are not trivial to interpret and to extract relevant insight from. While Vasudevan (2008) focuses on numerical aspects, i.e., parameters and key performance indicators (KPIs), of Pareto-optimal options, Duchateau (2016) also examines architectural aspects. By interactively exploring the Pareto set, insight can be gained with respect to why criteria interact or conflict and how to resolve potential conflicts.

Pawling et al. (2014) and Andrews (2018a) investigate style as a cross-cutting characteristic in design that is often hard to analyze and quantify. The DBB approach facilitates the exploration of style decisions, which can manifest as, e.g., modularity, adaptability or producibility (Andrews 2018a). By making use of the packing approach (van Oers 2011), deNucci and Hopman (2012) capture arrangement-related rationales of designers. The captured rationales may then be reused to guide the generation of new designs. By providing also unexpected, unorthodox design options, the packing approach can help triggering designers spelling out their rationale and thereby making parts of their style explicit.

The DBB approach has most often been applied to complex naval designs. Calleya (2014) presents an extension of the DBB towards lowering emissions (Figure 2.22), which has been applied to several merchant ships.

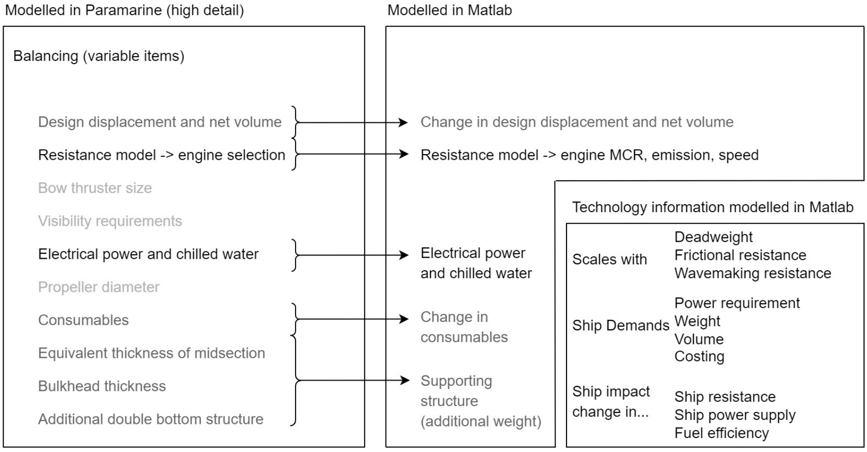

Figure 2.22: Ship impact model, redrawn from Calleya (2014)

The ’Ship Impact Model’ can be applied on top of an existing model in Paramarine (DBB) and enables exploring different carbon-reducing technologies. Applications for merchant vessels, are documented by Calleya, Pawling, and Greig (2015b), Calleya, Pawling, and Greig (2015a), and Calleya et al. (2016). The model has enabled a case-based assessment, which resulted in more accurate performance predictions and a better understanding of emission abatement options.

2.3.4 Business-centric ship design

Business-centric design methodologies, such as the ones described by Brett et al. (2006b) and Ulstein International AS (2017), have strong roots in a design management perspective, building upon the premise that “it is more important to maintain control over all the major elements in the overall decision making process than the details of the sub-elements of the solution in question” (Brett et al. 2006a, page 124). The central idea of this methodology is to structure and somewhat formalize the process of requirements elucidation by working through the different modules, depicted in Figure 2.23, jointly with a client. As such, a business-centric design methodology puts strong emphasis on the systemic perspective, i.e., the integration of the ship design into a business case and existing (transport) system (Brett et al. 2018). The methodology is therefore well-positioned for an extension of system boundaries (Hagen and Grimstad 2010).

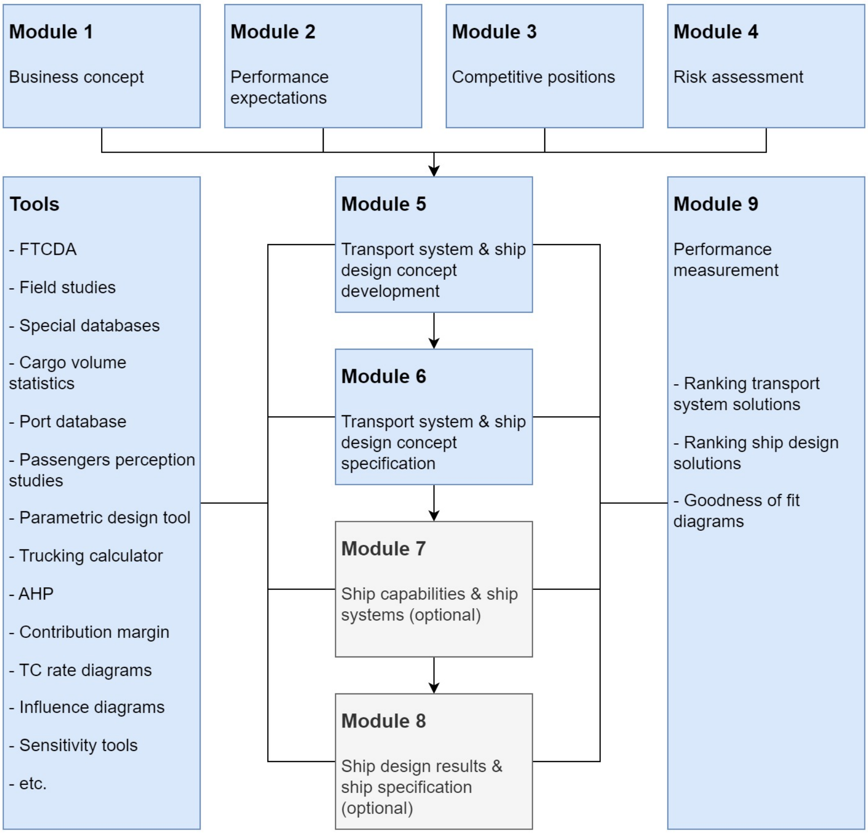

Figure 2.23: Ulstein ABD methodology, redrawn and adapted from Brett et al. (2018)

Modules 1 to 4 assess the business proposition from different perspectives. Module 5 diverges on potential logistic concepts, while module 6 converges on the same topic. Module 7 translates the overall system requirements into ship requirements for which a suitable concept is settled in module 8. Module 9 finally assesses the developed solution or solution set in the light of the business case. Brett et al. (2006b) find that new and innovative logistic solutions do not necessarily require new and innovative ship designs. The methodology is therefore supported by databases of existing solutions as well as parametric concept design tools, such as the one described by Ebrahimi, Brett, and Garcia Agis (2019).

The Ulstein Accelerated Business Development (ABD) methodology makes extensive use of KPIs for the ranking and evaluation of solutions. As a minimum, these KPIs shall address the perspectives shown in Figure 2.24. Ulstein and Brett (2015) discuss the different perspectives as “design for efficiency” (technical, operational, commercial), “design for effectiveness” (smarter, safer, greener) and “design for efficacy” (flexibility, robustness, agility).

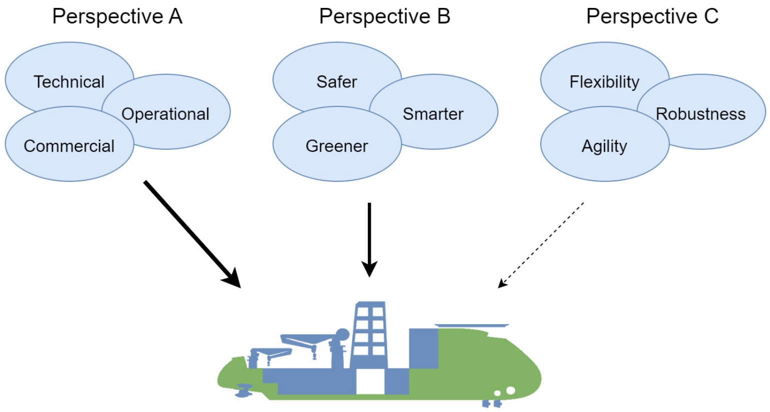

Figure 2.24: Performance evaluation perspectives, redrawn from Ulstein and Brett (2015)

The development of KPIs and solutions generally brings to surface stakeholder expectations and requirements, as well as possible conflicts between stakeholders (Ulstein and Brett 2015). Ill-defined design problems can therefore be identified and addressed (Garcia Agis et al. 2019). Although Ulstein and Brett (2009) highlight the importance of proactively discussing future uncertainty and appropriate response strategies, this aspect is to date only integrated to a limited extent into the methodology, mainly through modules 3 (“competitive positions”) and 4 (“risk assessment”).

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The four reviewed ship design methodologies draw upon the different elements described in Section 2.2. In many cases, the methodologies have been subsequently enhanced with additional elements, such as the addition of a rigorous set-based approach to configuration-based design (van Oers 2011). Low-emission technologies and ambitions are explicitly addressed in optimization-based design (HOLISHIP, Papanikolaou 2019) and through the Ship Impact Model as an extension to configuration-based design (Calleya 2014). Both methodologies, however, are currently limited in their preliminary exploration of diverse design concepts and their capability to address lifetime uncertainty related to alternative fuels.

2.4 GHG emission abatement options

The previous sections reviewed the topic of design from a generic perspective towards specific prescriptive design methodologies. In short, these sections dealt with the *design process*. As argued by Rechtin (1992) and Andrews (2018b), successful design requires the study of the (sub-)system(s) in question to be able to discover and manage important design drivers. This section will therefore review GHG abatement options more closely, and thus address the *product alternatives* as opposed to *process alternatives.*

Numerous studies on different abatement options have been conducted, ranging from logistical changes (e.g., Lindstad and Eskeland 2015, on ship speed and size) and onboard technical measures (e.g., Eide et al. 2009; Lindstad and Bø 2018) to alternative fuel options (e.g., Vergara, McKesson, and Walczak 2012 on synthetic fuels and nuclear energy, DNV GL 2019a for a broad review of alternative fuel options).

Meta-studies, such as Gilbert et al. (2014), Bouman et al. (2017), and Balcombe et al. (2019), provide a broad picture of the general effect and feasibility of GHG abatement options. Figure 2.25 shows a statistic evaluation of GHG emission abatement effect of several options reported by different studies. In many cases, for instance for wind propulsion, the reported GHG emission reduction effect is case-dependent and thus cannot be generalized (Calleya 2014). This can explain parts of the variance displayed in Figure 2.25. By generalizing, however, such meta-studies can set the boundaries for each individual case and provide an idea of the order of magnitude in GHG emission reduction effect that can be expected.

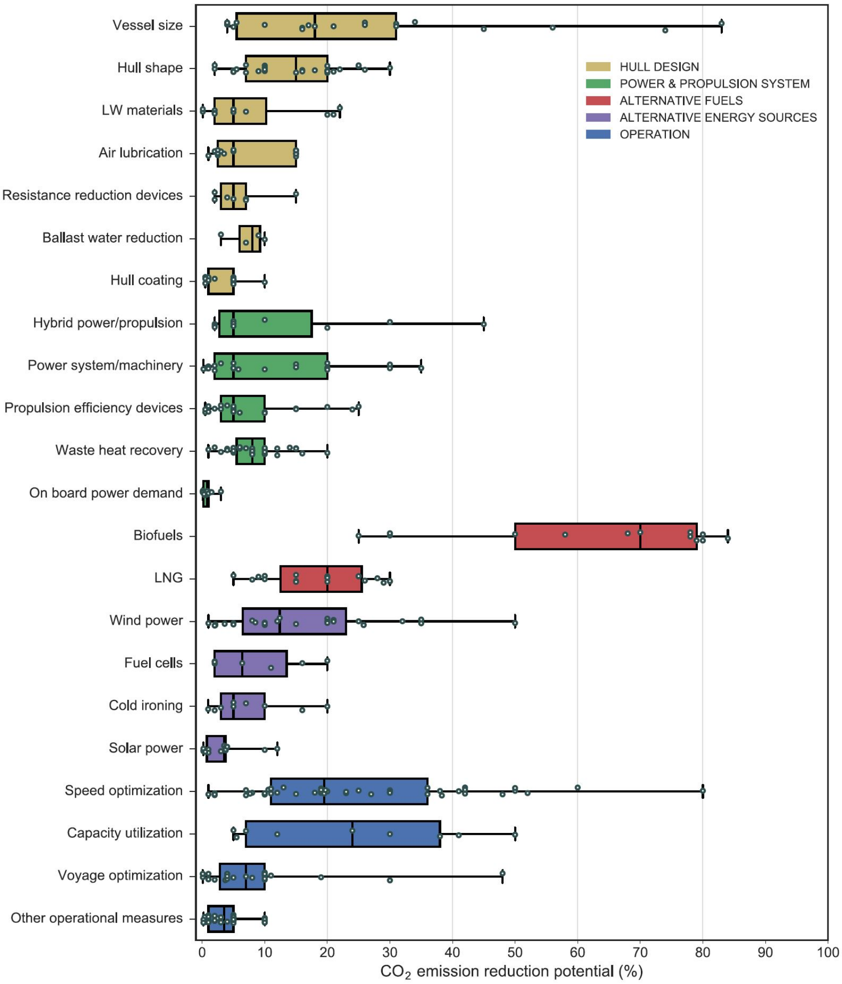

Figure 2.25: CO_2 emission reduction potential of different abatement options, reprinted from Bouman et al. (2017)

For the discussion of the individual GHG emission abatement options and their implications for ship design, it may be useful to return to the five aspects of complexity taxonomy (Rhodes and Ross 2010). Namely, the taxonomy comprised the aspects of structural, behavioral, contextual, temporal and perceptual complexity. The following section reviews the abatement option of alternative fuels, and the corresponding involved complexities, specifically. These complexities come in addition to the general uncertainty, that has been described as the background for this thesis in Section 1.1.

2.4.1 Alternative fuels

Alternative fuels have recently received a fair amount of attention in shipping and are reviewed in several studies (e.g., Wang and Wright 2021; Brynolf et al. 2022). Andersson et al. (2020) suggest taking a systems perspective on fuels. Economic, environmental and social criteria need to be considered in the fuel selection process (Psaraftis 2019; Ashrafi, Lister, and Gillen 2022) and as of time of writing of this thesis, there is yet no clearly superior fuel (Xing et al. 2021). Among the most commonly cited fuels are hydrogen, ammonia, methanol, liquid natural gas (LNG, consisting mainly of methane), and long-chained hydrocarbon fuel oils such as very low sulfur fuel oil (VLSFO) or marine gas oil (MGO). Wang and Wright (2021) provide an overview of the chemical and physical properties of the different fuel options. This subsection will briefly review alternative fuels and their relation to conceptual ship design from a 'five aspects of complexity' perspective.

Structural complexity - Alternative fuels generally come in the form of different chemical compounds, which can in many cases be stored in multiple form, e.g., pressurized or cryogenic. The fuels' storage forms generally have different volumetric and gravimetric densities for both the fuel and the fuel container, and may require different auxiliary systems (Mestemaker, van den Heuvel, and Gonçalves Castro 2020). Not all storage systems are compatible with all fuels (DNV 2021b), and the compatibility with intermediate processing and energy converters need to be considered (Taccani et al. 2020). Hybrid combinations of engines and electric power systems further increase the structural complexity (Taccani et al. 2020).

Behavioral complexity - The combustion or conversion of the same chemical compound in different energy converters may lead to differing emissions (Taccani et al. 2020; Mestemaker, van den Heuvel, and Gonçalves Castro 2020; Lindstad et al. 2021), depending on factors such as temperature of the process, completeness of the chemical reaction, compression and friction losses. As Krivopolianskii et al. (2019) and Lindstad et al. (2020) point out for the case of methane slip, the relation between conversion efficiency and GHG emissions is not necessarily linear, particularly not under a well-to-wake perspective (Lindstad and Rialland 2020). A fuel's global warming potential may vary depending on time horizon and geographical location (Lindstad et al. 2015). Different investment costs as well as maintenance costs moreover contribute to behavioral complexity (Kim et al. 2020). Some undesired effects may be mitigated by additional auxiliary systems such as exhaust gas after-treatment (Trivyza, Rentizelas, and Theotokatos 2018).

Contextual complexity - The same chemical compound can be produced from different feedstocks. Most commonly, the fossil sources, biomass and renewable electricity are considered as main energy feedstocks. Secondary feedstocks may be required for some fuels, such as CO_2 for hydrocarbon fuels or nitrogen for ammonia production (Dias et al. 2020). Grahn et al. (2022) show that the combination of biomass and renewable electricity can lead to economically and environmentally attractive fuels. Both fuel costs and corresponding well-to-tank emissions are dependent on production processes. Fuel costs, in addition, are highly dependent the costs of feedstocks used for production (Lloyd's Register and UMAS 2020; DNV GL 2020; Korberg et al. 2021). As exemplified in 2022, the market pricing of fuels can significantly differ from production costs (Solakivi, Paimander, and Ojala 2022). For a ship on a specific route, fuel availability may complicate the selection process (Lehtveer, Brynolf, and Grahn 2019) as well as local statutory requirements (Lindstad and Eskeland 2015).

Perceptual complexity - While previous complexities may be said to be more or less objective, perceptual, i.e., stakeholder-dependent aspects, affect the selection of fuels. Different stakeholders, be they actively involved shipowners or the passively affected public, can have different interests and thus there preference for certain criteria and eventually fuels may differ (Xing et al. 2021). Ashrafi, Lister, and Gillen (2022) and Slotvik (2022) empirically show the high variability of such preferences.

Temporal complexity - All four previously listed complexities involve a temporal aspect, i.e., they evolve over time. Such evolution may be the introduction of new technologies with new behavior, the change of feedstock prices or the change of preferences and regulations. The temporal aspect of complexity is exemplified by the time-dependency of various scenario fuel cost forecasts (e.g., Lloyd's Register and UMAS 2020; DNV 2022) and discussions around market-based measures, of which some are thought to evolve over time (Lagouvardou, Psaraftis, and Zis 2020). In the presence of change, a fuel's transition capabilities as well possible retrofit options need to be considered (Lindstad et al. 2020).

In short, the selection of alternative marine fuels needs to consider many complexities. Additionally, deep uncertainty prevails in particular for - but not limited to - fuel price developments over time (Trivyza 2019; Zwaginga and Pruyn 2022). The situation can be summarized as "the multicriteria decision-making approach does not seem to solve this [alternative fuel selection] problem effectively owing to uncertainties around the weightings of criteria and the preferences of the different stakeholders involved" (Xing et al. 2021, page 3).

2.5 Literature summary

Sections 2.1 to 2.3 have reviewed design and the conceptual ship design process. Section 2.4 has examined different complexity aspects (Rhodes and Ross 2010) associated with GHG abatement options generally, and alternative fuels specifically. Jones (1992) asserts that a designer needs methods that comprise the span of complexity of the product to be designed. The following chapter will therefore theorize towards how the complexities can be tackled effectively by means of the examined methodological elements.

3 Theorization

"There is nothing so practical as a good theory" (Lewin, 1948)

Weick (1995) describes a continuum from very vague theory to less approximate, well-defined theory. In order to demarcate theorizing from theories, he compares it to "process and product": While theorizing is the process, including all struggles and approximations, theory is the final product. To understand theory, and potentially evaluate or improve it, it is necessary to understand the context of its development. One of the first important steps towards a theory is to formulate testable hypotheses. Thus, this chapter describes and discusses the development of working hypotheses[1], that will be tested in the research work (papers) towards being answers to the initial research questions.

RQ1 *How to effectively explore and synthesize low-emission conceptual ship designs?*

System-based ship design, as proposed by Levander (1991), represents a pragmatic, though systematic and logically founded approach to synthesizing a conceptual ship design, based on the idea of catalog-like coefficients to map from functions to form elements. With respect to low-emission technologies, system-based ship design exhibits two challenges: First, the variety of low-emission components can be addressed through a set-based approach in order to compare different options. The choice of different components, however, can change the system architecture (functions and connections between components), making it difficult to compare the different options on the same basis. Second, depending on the choice of components and their integration into an overall system architecture, the overall system's behavior and performance can change non-linearly. To illustrate the first point, a fuel cell-electric propulsion system requires a number of different components than a direct drive with a combustion engine. Depending on the required range, weight and volume of the individual components, as well as the propulsion system in its entirety can differ significantly, which in turn can affect their

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[1] Working hypothesis: "a hypothesis suggested or supported in some measure by features of observed facts, from which consequences may be deduced which can be tested by experiment and special observations, and which it is proposed to subject to an extended course of such investigation, with the hope that, even should the hypothesis thus be overthrown, such research may lead to a tenable theory." (Benjamin Eli Smith, ed. (1910). *The century dictionary and cyclopedia*. Vol. 11. New York: The Century Co., p. 616)

size (due to additional weight) as well as location in the arrangement. The second point then follows as a consequence of the first one: Fuel cells and combustion engines, for example, experience their best efficiency at different relative power levels. This in turn may influence the ship's routing or refueling strategy.

In order to synthesize, i.e., generate or assemble, structurally different design options, a systems engineering approach with a mapping from functions over logical entities towards physical entities has shown promising in aircraft design (Liscouet-Hanke and Huynh 2013). The approach enables generating diverse system architectures, meaning that the same main function may be provided by two different component alternatives, which themselves may require different sub- and auxiliary functions. Working principles and design catalogs (Pahl et al. 2007) enable the definition of different principle solutions for the same function. That is, they reduce the complexity of the principle solution down to its main function to be provided. By treating such principle solutions as design modules (Wolff 2000) within an overall system architecture, the principle solutions' complexity can be encapsulated and potentially reused in a variety of applications. The combination of these three approaches (SBSD, system architecture, modularization of working principles) may thus help tackling the structural complexity of low-emission technology. Simulation, on the other hand is commonly employed to address behavioral complexity aspects. Model-based systems engineering puts forward the idea of defining a computational model to serve as a common, usage independent source of information. By basing both the system synthesis and analysis through simulation on the same model, MBSE can help connecting these two steps and therefore support the exploration of designs. These theoretical considerations lead to Working Hypothesis 1 (WH1) as a tentative answer to RQ1:

WH1 *A set-based approach based on modular SBSD, combined with a systems architectural model and voyage simulation, effectively enables exploration and synthesis of low-emission ship designs.*

While WH1 addresses specifically the structural and behavioral complexities associated with low-emission technology, it does not cover temporal and contextual complexities as well as uncertainties sufficiently. For alternative fuels, the combination of these aspects are of particular importance. This is illustrated by the dependency on varying feedstock prices (Brynolf et al. 2018), potential carbon pricing (Lagouvardou, Psaraftis, and Zis 2020) or fuel switches and retrofit options (DNV 2022). RQ2 in particular requests addressing such temporal and contextual complexities:

RQ2 *What is an effective method for selecting among alternative ship fuels and power systems under lifetime uncertainty and considering flexibility?*

Scenarios are generally used in different ways to handle temporal and contextual complexities as well as uncertainties (Schoemaker 1995). Section 2.2.8 has outlined the respective advantages of involved and detached scenario generation. Many of the applications documented in literature (e.g., Gaspar et al. 2015; Lloyd's Register and UMAS 2020; Korberg et al. 2021; DNV 2022) make use of a more involved way of generating scenarios, i.e., they make use of manually constructed scenarios. More detached ways of generating scenarios for decision-making in alternative fuels are described to a lesser extent for alternative fuels, but have shown applicability to other decision-making situations with strong contextual and temporal uncertainties (Balland et al. 2013; Niese, Kana, and Singer 2015; Pantuso, Fagerholt, and Wallace 2016). Real-options analysis is commonly used to evaluate flexibility in engineering (De Neufville and Scholtes 2019) and can be combined with optimization in general and stochastic optimization in particular. Working Hypothesis 2 therefore describes the tentative answer to be tested for RQ2:

WH2 *Stochastic optimization effectively helps to select among alternative fuels and power systems under lifetime uncertainty while considering flexibility.*

The theoretical considerations for each working hypothesis are outlined with respect to the prior literature analysis. Many fundamental aspects for the theorization are borrowed from previous research work within the Marine Systems Group, Department of Marine Technology, Norwegian University of Science and Technology (NTNU). Table 3.1 lists previous doctoral theses that significantly influenced this research work.

Table 3.1: Previous doctoral theses at NTNU influencing this research

Author	**Thesis title**	**RQ in this thesis**	**Most significant influence on this work**
Erikstad (1996)	"A decision support model for preliminary ship design"	RQ1	Concept exploration models for conceptual design
Kroneberg (2000)	"Innovation in shipping by using scenarios"	RQ2	Scenarios for future uncertainty
Gaspar (2013)	"Handling aspects of complexity in conceptual ship design"	RQ1, RQ2	Complexity aspects, specific methods for handling complexities such as epoch-era analysis and encapsulation
Lindstad (2013)	"Strategies and measures for reducing maritime CO2 emissions"	RQ1	Non-linear dependency of emissions on speed and hull form parameters
Balland (2013)	"Optimization models for reducing air emissions from ships"	RQ2	Optimization under temporal and contextual uncertainty
Pantuso (2014)	"Stochastic programming for maritime fleet renewal problems"	RQ2	Optimization under temporal and contextual uncertainty

Table 3.1: Previous doctoral theses at NTNU influencing this research (continued)

Author	**Thesis title**	**RQ in this thesis**	**Most significant influence on this work**
Patricksson (2016)	"Decision support for conceptual ship design with focus on a changing life cycle and future uncertainty"	RQ2	Optimization under temporal and contextual uncertainty
Choi (2018)	"Modular Adaptable Ship Design for Handling Uncertainty in the Future Operating Context"	RQ1	Modularity and changeability
Pettersen (2018)	"Resilience by latent capabilities in marine systems"	RQ1	Functional mapping
Rehn (2018)	"Ship design under uncertainty"	RQ2	Changeability under temporal and contextual uncertainty
Sandvik (2019)	"Sea passage scenario simulation for ship system performance evaluation"	RQ1	Voyage simulation
Garcia Agis (2020)	"Effectiveness in decision-making in ship design under uncertainty"	RQ2	Decision-making strategies under uncertainty
Ebrahimi (2021)	"Handling ship design complexity to enhance competitiveness in ship design"	RQ1, RQ2	Encapsulation and the need to consider different possible futures

Working Hypotheses 1 and 2 will be tested as tentative answers to the corresponding research questions. Their validity still needs to be probed empirically. The following chapter describes the specific method used for the validation of the working hypotheses and outlines how this method is grounded in epistemology.

4 Research methodology

"When balancing scholarliness and usefulness in ship design research, the decisive factor should always be usefulness." - A. C. Habben Jansen (2020)

The selected paradigm to a research problem certainly influences the way the research problem is approached, examined and potentially solved. Section 4.1 describes different research paradigms and outlines the metaphysical position that is adopted in this thesis. Section 4.2 explains how the perspective taken is linked to this thesis' research method.

4.1 Metaphysical positioning of this research work

Guba (1990a) offers a general definition of research paradigms as "a basic set of beliefs that guides action". He describes paradigms as cross-cutting through ontology, epistemology and methodology. The four paradigms referred to in the book are categorized according to the three cross-cutting elements in Table 4.1. It should be noted that the listed paradigms are neither complete, nor is there full agreement on what these paradigms precisely consist of (Guba 1990b).

Table 4.1: Alternative paradigms according to Guba (1990a)

Paradigm	Positivism	Postpositivism	Critical Theory	Constructivism
Ontology	Realist	Critical realist	Critical realist	Relativist
Epistemology	Dualist/ Objectivist	Modified objectivist	Subjectivist	Subjectivist
Methodology	Experimental/ manipulative	Modified experimental/ manipulative	Dialogic, transformative	Hermeneutic, dialectic

Firestone (1990) sketches a triangle of conflicting goals for paradigms: These are generalizability, precision and existential realism. He notes that positivism attacks generalizability and precision, while constructivism better addresses existential realism. Each of the paradigms thus possesses its inherent strengths and weaknesses in addressing scientific problems.

On the implications of alternative paradigms for practice, Eisner (1990, page 89) writes that “by definition, the introduction of alternative paradigms for inquiry undermines the tacit but widely held belief that here is only one dependable way to know, something vaguely called ‘the scientific method’”. The nature of the problem under study influences the perspective taken: “people cope with important problems in ways that depend on the kind of problem the problem is” (Eisner 1990, page 91).

The notion that different paradigms have their own strengths and weaknesses and even goals, such as generalizability for instance, affects the perspective taken in this thesis. Section 4.2 describes how and why the ’validation square’ (Pedersen et al. 2000) is employed in this thesis. By drawing on elements from different epistemologies, the validation square seeks to accommodate the different paradigms in a pragmatic, problem-solving way. As such, this perspective may come close to what Creswell (2014) calls ’pragmatism’: “researchers emphasize the research problem and use all approaches available to understand the problem”.

According to Firestone (1990, page 109) “just as cultural diffusion leads to creativity, cross-paradigm research can be extremely fruitful”. Such “confluences” of alternative paradigms have been anticipated by Guba and Lincoln (2005). The research problem in this thesis is thus approached from more than one perspective, as I will explain in more detail in the following section.

4.2 Research method

This research aims at enhancing concept ship design methodology to better cater for GHG emission reduction ambitions. More specifically, it aims at developing rational problem-solving methods related to lowering emissions from ships. But how to develop, apply, verify and finally validate better methods? This section outlines the approach taken in this thesis to answer those questions.

“Should ship design research be scholarly or useful, or can the two be combined?” (Habben Jansen 2020, page 96). Habben Jansen argues that in ship design research, being a problem-led domain, the usefulness should be prioritized over scholarship. This is in line with Popper (1962, page 306), who characterizes pure science as “search for knowledge” and applied science as “search for powerful instruments”. “The difference is that, in the search for knowledge, we are to find true theories – which correspond better to the facts; whereas in the search for powerful instruments we are, in many cases, quite well served by theories which are known to be false" but they serve a purpose. Ship design, whether viewed as engineering or architecture, is generally part of the applied sciences. Thus, it is necessary to speak of 'better' or 'inferior' design methods and theories, and this has an impact on the research method applied in this thesis.

Pedersen et al. (2000, page 4) state that "a 'better' method is equivalent to a more useful method". Similarly, when comparing clinical and design method research, Frey and Dym (2006, pages 48-49) emphasize that "the application of design methods depends strongly on judgment of the designer who applies them, and their effectiveness is almost assuredly compromised by poor implementation". The effectiveness and therefore the usefulness of the design methods is not only dependent on the designer and his or her application of them, but also on the competing methods: 'better' is always a comparative attribute. For these reasons, the categories 'right' and 'wrong' seem difficult to apply to design methods, which impedes pure falsification. What is required, therefore, is a method for what Popper calls verisimilitude: A method for establishing "better or worse approximations" (Popper 1962, page 311).

Pedersen et al. (2000), and later followed by Seepersad et al. (2006), resolve the conflict in research on design methodology by means of the validation square depicted in Figure 4.1. In ship design research, the validation square has previously been employed by Nordin (2014) and Habben Jansen (2020).

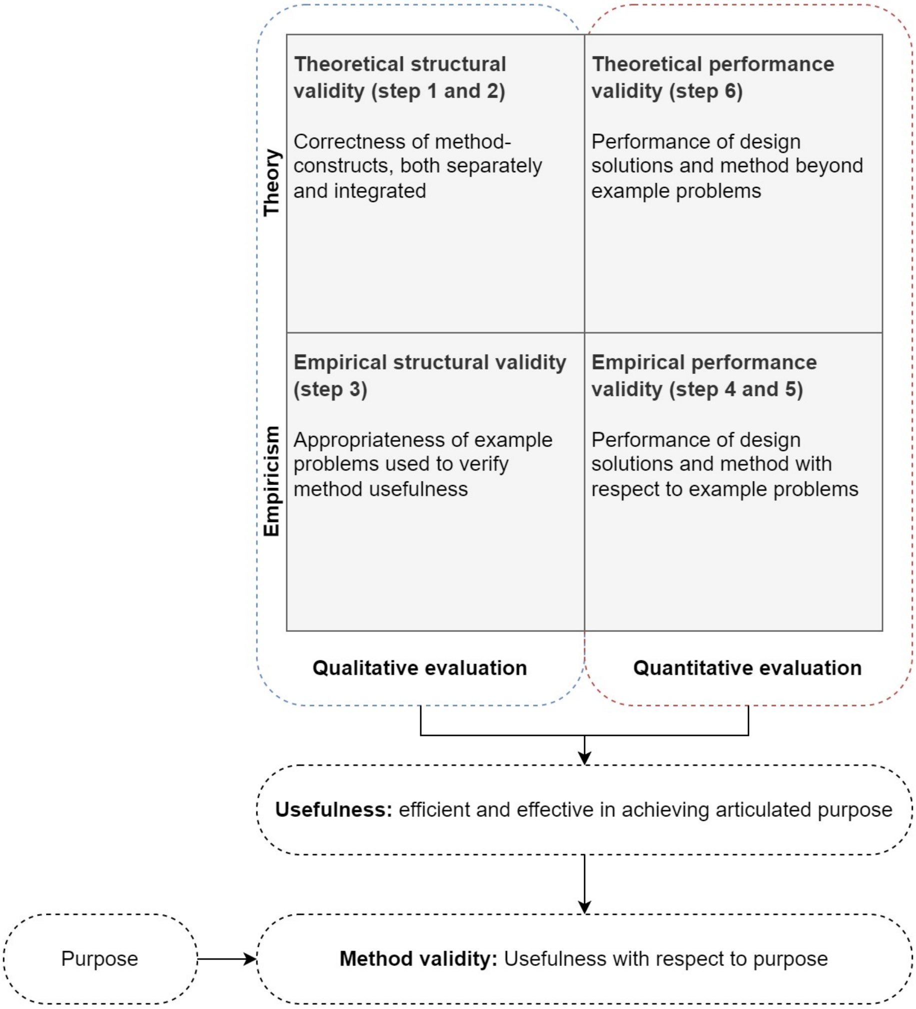

Figure 4.1: The validation square, redrawn and adapted from Pedersen et al. (2000)

The validation square draws upon elements of the spectrum between theoretical structural validity (is the method consistent and logic?) and empirical performance validity (do the methods and produced designs perform as expected?). In this research work, a design method's usefulness, in essence, is evaluated with respect to a specific purpose. As this approach draws on methods from different epistemologies, it is a pragmatic approach for evaluating design methods. It acknowledges weaknesses of the different epistemologies and aims to combine their strengths into an approach to establish the 'better' or 'worse' of a design method. Methods can be falsified if they are logically inconsistent, but their usefulness (being effectiveness and efficiency) needs to be seen relative to its competitors. The principle of usefulness as a relative criterion for any theory's success is reinforced by Kuhn (2012).

According to Pedersen et al. (2000), the validation square can be broken down into the individual steps shown in Table 4.2.

Table 4.2: Validation steps and research methods in this thesis

Step	Validation step according to Pedersen et al. (2000)	Quadrant in the validation square
1	Accepting the construct's validity	Theoretical structural validity
2	Accepting method consistency	Theoretical structural validity
3	Accepting the example problems	Empirical structural validity
4	Accepting usefulness of the method for some example problems	Empirical performance validity
5	Accepting that usefulness is linked to applying the method	Empirical performance validity
6	Accepting usefulness of the method beyond example problems	Theoretical performance validity

Although the design methods developed in this thesis are quantitative and partly qualitative, the research itself is more of a qualitative nature. The developed design methods are tested in case studies, which shall be representative for the research problem. The number of case studies however, is too low to permit a meaningful quantitative analysis. The theoretical performance validity will be what Pedersen et al. (2000) call "a leap of faith": Based on the findings from the case studies, one may expect the methods perform similarly outside the range of the case studies.

4.3 Classification of this research

Kothari (2004) provides a basic classification of research that can be used as a reference for comparison with related research. The basic categories relevant for this thesis are listed in Table 4.3.

Table 4.3: Classification of research according to Kothari (2004)

Category	**Description**
Descriptive versus analytical	Descriptive research aims to document the current state of affairs. Analytical research analyzes and evaluates the material.
Applied versus fundamental	Applied research is concerned with an immediate problem, while fundamental research aims for generalizations and formulation of theory.
Quantitative versus qualitative	Quantitative research is based on measurable quantities and amounts, while qualitative research is related to reasoning.
Conceptual versus empirical	Conceptual research relates to theories or abstract ideas. Empirical research is based on data, often verified through observation or experiments.
Field-setting versus laboratory versus simulation	Characterizing the research environment.
Exploratory versus formalized	Exploratory research develops hypotheses, formalized research implies a structured testing of hypothesis.

According to this taxonomy, the research presented herein can be classified as *analytical*, as it aims to establish relationships. It is *applied*, because it is grounded in the empirical problem of designing ships with lower GHG emissions. As indicated by the validation square in the previous section, both *quantitative and qualitative* elements are used in this research. The research has both *conceptual and empirical* aspects as the conceptualized design methods are applied to empirical problems and draws upon *simulation*. The development of design methods classifies it as *exploratory*, while the testing of these methods is *formalized* through the validation square.

5 Results

"Prediction is very difficult, especially when the future is concerned"

- Niels Bohr

This manuscript represents a paper-based thesis and thus, the research work of this thesis has been disseminated in the form of six main and four supporting papers. This chapter presents each paper and its relation to the research questions. The presentation of results serves as a basis for their discussion in the light of this thesis' research method, i.e., the validation square that was outlined in the previous chapter. That discussion follows in Chapter 6.

5.1 Main papers

This section summarizes the main papers and how they relate to this thesis. Their relation to this thesis in particular is presented in Figure 5.1. The research objective has been divided into two research question. For each of these questions, one working hypothesis has been formulated. The papers have each been written under the scope on of these working hypotheses.

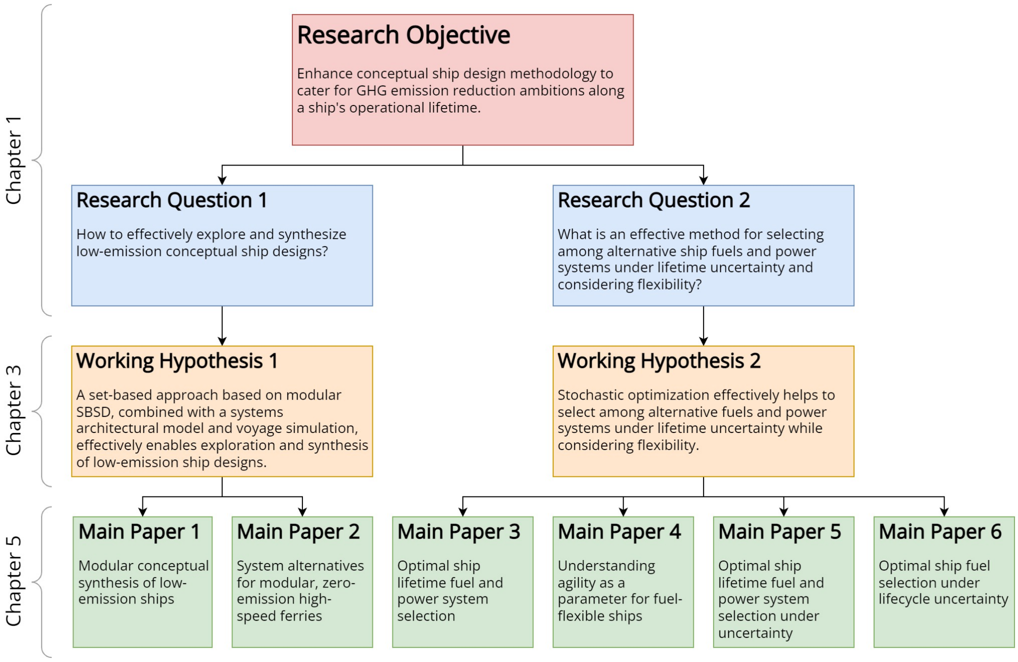

Figure 5.1: Main papers and their relation to this thesis

Main Papers 1 and 2 address RQ1, i.e., they focus on the structural and behavioral complexities on a more general basis. It should be noted that Main Papers 1 and 2 make use of discrete-event simulation to address system behavioral complexities. A more detailed description of this simulation technique is provided in Supporting Paper 1. Main Papers 3 to 6 address RQ2, which targets both the contextual and temporal complexities and uncertainties related to alternative fuels specifically. The two working hypotheses formulated in Chapter 3 have served as the starting point for each paper. Each paper tests and examines (parts of) the related working hypothesis and thus can potentially support or refute the hypothesis. The papers' sequence follows a chronological order. That means, results from earlier publications have influenced the successive research.

Main Paper 1

Modular Conceptual Synthesis of Low-Emission Ships
Benjamin Lagemann, Stein Ove Erikstad (2020)
Proceedings of the 12th Symposium on High-Performance Marine Vehicles; pp. 134-151; Cortona, Italy

Abstract With the ambition of lowering emission from shipping, today's ship designers face both the freedom and challenge to select from a large set of different ship system concepts during the conceptual design stage. In order to design competitive vessels, these options need to be assessed in an efficient and systematic way. Building upon established ship design methodologies, this paper presents a combined synthesis model adapted to low-emission ship design. By making extended use of modularity, namely component swapping and combinatorial modularity, the model enables flexibly synthesizing diverse ship configurations. To illustrate how the model can be used, we show how it can be implemented computationally and apply it to a RoRo transport case for the route Rotterdam - Halifax. An efficient discrete event simulation enables immediate performance evaluation. The ship designer can thus directly foresee the consequences of decisions and elucidate requirements on an informed basis.

Relevance for this thesis The paper describes the idea and implementation of a set-based SBSD synthesis model, combined with modularization of principle solutions and discrete-event simulation for performance evaluation. The platform is applied to a deep sea RoRo transport task.

Author contributions I have developed and implemented the computational model and written the draft of the paper. Stein Ove Erikstad has supervised the development process and reviewed the manuscript.

Main Paper 2

System alternatives for modular, zero-emission high-speed ferries
Benjamin Lagemann, Tobias Seidenberg, Christoph Jürgenhake, Stein Ove Erikstad, Roman Dumitrescu (2021)
SNAME International Conference on Fast Sea Transportation; Rhode Island, USA

Abstract Low emission requirements exert increasing influence upon ship design. The large variety of technological options makes selecting systems during the conceptual design phase a difficult endeavor. To compare different solutions, we need to be able to exchange individual systems and directly evaluate their impact on the design's economic and environmental performance. Based on the idea of model-based systems engineering, we present a modular synthesis approach for ship systems. The modules are coupled to a discrete event simulation and allow for a case-based assessment of system configurations. We apply this method to a high-speed passenger ferry and show how it can provide decision support for hydrogen- and battery-based system architectures.

Relevance for this thesis This paper applies the synthesis model, that is described in Main Paper 1, to a high-speed passenger transport task. Apart from the different ship mission, a number of additional principle solutions are applied within the synthesis model, such as a catamaran hull form, batteries and fuel cells. The paper moreover shows the merit of using design modules, being encapsulated principle solutions, for the exploring physical modularity, i.e., in this case a modular building strategy and potential adaptation of the drive train system for an extended range.

Author contributions I have implemented the computational model and written parts of the original draft. Tobias Seidenberg has assisted in the development process with relevant data for the case study and written parts of the original draft. Christoph Jürgenhake and Roman Dumitrescu have reviewed the paper. Stein Ove Erikstad has supervised the development process and provided manuscript review.

Main Paper 3

Optimal ship lifetime fuel and power system selection
Benjamin Lagemann, Elizabeth Lindstad, Kjetil Fagerholt, Agathe Rialland, Stein Ove Erikstad (2022)
Transportation Research Part D: Transport and Environment; Vol. 102; 103145

Abstract Alternative fuels and fuel-flexible ships are often seen as promising solutions for achieving significant greenhouse gas reductions in shipping. We formulate the selection of alternative fuels and corresponding ship power systems as a bi-objective integer optimization problem. We apply our model to a Supramax Dry-bulker and solve it for a lower bound price scenario including a carbon tax. Within this setting, the question whether bio-fuels will be available to shipping has significant effect on the lifetime costs. For the given scenario and case study ship, our model identifies LNG (liquified natural gas) as a robust power system choice today for a broad range of GHG reduction ambitions. For high GHG reduction ambitions, a retrofit to ammonia, produced from renewable electricity, appears to be the most cost-effective option. While these findings are case-specific, the model may be applied to a broad range of cargo ships.

Relevance for this thesis The article formulates a bi-objective optimization problem for the selection of ship fuel and power systems under an assumed certain, but changing lifetime scenario. By assuming a certain lifetime scenario, the article helps understanding and validation of the developed optimization model. Moreover, it shows that retrofits can be cost-optimal even under a known, but fundamentally changing lifetime scenario.

Author contributions I have developed and implemented the optimization model and written the original draft of the paper. Elizabeth Lindstad has been involved in the problem formulation, provided relevant data for the case study and reviewed the manuscript. Kjetil Fagerholt and Stein Ove Erikstad have been involved in the problem formulation and development of the optimization model and reviewed the paper. Agathe Rialland has reviewed the manuscript.

Main Paper 4

Understanding agility as a parameter for fuel-flexible ships
Benjamin Lagemann, Stein Ove Erikstad, Per Olaf Brett, Jose Jorge Garcia Agis (2022)
14th International Marine Design Conference; Vancouver, Canada

Abstract With the need for lower-emission maritime transport solutions, shipowners and designers face uncertainty when it comes to the selection of fuel today and in the future. The effects of this uncertainty can be mitigated to a certain extent by fuel-flexible machinery and containment systems When developing such fuel-flexible designs, capability, changeability and agility are important parameters to be considered. Thus, the required time and cost consumed for conversions or retrofits at a later stage during the vessel's lifetime need to be addressed in the early design phase. We apply and discuss the concept of agility for both existing flexible solutions and new ship design alternatives in this paper.

Relevance for this thesis This paper investigates the aspect of agility specifically in the context of fuel-flexible ships. Based on a literature study, agility is defined as 'speed of change' in the case of fuel-flexible ships. It is shown, that the appropriate level of agility is dependent on the expectations towards the future, i.e., structurally different scenarios as well as the volatility of fuel prices.

Author contributions I have performed the literature study, implemented the optimization model and written the paper draft. Stein Ove Erikstad has provided the idea for this paper, supervised the work and reviewed the manuscript. Both Per Olaf Brett and Jose Jorge Garcia Agis have assisted in the problem formulation and reviewed the paper.

Main Paper 5

Optimal ship lifetime fuel and power system selection under uncertainty
Benjamin Lagemann, Sotiria Lagouvardou, Elizabeth Lindstad, Kjetil Fagerholt, Harilaos N. Psaraftis, Stein Ove Erikstad
Transportation Research Part D: Transport and Environment; Vol. 119; 103748

Abstract Ship designers face increasing pressure to comply with global emission reduction ambitions. Alternative fuels, potentially derived from bio-feedstock or renewable electricity, provide promising solutions to this problem. The main challenge is to identify a suitable ship power system, given not only uncertain emission requirements but also uncertain fuel and carbon emission prices. We develop a two-stage stochastic optimization model that explicitly considers uncertain fuel and carbon emission prices, as well as potential retrofits along the lifetime. The bi-objective setup of the model shows how the choice of optimal power system changes with reduced emission levels. Methanol and LNG configurations appear to be relatively robust initial choices due to their ability to run on fuel derived from different feedstocks, and their better retrofittability towards ammonia or hydrogen. From a policy perspective, our model provides insight into the effect of the different types of carbon pricing mechanisms on a shipowner's decisions.

Relevance for this thesis The article builds upon the selection method presented in Main Paper 3. The method is enhanced by considering uncertain fuel and carbon prices through stochastic programming. By considering these important uncertainties explicitly, the method is thought to move closer to reality than a method ignoring these uncertainties. For a shipowner and designer, the stochastic selection method enables decision-making across instead of within scenarios. It is shown that dual-fuel engines, potentially with future retrofits, represent a relatively robust here-and-now decision. The case study shows that a policy's target GHG emission level is more important for selecting the initial ship power system selection than whether the policy comes in the form of a command-and-control strategy or as a market-based measure.

Author contributions I have developed and implemented the optimization model, written the majority of the original draft and collected data for the case study together with Sotiria Lagouvardou. Sotiria Lagouvardou has written parts of the original draft, assisted in the problem formulation and model development. Kjetil Fagerholt and Stein Ove Erikstad have contributed to the development of the optimization model and reviewed the manuscript. Elizabeth Lindstad has been involved in the problem formulation, contributed with relevant data for the case study and reviewed the manuscript. Harilaos N. Psaraftis has reviewed the paper and specifically contributed with a policy perspective.

Main Paper 6

Optimal ship fuel selection under life cycle uncertainty
Jesper J. Zwaginga, Benjamin Lagemann, Stein Ove Erikstad, Jeroen J. F. Pruyn
Submitted to the World Conference on Transport Research WCTR 2023, Montréal, Canada and under review in a peer-reviewed journal

Abstract Ship designers face increasing pressure to comply with global emission reduction ambitions. Alternative fuels, potentially derived from bio-feedstock or renewable electricity, provide promising solutions to this problem. The main challenge is to identify a suitable ship power system, given not only uncertain emission requirements but also uncertain fuel and carbon emission prices . We develop a two-stage stochastic optimization model that explicitly considers uncertain fuel and carbon emission prices, as well as potential retrofits along the lifetime. The bi-objective setup of the model shows how the choice of optimal power system changes with reduced emission levels. Methanol and LNG configurations appear to be relatively robust initial choices due to their ability to run on fuel derived from different feedstocks, and their better retrofittability towards ammonia or hydrogen. From a policy perspective, our model provides insight into the effect of the different types of carbon pricing mechanisms on a shipowner's decisions.

Relevance for this thesis This paper compares the stochastic programming model with an alternative model that is based on adaptive robust optimization. By making use of the same data set, the particular pros and cons of each method are discussed. It is shown that the data set, i.e., the uncertain fuel and carbon prices, is more important than the choice of mathematical method. The importance of biofuel costs and availability for shipping is highlighted in particular.

Author contributions Jesper Zwaginga and I have written the original draft. Jesper Zwaginga has developed and implemented the robust optimization model. I have assisted with the implementation of the robust optimization model, provided relevant data for the case study and contributed with the stochastic optimization model. Stein Ove Erikstad and Jeroen Pruyn have supervised the work and reviewed the manuscript.

5.2 Supporting papers

This section presents the supporting papers for this thesis. The supporting papers are not central for answering the research questions, but provide relevant background and further context to this research. Figure 5.2 relates these papers to this thesis.

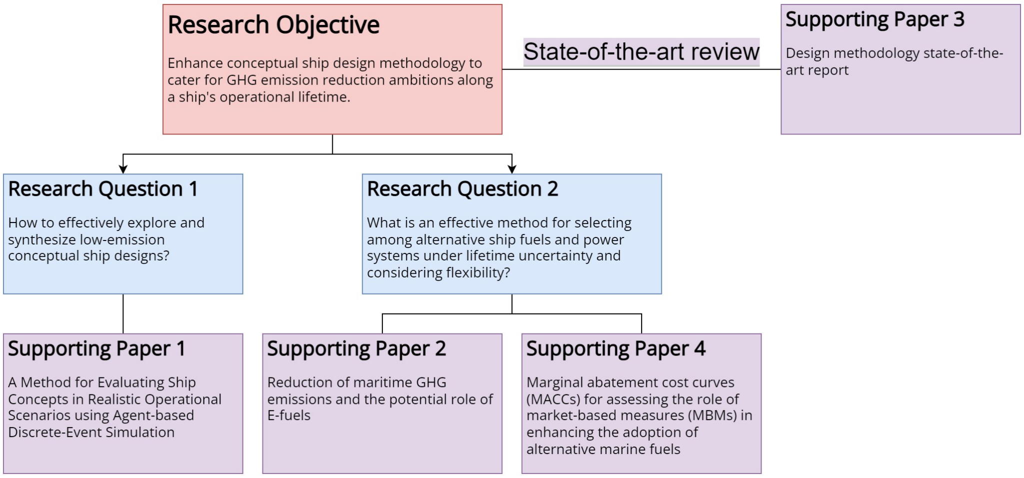

Figure 5.2: Supporting papers and their relation to this thesis

Supporting Paper 1 is connected with RQ1. It describes and documents discrete-event simulation as a method for ship performance analysis. Supporting Papers 2 and 4 are both linked to RQ2. Supporting Paper 2 describes a scenario-based cost estimation procedure for electrofuels, constituting one important group of alternative fuels. Supporting Paper 4 analyzes the required level of marked-based measures for the uptake of alternative fuels from a policy perspective. Supporting Paper 3 reviews the state-of-the-art of ship design methodology, and thus describes the research field, defined in the research objective, that shall be enhanced.

Supporting Paper 1

A Method for Evaluating Ship Concepts in Realistic Operational Scenarios using Agent-based Discrete-Event Simulation
Jon S. Dæhlen, Endre Sandvik, Agathe Isabelle Rialland, Benjamin Lagemann (2021)
Proceedings of the 20th International Conference on Computer and IT Applications in the Maritime Industries; pp. 141-150; Mühlheim, Germany

Abstract Meeting IMO's greenhouse gas ambitions generates need for designing low- and zero-emission ships within the maritime industry. Evaluating proposed conceptual ship systems in terms of energy efficiency, exhaust emissions and operability is a task of great complexity, even more under realistic operational profiles and weather conditions. This paper presents a simulation method developed for evaluating a ship concept across several years of realistic operation. The method allows for a user-defined operational scenario and simulates numeric hull, propulsor and machinery models based on agent-based discrete-event simulation in historic oceanographic data. A use case for a tanker is presented, demonstrating how the method, implemented through a simulation software, helps the naval architect in navigating among the various technologies available, being able to assess an early system design in a scenario spanning several years.

Relevance for this thesis This paper describes the basic idea and implementation of a ship voyage discrete-event simulator, which is used to address RQ1. The paper therefore complements Main Papers 1 and 2, which employ discrete-event simulation as a performance evaluation method, but do not focus on the implementation specifics.

Author contributions Jon S. Dæhlen has initiated and defined the scope of the paper and written the original draft. Endre Sandvik has performed the numerical simulations. Agathe Rialland and I have reviewed the manuscript.

Supporting Paper 2

Reduction of maritime GHG emissions and the potential role of E-fuels
Elizabeth Lindstad, Benjamin Lagemann, Agathe Rialland, Gunnar M. Gamlem, Anders Valland (2021)
Transportation Research Part D: Transport and Environment; Vol. 101; 103075

Abstract Maritime transport accounts for around 3% of global anthropogenic Greenhouse gas (GHG) emissions (Well-to-Wake) and these emissions must be reduced with at least 50% in absolute values by 2050, to contribute to the ambitions of the Paris agreement (2015). Zero carbon fuels made from renewable sources (hydro, wind or solar) are by many seen as the most promising option to deliver the desired GHG reductions. For the maritime sector, these fuels come in two forms: First as E-Hydrogen or E-Ammonia; Second as Hydrocarbon E-fuels in the form of E-Diesel, E-LNG, or E-Methanol. We evaluate emissions, energy use and cost for E-fuels and find that the most robust path to these fuels is through dual-fuel engines and systems to ensure flexibility in fuel selection, to prepare for growing supplies and lower risks. The GHG reduction potential of E-fuels depends entirely on abundant renewable electricity.

Relevance for this thesis This article quantitatively describes the cost-dependency of e-fuels on renewable electricity as their fundamental feedstock. Both the data and fundamental relationships have served as a basis for the stochastic programming model developed under the scope of RQ2.

Author contributions Elizabeth Lindstad has formulated the topic and scope of the paper, performed the data analysis and written the majority of the original draft. I have contributed with sections to the original draft and assisted with the data analysis. Agathe Rialland has supported the data analysis and, together with Gunnar M. Gamlem and Anders Valland, reviewed the manuscript.

Supporting Paper 3

Design methodology state-of-the-art report
Stein Ove Erikstad, Benjamin Lagemann (2022)
14th International Marine Design Conference; Vancouver, Canada

Abstract Marine systems design methodology is continuously evolving. On a strategic level, we have seen four major evolutionary tracks emerging from the sequential, iterative process captured in the classical design spiral. One is a model-based systems engineering approach that removes iterations by a structured mapping from needs to functions, and further to form elements that are finally synthesized into a complete design. Another is a set-based strategy, where a large number of designs are generated and analyzed, from which one or a few solutions are selected for further development. A third direction is a holistic optimization strategy where the major steps in the spiral model are integrated onto a common platform that enables the automatic identification of one or a few balanced, preferable solutions. Finally, as a strategy towards improved competitiveness through standardization in a typical engineered-to-order industry, we have seen the emergence of modular architectures combined with configuration-based design methods.

Across these four evolutionary tracks there have been several more focused developments on different levels of maturity. This includes design-for-sustainability, simulation of operations, design-for-flexibility to handle uncertainty and change, and design of wind-assisted vessels. Finally, we have pointed to some emerging developments that we find promising but have yet to mature into having a significant impact on industry-level applications. This includes artificial intelligence and machine learning, extended system boundaries, and digital twin technologies.

Relevance for this thesis This paper provides a state-of-the-art review of marine design methodology. As this thesis seeks to enhance ship design methodology, the paper captures the status quo of the target research field in 2022.

Author contributions Stein Ove Erikstad has initiated the paper, defined the scope and written the majority of the original draft. I have contributed with parts to the original draft and reviewed the remainder of the paper.

Supporting Paper 4

Marginal abatement cost curves (MACCs) for assessing the role of market-based measures (MBMs) in enhancing the adoption of alternative marine fuels
Sotiria Lagouvardou, Benjamin Lagemann, Harilaos N. Psaraftis, Elizabeth Lindstad, Stein Ove Erikstad
Submitted to Nature Energy

Abstract Uncertainties on the global availability and affordability of alternative marine fuels are stalling the shipping sector's decarbonization course. Several candidate measures are pro- posed at the International Maritime Organization, including market-based measures (MBMs), environmental policies like carbon taxes and emissions trading systems. Their implementation increases the cost of fossil fuel consumption and provides fiscal incentives towards greenhouse gas emissions reductions. MBMs can bridge the price gap between alternative and conventional fuels and generate revenues for funding the up-scaling of alternative fuels' production, storage and distribution facilities and, thus, enhance their availability. By estimating the fuels' implementation and operational costs and carbon abatement potential, this study develops their marginal abatement cost curves and estimates the optimal level of carbon pricing needed to render investments into alternative fuels cost-effective. The results can assist policymakers in establishing the fundamental factors and MBM design principles that can make MBMs a robust and effective decarbonization measure.

Relevance for this thesis The data set for this paper has been prepared along with the data for Main Paper 5. This paper looks at the choice of alternative ship power systems and fuels more from a policy perspective. The policy perspective, in turn, provides relevant information for the probability distributions used in the stochastic programming model. More precisely, this paper approximately corroborates the relatively large range of carbon prices considered in the stochastic programming model, that is described in Main Paper 5.

Author contributions Sotiria Lagouvardou has initiated the paper, defined the scope, performed the analysis and written the original draft. Sotiria Lagouvardou and I have both prepared the relevant data for the case study. I have assisted with the analysis and reviewed the manuscript. Harilaos N. Psaraftis has initiated and supervised the project, defined the scope of the paper and reviewed the manuscript. Elizabeth Lindstad has contributed with relevant data for the case study, assisted with the analysis and reviewed the paper. Stein Ove Erikstad has reviewed the manuscript.

This chapter has presented the papers included in this thesis. The papers' connection to the research questions as well as each paper's relevance for this thesis has been outlined briefly. The following chapter will discuss the papers in the light of this thesis' research method. Thus, the papers' contributions will be explained and evaluated with respect to the thesis' research objective.

6 Discussion and contributions

"The purpose of computing is insight, not numbers."

- Richard Wesley Hamming (1962)

This chapter discusses the results, presented in the previous chapter, in light of the research method, i.e., the validation square outlined in Section 4.2. First, the working hypotheses will be evaluated. Section 6.1 then identifies and discusses the contributions of this research. The practical implications of these contributions are outlined in Section 6.2. Finally, Section 6.3 reflects on the research approach.

Working Hypotheses 1 and 2 have been formulated to address different aspects of complexity. Therefore, the two working hypotheses are examined individually in this section, starting with WH1:

WH1 *A set-based approach based on modular SBSD, combined with a systems architectural model and voyage simulation, effectively enables exploration and synthesis of low-emission ship designs.*

Main Papers 1 and 2 have been developed under the scope of this working hypothesis. Figure 6.1 visualizes the relation between papers and the quadrants as well as individual steps of the validation square.

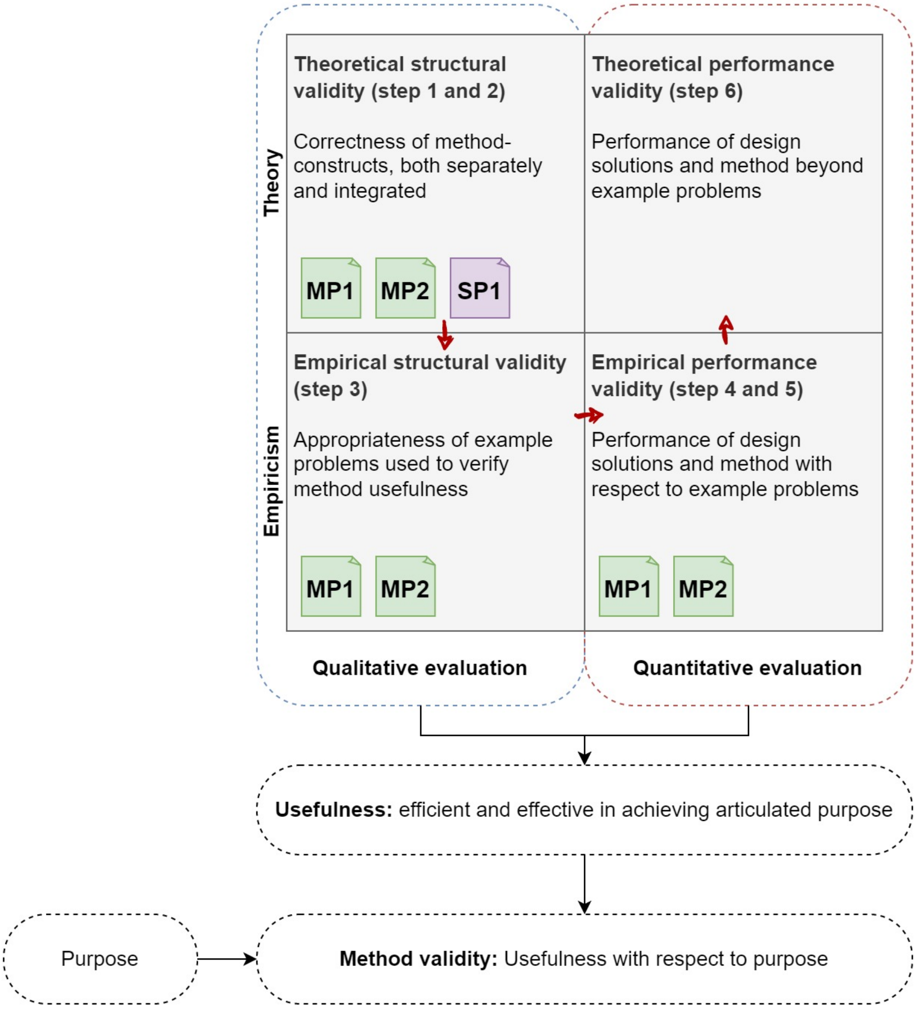

Figure 6.1: Links between papers and steps in the validation square for Working Hypothesis 1

In the following, steps (1) to (6) of the validation square are discussed individually.

(1) "Accepting the individual constructs constituting the method". This step assesses the individual constructs used within the method. Such constructs can be several procedures and techniques. The procedures and techniques are referenced and discussed in both Main Paper 1 and 2. The calm water resistance estimation procedures, based on semi-empirical models, may serve as an illustrative example: For Main Paper 1, a monohull cargo ship, the Holtrop and Mennen (1982) procedure has been used, while for Main Paper 2, a high-speed catamaran, a parametric regression model (based on Sahoo, Salas, and Schwetz 2007; Sahoo, Mason, and Tuite 2008) has been employed. While the former

has shown good agreement with comparable ship performances, the latter has shown a larger difference compared to the comparison ship. It has proven useful however, for wider parametric variations than specific model tests. Supporting Paper 1 describes the use of discrete-event simulation as a construct for performance analysis. Overall, the individual constructs are thus grounded in relevant literature.

(2) "Accepting the internal consistency of the way the constructs are put together in the method". Step (2) assesses the way the individual constructs are assembled within the method. The generic architecture of the computational model is described in the form of Unified Modeling Language (UML) diagrams in Main Papers 1 and 2. The proposed decomposition model is grounded in SBSD and combines a functional and logical decomposition. Each function is linked to a logical entity, which itself can entail further functional requirements. The general approach is grounded in design literature and thus this step is seen as fulfilled.

(3) "Accepting the appropriateness of the example problems that will be used to verify the performance of the method". Main Paper 1 describes the application of the method to a deep sea RoRo cargo ship. Main Paper 2 applies the same method to a short sea high-speed ferry. Both these missions and ship subsystems have been deliberately selected to be fundamentally different, in order to evaluate the method's applicability to a range of problems and potential solutions. The example problem in Main Paper 1 illustrates the model's application to a RoRo deep sea shipping case, which may be relevant for some of the shipowners within the SFI Smart Maritime. The case study in Main Paper 2 is based on the TrAM project (Papanikolaou et al. 2020). Both cases are appropriate example problems for this method and as such this step is considered fulfilled.

(4) "Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s)". Within Main Papers 1 and 2, the method has enabled the synthesis, analysis and comparison of different conceptual designs for the same mission. Looking beyond these two papers, the same method could be applied to diverse missions as well as subsystems. The initial purpose was to enable the synthesis and exploration of a diverse set of conceptual ship designs. As such, the example problems have indicated the method's usefulness for its purpose and this step is seen as fulfilled.

(5) "Accepting that the achieved usefulness is linked to applying the method". Main Paper 1 has focused on the development and description of how the method combines different constructs. The method was found to be generally useful for synthesizing different design options. However, the method has not been directly compared with its 'competitors'. Main Paper 2 is more supportive for this step, since it illustrates how the method allows the synthesis and analysis of alternative system architectures, which have not been described in literature for this particular case. The parametric *design modules* gave rise to a discussion of *building modules* in production, while accounting for inter-dependencies between weight/volume of the propulsion system and overall vessel size

and resistance. Capturing these effects was deemed important in order to compare high energy density (hydrogen) and low energy density (battery) carriers on a fair basis. The method has usefully supported these comparisons and thus step (5) is considered fulfilled.

(6) "Accepting that the usefulness of the method is beyond the case studies". This step, and thus the method's validity beyond example problems, cannot be assured. Steps 1 to 5, however, can help building confidence. The method has been developed as a combination of SBSD with design modules and an architectural configuration and discrete-event simulation for analysis. While these constructs are generally validated within the domain of ship design, both individual procedures and the way these constructs are put together needs to be critically discussed: Main Paper 2 has shown that the regression model for a round-bilge catamaran hull showed significant differences to the comparison ship, whose hull form was extensively optimized (Papanikolaou et al. 2020). This outlines that the developed method relies on reasonably accurate models and procedures to simulate a system's behavior. Assuring sufficient model accuracy is thus important, especially for more unconventional (sub)systems. Given satisfactory accuracy can be assured, the method has shown effectiveness in achieving its articulated purpose. The method enabled an interactive synthesis and rapid simulation/analysis of design options. With respect to resources spent on its use, it has thus shown to be efficient. As is typical for MBSE models, the method relies on a computational model and it should be noted that the implementation of this model has required significantly more resources than using the model. The method's overall efficiency with respect to purpose is thus dependent on the reuse and foreseen number of applications of the method. If the number of future applications, and thus reuse, is high, the interactivity and built-in automated procedures can pay off. On the contrary, a low foreseen number of applications may not justify the implementation of the method. Changes in the way the method is implemented, i.e., making use of different software tools or programming frameworks for instance, can likely reduce the implementation effort.

The first working hypothesis has been discussed in the light of the validation square. The discussion generally yields confidence in the working hypothesis and its effectiveness. The efficiency, however, should be assessed critically for each application. In the following, Working Hypothesis 2 will be discussed by means of the same research method.

WH2 *Stochastic optimization effectively helps to select among alternative fuels and power systems under lifetime uncertainty while considering flexibility.*

The links between the individual papers and the steps in the validation square are illustrated in Figure 6.2.

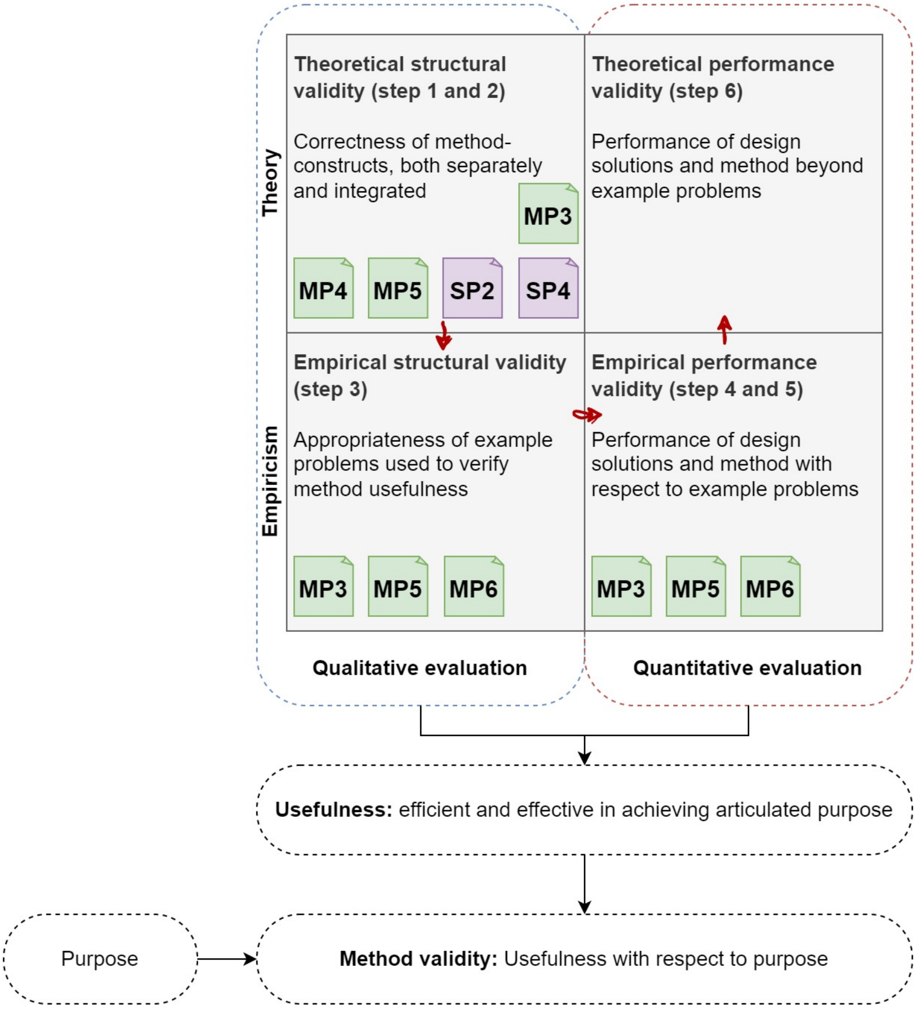

Figure 6.2: Links between papers and validation square for Working Hypothesis 2

The relations of the papers to steps (1) to (6) are outlined in the following.

(1) "Accepting the individual constructs constituting the method". The individual constructs used within this method are described and discussed in several papers: Main Paper 1 describes an optimization model, which considers flexibility for the selection of fuel and power systems within a *single* future scenario. The developed deterministic optimization model accounts for many complexities, e.g., future retrofits and lost cargo-carrying capacity due to fuels, but does not consider uncertainty. Based on the deterministic model's capability to address the complexity, Main Paper 5 describes and discusses the stochastic extension, which accounts for both complexity and uncertainty in the decision-making problem. More specifically, uncertainties with respect to fuel costs and carbon

pricing have been considered. The probability distributions assumed in the stochastic model are meant to capture expectations about the future. Any 'optimal' solution depends on these expectations, and this aspect has been examined in Main Paper 4 for different levels of agility. Despite this dependency, previous research (Pantuso, Fagerholt, and Wallace 2015) has shown that the consideration of different scenarios through stochastic programming can at least lead to 'better' solutions compared to ignoring uncertainty. Supporting Paper 2 explains the inputs and calculation procedure behind different scenarios for electrofuel costs. Supporting Paper 4 approaches the fuel and power system selection problem from a policy perspective, i.e., it investigates the required level of marked-based measures to incentivize significant emission reductions. The results of Supporting Paper 4 corroborate the approximate range of the probability distribution for carbon pricing used in the stochastic model. The individual constructs have thus been described and discussed, and are found acceptable.

(2) "Accepting the internal consistency of the way the constructs are put together in the method". Main Paper 3 describes the integration of constructs into the deterministic optimization model. The paper serves specifically the validation of those parts dealing with complexity only, i.e., the consideration of future retrofits, fuel prices over time and loss of cargo-carrying capacity. The deterministic model is enhanced with a stochastic extension, described in Main Paper 5. In the stochastic extension, selected deterministic parameters are replaced with stochastic distributions, maintaining the internal consistency of the assembled construct.

(3) "Accepting the appropriateness of the example problems that will be used to verify the performance of the method". A Supramax bulk carrier has served as an example problem to examine the performance of both the the deterministic and stochastic method (Main Papers 3 to 6). Since this ship types represents a significant share of the global transport work in tonne-miles (Bengtsson 2018), this example is seen as relevant within a diverse industry (Stopford 2009) and in particular among the industrial partners of the SFI Smart Maritime. This step is thus seen as fulfilled.

(4) "Accepting that the outcome of the method is useful with respect to the initial purpose for some chosen example problem(s)". Main Paper 3 describes the application and the gained insight from the deterministic model to the example problem. The method has been deemed useful as it shows that retrofits can be cost-optimal even under deterministic conditions. The bi-objective nature of the model enabled the assessment the effect of GHG emission requirements on the choice of fuel and power system. In Main Papers 5 and 6, the stochastic extension has been applied, providing additional understanding of the effects of uncertainty on the problem. By creating new and relevant insight, the developed method has been deemed useful for the example problems.

(5) "Accepting that the achieved usefulness is linked to applying the method". To my knowledge, there has been no openly published method before, which considers both retrofits and uncertainty *across* scenarios in the selection of a wide range of alternative

ship fuel and power systems. Preceding reports (e.g., Lloyd's Register and UMAS 2020; DNV GL 2020) have published the outcome of extensive studies, as well as considerations and recommendations, but not disclosed the details of the applied method. In contrast, the developed deterministic selection method and its stochastic extension have been documented in Main Papers 3 and 5 and can thus be further applied to relevant case studies. Main Paper 6 compared the stochastic model with a robust optimization counterpart, which was developed based on the deterministic model (Main Paper 3), and it was found that both methods yield similar conclusions for the given case, albeit with nuanced differences in detail. Both methods were generally found to be useful and yield relevant insight.

(6) "Accepting that the usefulness of the method is beyond the case studies". Similar to the evaluation of Working Hypothesis 1, the usefulness beyond the case studies cannot be assured. The generic nature of the developed model, with its few ship type-specific inputs, builds confidence in the method's usefulness beyond the case studies. The general decision-making problem, that was expressed by the SFI Smart Maritime's industry partners, seems to be broadly similar across market segments and independent of the ship type. This supports the conjecture that the method is useful beyond the example problems.

The validation square is meant to evaluate a design method's usefulness with respect to a specific purpose. Overall, the evaluation has shown support for both working hypotheses, but also uncovered limitations. The final judgment of usefulness may vary, to some extent, depending on the eye of the beholder. The description of each step within the validation square and the stated considerations shall enable the reader to form her or his own final judgment of the usefulness.

6.1 Discussion of contributions

The previous section has evaluated the two initial working hypotheses through the validation square. From this evaluation, three main contributions can be identified:

C1	The coupling of a set-based approach with modular SBSD, a systems architectural model and discrete-event simulation for a case-dependent evaluation of conceptual designs
C2	A method for the selection of the optimal ship fuel and power systems considering flexibility throughout the lifetime
C3	An extension of the deterministic selection method (C2) that concurrently considers uncertainty through multiple stochastic scenarios

The relations between research questions, main papers and contributions are depicted in Figure 6.3.

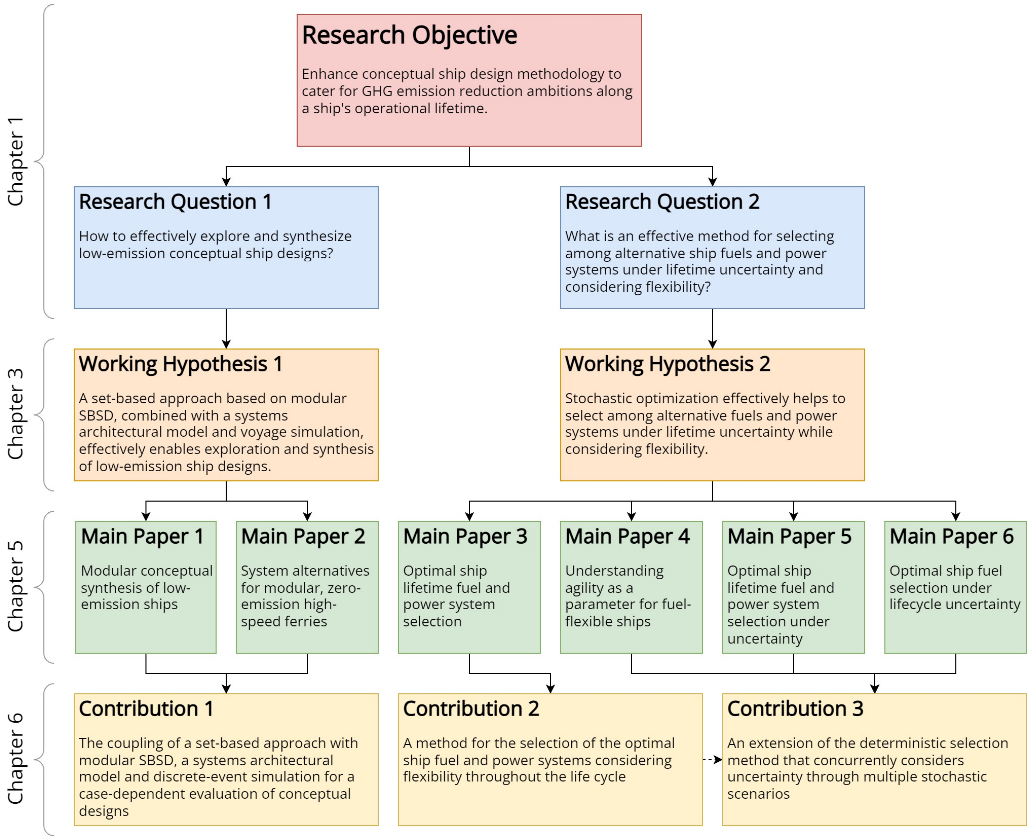

Figure 6.3: Research contributions

Working Hypothesis 1, through Main Papers 1 and 2, has led to Contribution 1, which is a ship synthesis model based on MBSE principles and combines SBSD with modularization, a set-based configuration approach and discrete-event simulation for performance analysis. The synthesis model has indicated useful characteristics for the synthesis and exploration of diverse designs. As noted in the previous section, the efficiency of this method depends on the expected reuse of the computational model.

Working Hypothesis 2 has resulted in two contributions: Contribution 2, documented in Main Paper 3, is a deterministic optimization model for the selection of ship fuel and power systems under known, but changing exogenous conditions (fuel costs and carbon prices). Contribution 3 builds upon Contribution 2, and represents an extension of the optimization model with a stochastic part to account for fuel cost and carbon price uncertainty. Thus, while the deterministic model addresses mainly the problem's complexity, the stochastic extension additionally helps to address the problem's inherent uncertainty. Albeit linked, the contributions are distinct: the deterministic model can be used to address *within-scenario* decisions. It has served as input to both the stochastic optimization model (Main Paper 5) as well as a robust optimization model developed by Jesper Zwaginga (comparison with stochastic model in Main Paper 6).

6.2 Practical implications

This research has been classified as 'applied' in Section 4.3. This section, therefore, examines the practical implications of this research, both from an industrial and academic standpoint, and both for the design process and product.

The MBSE approach which the ship synthesis model (Contribution 1) is based on, combined with aspects of modularization, SBSD, configuration-based design and discrete-event simulation, has shown to be useful for the synthesis and exploration of low-emission ships on a conceptual level. However, considerable resources were spent for the implementation. An industrial stakeholder should carefully consider its available software tools and how they can be coupled in a pragmatic way. The model aims at reuse of design modules, and the decision of whether or not to adopt such a model, therefore, should account for the expected reuse across future projects. The stepwise functional breakdown of the approach has supported the exploration of diverse configurations. The case studies have shown that aspects such as overall energy efficiency and building modularity can be effectively addressed.

The deterministic and stochastic optimization model (Contributions 2 and 3) of this thesis represent decision support methods specifically for the selection of alternative fuels and power systems. Both methods require relatively few ship type-specific inputs and can thus be readily applied by industrial stakeholders. Both methods help capturing important, but not all, complexities associated with the decision-making problem. Namely, these are: the impact of alternative fuels on the cargo-carrying capacity, the possibility of future retrofits, the consideration of well-to-wake GHG emission effect and the development of fuel prices. Importantly, and this may be seen as either an upside or a downside, both models require being explicit on expectations towards future fuel costs and carbon prices. In the case of the deterministic model, these expectations would assume perfect foresight, whereas the stochastic model requires specifying ranges with associated probability distributions. The comparison of the stochastic model with a robust optimization counterpart has indicated that the most important point is to account for the uncertainty, rather than ignoring it. For the case study of a Supramax bulk carrier, both methods indicate that flexible dual-fuel engines, at present for LNG and methanol, represent a more robust decision for the future than less flexible mono-fuel Diesel engines. The study has moreover indicated, that the expected well-to-wake emission reduction level is more decisive for the selection of ship fuel and power systems than whether the enforcing policy is of a market-based measure or command-and-control type.

From an academic perspective, the combination of different methodological elements in the ship synthesis model (Contribution 1) has shown to be useful, yet resource-intensive to implement and maintain, especially within an academic environment. If different software tools are available for implementation, this can potentially ease the development and successive maintenance. Moreover, the model made used of semi-empirical formulas for several of the design modules. Assuring an appropriate accuracy of such formulas or procedures has shown to be important. For more unconventional and potentially innovative components, this can represent an avenue of further research which seems useful from a design perspective. The industrial implications of the deterministic and stochastic model may to some extent also apply to academia. In addition, the case studies have suggested biofuels as a likely cost-effective option for GHG emission abatement. This corroborates the findings of other studies (Korberg et al. 2021; Grahn et al. 2022). The sustainable availability of these fuels for international shipping is thus as relevant subject of research. Research has shown that cost-effectiveness is important, but not the only factor affecting the decisions (Balland et al. 2015; Ashrafi, Lister, and Gillen 2022; Slotvik 2022). The brute force technique, complementing the implementation in a commercial solver in Main Article 5, can help analyzing such options that are beyond the cost-effective Pareto front.

Table 6.1 summarizes the discussed practical implications both from an industrial and academic perspective, as well as for the design process (methodological implications) and product (technological implications).

Table 6.1: Summary of practical implications of this research for industry and academia, and design process and product

	Methodological, i.e., for the *design process*	**Technology-oriented, i.e., for the *product***
Industry	• The ship synthesis model can be used for both conventional and more unconventional configurations, but resource expenditures should be assessed against expected reuse. • Selection of alternative ship fuels and power systems is affected by uncertainty. This uncertainty should be considered, for instance with a stochastic model, rather than ignored.	• Considering the entire energy process chain, from energy harvesting to onboard use, is decisive for a fair comparison, e.g., of hydrogen and batteries in short-sea applications. • Dual-fuel engines currently seem to be a more robust choice for the future than mono-fuel Diesel engines. • Ships combusting long-chained hydrocarbon electrofuels, such as synthetic Diesel produced from renewable electricity, are unlikely to be cost-effective options for GHG emission abatement.
Academia	• Research on better coupling of tools for synthesis and discrete-event simulation required. • Improved simple behavior models of components, e.g., hull forms or energy converters, seem useful from a design perspective. • Contribution 2 can be used as a basis for the development of further ship fuel and power system selection methods. • Contribution 3 can be applied to further case studies and is relevant to be tested with varying risk preferences.	• Biofuels are likely to be a cost-effective option for GHG emission reduction. Further research into the sustainable availability of these fuels for international shipping is relevant.

6.3 Evaluation of the research approach

This research has been of an explorative type with a subsequent formalized evaluation. Based on existing literature, working hypotheses have been formulated as to denote conjectured enhancements of design methodology. The constructs described within the working hypotheses were developed, implemented and tested in case studies, which was documented in this thesis' main papers. The validation square has served as a formalized *research method* for the evaluation of the developed *design method*s. Even though the validation square attempts to formalize the evaluation process as far as possible, it still leaves some judgmental freedom to the researcher. In this thesis, I have therefore attempted to transparently describe the considerations for each step, in order to enable the reader forming her or his own final judgment. I have perceived the validation square as a relatively pragmatic research method to evaluate prescriptive design methods. However, it is to be noted that the judgmental freedom in the evaluation represents at times a demanding procedure. This can be evoked, for example, through the lack of directly comparable design methods, i.e., design methods with the same purpose. Also, the lack of standardized design problems can represent a challenge: How can two methods with the same purpose be evaluated when applied to different example problems? I have not found any satisfactory resolution of these issues other than documenting the methods and case studies as transparently as possible for potential future comparisons. Thus, when investigating prescriptive design methodology, the validation square seems to me like pragmatic compromise.

7 Conclusion and limitations

“Knowing is not enough; we must apply. Willing is not enough; we must do.”

- Johann Wolfgang von Goethe

This chapter summarizes the conclusions and outlines the limitations of this research. Some of these limitations could be natural starting points for further work. In addition, the last section outlines potential research avenues whose ideas sprang from the present inquiry process.

7.1 Concluding remarks

This thesis addresses the conceptual design of low-emission ships. The research work has been disseminated in six main papers and four supporting papers. From these papers, three main contributions are identified.

The first contribution is a synthesis model based on the coupling of a set-based approach with modular system-based ship design, a systems architectural model and discrete-event simulation for a case-specific evaluation of conceptual designs. The synthesis model addresses specifically structural and behavioral complexity aspects. The second contribution constitutes a method for the selection of the optimal ship fuel and power systems over a lifetime, considering flexibility in the form of retrofits and fuel switches. The method is based on deterministic optimization, that is, a single scenario for fuel costs and carbon price development is assumed. Thus, the method accounts for important contextual and temporal complexity aspects. The third contribution builds upon the second one by explicitly accounting for uncertainty with respect to fuel costs and carbon prices. The uncertainty is modeled as probability distributions and the developed method is based on stochastic programming. The consideration of uncertainty through probability distributions yields more robust solutions than ignoring uncertainty: Even though the probability distributions can only represent expectations about the future, they induce solutions that sustain an acceptable performance under changing external circumstances, as well as suggesting flexible options for fuel switches and retrofits.

The contributions are of instrumental value in conceptual ship design, i.e., they can be seen as enhancements of a designer's 'toolbox'. Being instruments, it is important to apply the contributions with pragmatism. The ship synthesis model (Contribution 1), for instance, has been implemented as a Java code with discrete-event simulation that was coupled to a three-dimensional browser-based visualization. In an organization that intends to apply the same approach, there may already be a number of existing software tools with (partially) similar functionality. If these can be coupled to provide roughly the same overall functionality (combination of design modules, visualization and ship voyage simulation), this could constitute a pragmatic adaptation and implementation. Regarding the deterministic and stochastic optimization model, a pragmatic adaptation could mean the choice of different upper and lower bounds or distributions for fuel costs, or the change of risk preference in the objective function.

7.2 Limitations

This research has made use of working hypotheses that were tested in a low number of case studies. The case studies have shown reasonable support for the working hypotheses. However, a larger number of case studies would be desirable in order to either strengthen or refute the working hypotheses.

As pointed out in the discussion, the ship synthesis model's efficiency depends on both the foreseen reuse and the effort spent on the implementation of the computational model. It is likely that the coupling of different software tools or programming frameworks can lower the resource effort required. Moreover, Main Paper 2 has highlighted the criticality of appropriate model accuracy, in this case for a calm water resistance evaluation procedure. The availability of subsystem models thus puts limits on the entire approach's applicability. This is of particular importance for unconventional designs, which might lack appropriate behavior models for new subsystems. Besides, the synthesis model has so far only been tested for a limited number of relevant low-emission components. Its effective applicability to other technologies and components, e.g., wind propulsion systems, still needs to be investigated.

The deterministic and stochastic optimization model address the selection of ship fuels and power systems from a cost-effectiveness viewpoint. Previous research has shown that cost-effectiveness is a necessary, but not a sufficient aspect to be considered in similar decision-making situations (Andersson et al. 2020; Ashrafi, Lister, and Gillen 2022). Similar to Slotvik (2022), future research may thus aim for a better consideration of aspects beyond cost-effectiveness. During the work on the deterministic and stochastic optimization model, the general rationale has been to simplify complexity wherever possible, in order to focus on the most important aspects of complexity. The simplifications resulted in a linear mathematical model with binary variables. Implicitly assumed is a constant conversion efficiency for all power systems as well as a single fuel type. For instance, either bio-methanol or electro-methanol may be used, but not a blend of these. In reality, both fuel blends as well as power systems with significantly different efficiency characteristics, such as fuel cells, are potentially relevant options. Regarding uncertainty, the stochastic optimization model aimed at focusing on the presumably most important uncertainties in the decision-making problem, i.e., fuel costs and carbon prices. No uncertainty is considered with respect to future retrofit prices or additional options potentially becoming available over time. The central idea behind using stochastic optimization was to use ranges of possible outcomes, with the possibility to assign less likelihood to extreme scenarios. It seems natural and important to question the probability distributions applied in the case study. Most importantly, they enable capturing future expectations explicitly without the necessity to commit to a certain single scenario. Nevertheless, the model requires the specification of ranges for the distributions of fuel costs and carbon prices and thus, the approach is limited by the ability to approximately estimate upper and lower bound values. Last but not least, the objective function for in the stochastic model is based on an expected value formulation. This may not be representative for all stakeholders, and certain stakeholders may prefer a more risk-averse standpoint. The comparison between stochastic and robust optimization has indicated that the effect of such preferences may not be significant for the selection of the initial ship power system. However, this evidence regarding risk preferences is still weak and should be further investigated. The following section will outline further avenues of relevant potential research.

7.3 Further work

The previous section has already touched upon further work that takes this thesis' limitations as a starting point. This section takes a broader view and suggests additional subjects for investigations. The ideas for these subjects sprang from the work on and findings of this thesis during the past three and a half years.

The two methods in this thesis have been developed under the scope of one working hypothesis each, in order to address structural/behavioral and contextual/temporal complexity aspects respectively. Further research could investigate if and how these two methods should be tied better together, e.g., how to effectively make use of discrete-event simulation within multiple future scenarios. In this context, not only the simulation of a single ship, but also of a larger fleet seems to be relevant. Moreover, the integration of the two methods into daily design processes could be further researched: Should developing scenarios be included as an additional module within a business-centric design methodology (Brett et al. 2018)? And if so, how can the relevant stakeholders best be integrated in the process?

This thesis (Main Paper 4) has pointed towards agility as a parameter for fuel-flexible ships. The paper only exemplified certain options to design power systems with a certain level of agility. Further options could be explored, and in particular their engineering design implications: Which systems, e.g., piping, fuel supply and storage, can be designed for reuse, independently of the choice of fuel? Which system interfaces can be defined today in order to effectively prepare for future retrofits?

Many of the alternative ship fuels require new infrastructure for production, storage, distribution and bunkering. There may exist significant synergies (economies of scale, better availability etc.) between fuels sharing parts of this infrastructure. Also, synergies may exist for ships running on the same type of fuel instead of many ships running on many different types of fuels. Even though such a common fuel may initially not seem cost-optimal for an individual design, those synergies could ultimately render the fuel preferable. For instance, such synergies may cause the fuel to be become available at a more competitive price. Therefore, the selection of the 'best' fuel may be affected by the decisions of peers: If all shipowners were to opt of ammonia for example, those that initially preferred hydrogen might switch. This illustrates that the decision-making problem would be affected by other stakeholders' behavior, and thus the application of game theory might be an interesting avenue of further research. Related to this, a systematic approach to the design of green corridors (Moyano et al. 2012; Panagakos 2012) seems to be a relevant topic in the future. The availability of sustainable biomass to shipping would be another important topic of further research. Grahn et al. (2022) suggest the combination of biomass and renewable electricity as feedstocks for fuel production and thus combine advantageous characteristics of both feedstocks. Such fuels would constitute a relevant subject for future investigations and may be interesting to consider in the deterministic or stochastic selection method.

As argued in this thesis, the selection of alternative ship fuels and power systems is affected by future uncertainties. Macroscopically, the shipping industry has shown a tendency for compliance rather than significant over-achievement of environmental ambitions (Faber et al. 2020). That is, while there are examples of proactive actors, the shipping industry as a whole tends to comply with rather than over-achieve the sector's ambitions. The adoption of some emission reduction measures is therefore delayed until becoming necessary for compliance. In the light of the overall need to reduce GHG emissions significantly, globally and quickly, two further research directions seem relevant: First, how could significant emission reductions be embedded into shipping contracts? These could incentivize more effective reduction measures in order to accelerate decarbonization beyond statutory compliance. The second further direction could look into how high ambitions could be realized already today, for instance through the adoption of wind propulsion or other technological options that are available in relatively short time.

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Appendix A: main papers

Main Paper 1

Modular Conceptual Synthesis of Low-Emission Ships
Benjamin Lagemann, Stein Ove Erikstad (2020)
Proceedings of the 12th Symposium on High-Performance Marine Vehicles; ISBN: 978-3-89220-718-4; pp. 134-151; Cortona, Italy

Modular Conceptual Synthesis of Low-Emission Ships

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Abstract

With the ambition of lowering emission from shipping, today's ship designers face both the freedom and challenge to select from a large set of different ship system concepts during the conceptual design stage. In order to design competitive vessels, these options need to be assessed in an efficient and systematic way. Building upon established ship design methodologies, this paper presents a combined synthesis model adapted to low-emission ship design. By making extended use of modularity, namely component swapping and combinatorial modularity, the model enables flexibly synthesizing diverse ship configurations. To illustrate how the model can be used, we show how it can be implemented computationally and apply it to a RoRo transport case for the route Rotterdam - Halifax. An efficient discrete event simulation enables immediate performance evaluation. The ship designer can thus directly foresee the consequences of decisions and elucidate requirements on an informed basis.

1. Introduction

'How can we reach the IMO 2050 ambition, *IMO 2018*, for ship GHG emissions?' is an increasingly urgent question. Given the most optimistic projections in terms of least presumed emissions, shipping GHG emissions in 2050 will be as high as in 2008, *IMO (2015)*. Such a scenario already implies a high uptake rate of efficiency measures. In this light, the IMO GHG emission goals for 2050 may seem ambitious. Yet, they represent what is deemed as shipping's fair contribution to the Paris agreement, *UN (2015)*.

Translation of the IMO ambitions into a per-ship-basis is currently under discussion. Generally, we can identify three main levers for GHG emission reductions in shipping, Fig.1.

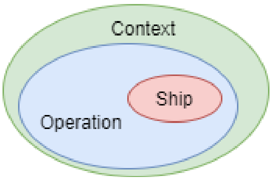


Fig.1: Levers for shipping emission reduction

Operative measures, such as speed reductions, are debated, *IMO (2018)*, and in some cases already implemented voluntarily. Green technologies are said to significantly advance emission reductions in the future. In many cases, these advanced technologies make use of synthetic fuels produced by electric energy. Local emissions can thus be avoided, but well-to-tank emissions need to be assessed. Hence, the context the ship operates in (external infrastructure etc.) determines whether the technology will achieve reductions in practice or not.

The focus of this paper is on ship GHG emission reductions that can be achieved during the design phase. More specifically, we will look into the conceptual design phase (also called early, preliminary design or feasibility study), where not only a large fraction of costs is determined, but also the main concept for the ship is set. The design space, and thereby the freedom for change, gradually reduces from preliminary design to manufacturing, *Mistree et al. (1990)*. Hence, we find the largest lever to reduce ship emissions in the conceptual design phase.

All three levers shown in Fig.1 will influence ship emissions. As both context (e.g. refueling locations or regulations) and operation (e.g. required speed) impose requirements upon the ship, these need to be thoroughly examined. One should at the same time keep in mind that the ship is in fact serving a purpose different from emission reduction. Emissions are thus a by-product while achieving the ship's intended purpose.

Fig.2: Wind-power car carrier, developed jointly by KTH Stockholm, SSPA Gothenburg and Wallenius Wilhelmsen

There are numerous proposals for ships, built or under design, that each serve a distinct mission while maintaining low-emission levels: Wind-power cargo vessels as proposed by NEOLINE, https://www.neoline.eu/wp-content/uploads/2019/07/NEOPOLIA_NEOLINE_2019_07_PressRelease.pdf, and KTH, https://www.kth.se/en/aktuellt/nyheter/ett-hallbart-fartyg-kommer-lastat-1.965511, Fig.2, or hydrogen-driven solutions as investigated by *Raucci et al. (2015)*. Those examples prove that large emission reductions can be achieved. Thanks to their low emission levels, some of the presented solutions could likely be part of a shipping fleet in 2050. However, when tasked with a new ship design today, we will quickly get to the question “What is a better ship?”, *Ulstein and Brett (2015)*: Would a hydrogen-powered vessel be the preferred choice? Could even a purely wind-powered solution be feasible? Couldn't we design a ship that can be retrofitted in 10 years, when a certain technology is likely to be more mature?

Ship design requirements are different from case to case. Thus, achieving emission reductions is not as straightforward as taking a marginal abatement cost curve to find the best solution, *Kesicki and Strachan (2011)*. Its underlying assumptions are most likely different from the design task at hand. Consequently, as part of the requirements elucidation process, *Andrews (2003,2011)*, the previous 'better ship' questions need to be answered for each new design case. Due to the large number of different alternatives and their many interactions and intersections, the design process appears to be ill-structured, *Simon (1973), Pettersen et al. (2018)*, and complex. *Gaspar et al. (2012)* identify five complexities of ship design: structural and behavioral complexities associated with the ship (components and their emerging behavior); contextual and temporal complexities as the ship subject to changing operations and context over time; perceptual complexity referring to diverse and possibly contradictory stakeholder expectations.

We have outlined the three main levers for emission reductions in shipping, Fig.1, as well as how they relate to the complexities in ship design. All three factors should be incorporated in the requirements elucidation process. For this to be done successfully, we need both a holistic life-cycle analysis, *Papanikolaou (2010)*, as well as a conveniently fast ship synthesis model. The present paper will focus on the ship synthesis part, keeping context and operation constant. After recalling the generic design process, we will review a set of ship design approaches with respect to their applicability to low-emission conceptual design. Based on the reviewed methodologies, we will then attempt to formulate a combined ship synthesis model considering emission performance from the very beginning of the design process. We will describe how this model can be implemented computationally and illustrate its use by quickly synthesizing a conventional diesel- and an ammonia-driven RoRo ship.

2. The generic design process

Simon (1996) defines design as “changing existing situations into preferred ones”. Thus, design starts with a need to change a situation. As for engineering design, such a need is usually met by the specification of an artifact. This artifact attempts to meet the stated need by means of certain functions which are enabled by the artifact's form. *Coyne et al. (1990)* and *Suh (1990)* illustrate this process as a mapping from need via function to form:

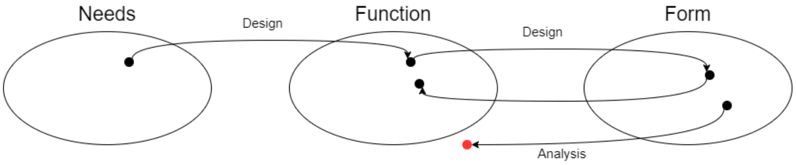


Fig.3: Design as a mapping between different domains

We can see that design is different from analysis. No straightforward deductive step from function to form exists. If we propose a certain form, we can evaluate if its attained performances meet the intended ones. If that is not the case, we need to alter the form and verify it again. Design thus often represents an iterative process with changes on form and perhaps even functions. If we realize that our intended performance (e.g. high speed at low emission levels) is not attainable or too costly, we might be willing to change them. *Andrews (2003,2011)* refers to this process as 'requirements elucidation'.

3. Established ship synthesis models

Within this section, we will briefly review and compare three influential ship synthesis models: system-based ship design (SBSD), *Levander (1991)*, the design building block approach (DBB), *Andrews and Dicks 1997),* and the packing approach, *van Oers (2011)*. These synthesis models have been widely discussed and used in the past. They are not mutually exclusive, rather they share many common ideas and thus can often be combined. Van Oers' packing approach for instance builds upon the design building block methodology as a parametric ship description.

Ship design is often seen as a subset of engineering design or systems design. Nevertheless, ship design also features a spatial, architectural aspect. In order to be precise about terminology when comparing the synthesis models, we will use a discrimination inspired by *Kroes et al. (2008):*

- Architectural design: Concerned with the spatial arrangement
- (Systems) engineering design: A reductive, hierarchical perspective emphasizing (sub-) system interactions

The architectural aspect has historically been more influential for service ships (e.g. cruise ships or warships) than for cargo ships. It is still is to be proven that this will also be the case potentially unconventional, low-emission ship designs in the future.

Within systems engineering, we additionally define the term topology as:

- System topology: “connectivity between parts of the ship”, *van Oers (2011)*

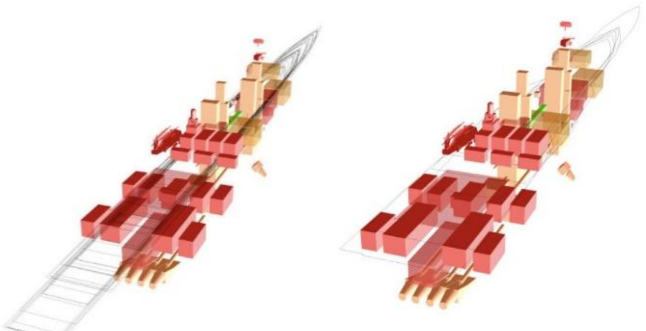
Mission - We have outlined in Section 2 that design originates from a purpose. For a ship, this purpose is usually described as a mission. The focus of SBSD has been civil ship missions (transport and service missions), whereas both the DBB and the packing approach are targeting service vessels (civil and naval) that are considered more architecturally complex. A mission statement translates into requirements. *Van Oers (2011)* underlines that the negotiable ones of these can be subject to an exploration.

<u>Functional and system breakdown</u> - Both SBSD and the DBB start out with a functional breakdown. Due to the unlike target missions, the breakdowns are somewhat differing:

Table I: Functional breakdown structure of SBSD and the DBB methodology

SBSD, *Levander (2012)*		DBB, *Andrews and Dicks (1997)*			
ship functions	payload functions (for cargo)	float	move	fight/operations	infrastructure
structure	cargo units				
equipment	cargo spaces				
accommodation	cargo handling				
machinery	cargo treatment				
tanks					

The detail of the functional breakdown in SBSD is increased for a specific ship mission and then mapped into a system breakdown. Such detailed breakdowns ease the handling of systems and enable a quick weight and space estimate. If used in a spreadsheet fashion, this type of breakdown however appears to be somewhat rigid when exploring a wide solution space. The designer seems to be somewhat locked to certain system topology that hampers a wide exploration. Hence, maintaining flexibility for the system breakdown is key for low-emission ship design. As for the DBB approach, the functional groups are mapped to so-called super building blocks. The selection of super building blocks is denoted "major feature selection", *Andrews and Dicks (1997)*, and represents the most important conceptual design decisions. Building blocks can be assembled and architecturally positioned. According to *Pawling (2007)*, this procedure particularly fosters the exploration of innovative, unconventional designs. *Andrews et al. (2010)* enhance the DBB approach with a library for different system options. Again, this strongly supports innovative system compositions and enables concurrent investigation of diverse concepts, Fig.4. *Calleya (2014)* presents a "ship impact model" to assess the impact of certain carbon reducing technologies on a given ship model. This enables a case-based impact assessment, but does not consider emissions from the very beginning, i.e. integrated into the design DBB design methodology.



a) Monohull b) Trimaran

Fig.4: DBB visualization of two different ships for the same mission, *Andrews et al. (2010)*

<u>Generating diverse configurations</u> - The intention of SBSD and the DBB methodology is to systematically support the designer in the preliminary design phase. The main decisions (what systems, where to place) are thus to be taken by the designer a-priori to design evaluation. As illustrated by Fig.4, the DBB methodology encourages generating diverse configurations. Van Oers' packing approach does not relief the designer of making decisions. The key difference however is that decisions are made a-posteriori to the synthesis phase: A set of diverse ship configurations is generated and evaluated by a search algorithm. Only non-negotiable requirements (e.g. positive GM) are considered as a threshold. Negotiable requirements are not considered as a threshold, but can be elucidated a-posteriori to the design evaluation. Hence, when the designer faces the proposed designs generated by the search algorithm, performance data is directly accessible and can guide the process of (negotiable) requirements elucidation.

Engineering and architectural design aspects - All three design approaches contain a numerical ship description and make use of experience to estimate system parameters. SBSD reveals relevant system parameters (e.g. weight/kW for an engine) to the designer, while the packing approach makes use of *van der Nat's (1999)* sizing functions containing hard-coded experience. Similar relations are used for sizing DBBs. Rather than on numerical relations, the focus of the DBB and the packing approach is on architectural design aspects. Although *van Oers (2011)* describes certain overlap rules supplied to the search algorithm, he notes that architectural aspects are often negotiable and will lack completeness when stated a-priori. SBSD does not directly focus as much on architecture as the two other approaches. Nevertheless, its open and simple system descriptions have proven to be useful for design of architecturally complex vessels too, as they enable repositioning and quick estimations for the center of gravity for instance, *Levander (2009).*

Hull design - Both SBSD and the DBB adhere to a "wrapping" approach for hull design: "Instead of fitting systems into a hull we fit a hull to the system description already made", *Levander (1991).* Van Oers, within his search algorithm, employs a "packing" strategy. That is, all systems are positioned within a given hull form. If hull dimensions are selected as variables for the search algorithms, different hull sizes for the same systems can be generated, yielding different packing densities and covering diverse configurations.

Modular aspects - All three design approaches make use of basic concepts of modularity, which is further discussed in Section 4.2. Weight, space and position attributes are assigned to each system and the particularly the DBB approach fosters interactive positioning of such modules. Van Oers notes that systems can be exchanged for alternative systems to generate diverse system topologies.

Triggering unconventional designs - The goal of the three preliminary design approaches is to trigger exploration of diverse configurations - including potentially unconventional ones. Their respective means to do so, are however slightly different:

- SBSD uses a simple and parametric system description. Not only does it provide the designer with a list of required systems, but also reveals the most important system characteristics.
- The DBB methodology uses an interactive block assembly of ship systems, providing necessary numerical tools one the side. The designer can thus focus on generating diverse designs and particularly elucidate architectural requirements.
- Elucidating requirements is a notion shared by the packing approach. The key difference is the speed of doing this: With an a-posteriori selection approach, the designer is relieved from manually balancing and evaluating designs. Requirements are thus elucidated by directly revealing decision implications.

The three presented design approaches provide a stepwise design methodology, starting with a mission, proceeding via functions and finally specifying a form. Generally, the questions 'where to place systems?', 'what system size?' and 'what implications?' seem to be widely covered. What appears to be missing is how to rapidly generate and investigate diverse system typologies, in particular for those systems that drive emissions. In the next section, will attempt to combine the successful features of these three synthesis models by extending the use of modularity.

4. A combined modular synthesis model

Our combined synthesis model shall in principle target the same missions as SBSD. Yet, we slightly adapt the 'crux of the task', *Pahl et al. (2007)*: Synthesize diverse ship configurations for a given mission, paying due regard to required emission reduction measures and goals. Albeit still generic, our combined synthesis model will naturally be biased towards this problem description. More specifically, it shall address the necessary flexibility for generating diverse system topologies.

4.1 Ship functions

We have outlined that a generic and flexible function-system mapping is crucial in order to not limit the solution space. However, functions need to be provided by specific systems. Hence concrete, precise functions would be desirable. Before discussing the high-level functional breakdown, we shall briefly take a look at aviation. The flexible mapping issue from function to form is shared by aircraft designer and depicted by *Esdras and Liscouet-Hanke (2015)*:

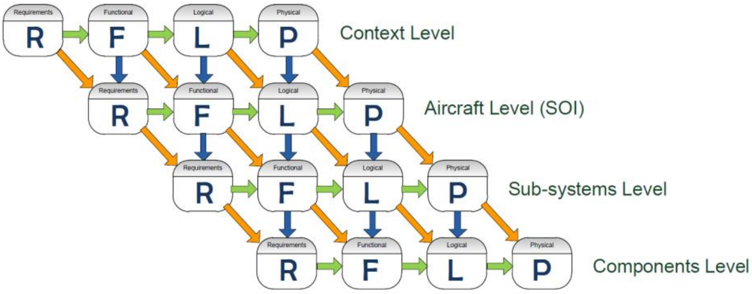


Fig.5: Proposed RFLP model in alignment with the left-hand part of the systems engineering V-model, *Esdras and Liscouet-Hanke (2015)*. (R=requirements; F=functional; L=logical; P=physical)

As illustrated in Fig.5, the functional decomposition at the aircraft level (SOI, system of interest) influences the logical system structure, but similarly the functional and requirements structure at the sub-system level.

Introducing a logical layer is similar to the combination of different working principles, *Pahl et al. (2007)*. Working principles do not refer to a specific embodiment (e.g. an M10 bolt), but rather refer to the underlying logical concept (e.g. frictional connection). Thanks to this abstraction, a logical item becomes less specific but more flexible. It can represent a number of different embodiments grouped under the same working principle, without necessarily implying a specific form. Abstracting the underlying physical concept, a logical representation can thus simplify an entity's interface. *Simon (1996)* claims that most artifacts, being artificial or not, bear such simple interfaces and they facilitate combination into more complex structures: ”The more complex [systems] arise out of a combinatoric play upon the simpler”, *Simon (1996)*. We should keep in mind, however, that eventually also the more flexible logical entities need to be mapped to specific physical items (the physical space in Fig.5).

In order to facilitate a more flexible synthesis model, we shall now apply such a logical layer in between the mapping from functions to concrete systems. Inspiration for the functional breakdown is taken from both SBSD and the DBB methodology (see Table I). Due to the differing 'crux of the task', our functional breakdown will be somewhat different. We show the functional breakdown and its mapping to logical systems for a RoRo transport vessel, Fig.6. Before discussing the proposed mapping between functions and logical systems, we shortly introduce each of the functions and logical systems shown in Fig.6.

A generic vessel will require the high-level functions 'provide vertical force', 'provide volume', 'provide stability', 'provide strength' in order to be present. With these functions, the vessel can float at a certain immersion in equilibrium condition and will not collapse. For the vessel to become a ship, we generally need to 'provide thrust' and to 'avoid resistance'. The latter function seems rather parasitical than useful, but will always be present to a certain extent. Moreover, a moving ship needs to be controlled in some way. *Papanikolaou (2010)* terms the functions described so far as “inherent”. For a RoRo cargo ship, we then add the functions 'load/unload' and 'cargo voyage handling' to the portfolio. For other ship types - e.g. service ships - these functions would need to be replaced by their respective mission-specific functions as shown by *Levander (1991, 2012)* and *Erikstad and Levander (2012)*.

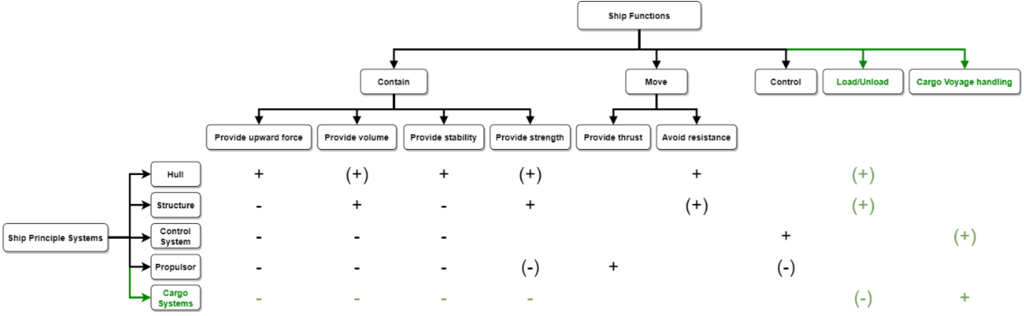


Fig.6: Proposed mapping from functions to logical systems for a RoRo cargo ship (generic=black, mission-specific=green)

The logical systems that fulfil the basic functions of a generic ship are termed 'hull', 'structure', 'control system' and 'propulsor'. For our specific RoRo cargo ship, we will add 'cargo systems' to the list. This division may not seem obvious, as the hull generally describes the shape of the structure and these two cannot directly be separated. However, these logical systems coincide well with the decision-based design paradigm, *Mistree et al. (1990)*, and the 'major feature selection', *Andrews and Dicks (1997)*, during the preliminary design phase: What kind of hull shape would be suitable? What structural concept and material should be used? Should the vessel be operated by humans or be controlled autonomously? What kind of propulsion system should propel the vessel? What cargo system do we need? In theory, these decisions can be made independently from each other which is why we specify them as separate 'logical systems'. We will discuss their dependencies and relations now to clarify this issue.

4.1.1 Function - logical systems mapping

The function ‘provide upward force’ is generally enabled by the hull lift concept (buoyancy, hydrodynamic, aerodynamic). All other systems consume the upward force by their weight. For a balanced ship, consumption consequently needs to match supply.

The ‘provided volume’ is generally not directly limited by the hull form - at least not for surface ships. In most cases, the hull determines the projected area upon which volume can be extruded. But this is not a strict limitation either. Instead, it is often (but not always) the structure that provides the total volume needed for all other systems. Alike *Liscouet-Hanke and Huynh's (2013)* “equivalent design volume” for aircraft systems, each system will consume a certain amount of the provided volume.

‘Stability’ is a ship property affected by the hull form and center of gravity as well as the spatial arrangement (bulkheads, decks, down-flooding points etc.) of the ship. If we focus on linear intact hydrostatics in the preliminary design phase, we can neglect the influence of the compartmentation. In other words, we do not make any premises with respect to the internal subdivision. In this case, stability becomes a property of the hull form ($KM = \frac{I_{WL}}{\nabla} + KB$) as a supplier and the systems as consumers in terms of KG.

Global ‘strength’ is a compromise of hull form, structural material and application, and the cargo to be loaded. Different propulsive means or other systems can affect this function too, but more on a local than global level. Given a specific hull form and cargo storage concept (large open deck areas for our RoRo case), we could say that the structural concept needs to be compatible with these two. For a fast and small RoRo vessel for instance, we could imagine the same cargo storage and loading concept (roll-on-roll-off cargo on large open decks) and the same hull concept (say catamaran in this case) but with different structural concepts: Steel, aluminum and perhaps even composite structures might all be feasible and could be worth an investigation.

‘Providing thrust’ is often the largest source of ship life cycle emissions. However, this is only true for particular kinds of propulsive systems: While a propeller will need rotational power supplied and therefore most likely some energy stored onboard, a sail will generally not require the storage and conversion of chemical energy.

For most ships, ‘resistance’ is mainly determined by the hull form. Wind resistance, as a result of volume above the free surface, is generally a smaller fraction. Hence, we will neglect it for now, but acknowledge that it could in principle be associated with the structure.

A ship's ‘control’ can be plied by humans as well as artificial computer systems. Different criteria with respect to usability and safety will arise, but both solution principles can theoretically exercise the control function.

‘Loading and unloading cargo’ is often done by port operators in the case of RoRo ships. Hence, loading requirements upon the ship can be seen as comparatively low - only the hull and structural concept need to be suitably chosen for this function. Again, we could describe this as a combinatorial issue.

‘Cargo voyage handling’ is a function with different requirements for each specific ship. In case refrigerating units or ventilation are required, the specific magnitude of these functions needs to be supplied by the cargo systems.

We have discussed our proposed mapping from functions to logical systems and seen that some of the interactions (those marked in parentheses in Fig.6) can either be neglected in the preliminary design phase or are of a combinatorial nature. This has often been observed by system theorists, claiming that systems can be divided into “leaky modules”, *Goel and Pirolli (1989)*, and have “near decomposability”, *Simon (1996)*: “the `inner environment' of the whole system may be denoted by describing its functions, without detailed specification of its mechanisms, so the 'inner environment' of each of the subsystems may be defined by describing the functions of that subsystem, without detailed specification of its submechanisms”, *Simon (1996).* This theoretical hook seems to fit well here. Certain interactions - vertical force, volume and stability - apply to all systems and can only be neglected when we exclude the architectural aspect. In the next section, will explain how modularity can be (and has been) used to align these interactions with 'simple interfaces'.

4.2 Modularity

“The primary action of modularity is to enable heterogeneous inputs to be recombined into a variety of heterogeneous configurations”, *Schilling (2000)*. Modularity can thus help to decompose systems into recombinable parts, often called blocks or modules. Modularity is frequently employed for producing customized products, such as different product variants in the automotive industry for instance, *Salvador et al. (2002)*. Salvador et al. define four different concepts of modularity by classifying with respect to interface and platform, Fig.7.

In shipbuilding, modularity has already been used to some extent, e.g. when assembling pre-manufactured blocks or cruise cabins. Some ships, such as the research vessel 'Jacob Brei', https://www.shipandoffshore.net/news/shipbuilding/detail/news/hydrographic-swath-for-estonia.html, use component swapping modularity in order to enable easy retrofit.

Choi and Erikstad (2017) and *Choi et al. (2018)* found that modularity, thanks to its recombination capabilities, often proves useful to cope with future uncertainty. However, *Erikstad (2019)* reminds us that “modularity in most cases comes at a cost. These include less optimized physical architecture, and correspondingly increased weight and size.”

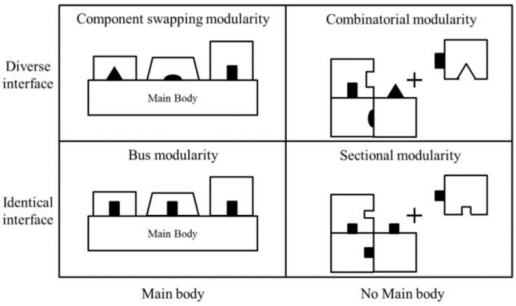


Fig.7: *Salvador et al. (2002)*'s different types of modularity from *Choi and Erikstad (2017)*

Some aspects of modularity have already been employed within the SBSD, DBB and packing approach. We will analyze their use of modularity within the next section and argue how and why using modularity should be increasingly used within our synthesis model.

4.2.1 Extending modularity as a conceptual synthesis concept

In all three reviewed synthesis models as well as our proposed function - logical systems mapping, certain ship functions are influenced by all systems: These functions mainly concern provision and consumption of vertical force, space and stability. Corresponding to *Salvador et al. (2002)*, we may formalize these common interactions as 'bus modularity'.

In addition, we have seen that certain ship functions (e.g. provide thrust) only relate to specific systems. Depending on their logical nature, these systems can require secondary systems: A propeller will need some system to provide rotational energy which, in case of an electric motor, requires some kind of electric energy provider. For the ship as an integration platform, these subsequent functions are less relevant. They mainly concern interactions between systems and are dependent on the logical type of the systems. We have outlined that a systematic combination of entities is facilitated by simple interfaces, collected for instance in a design catalog. The multitude of possible combinations, however, quickly grows and complicates the use of design catalogs. Instead, we can make use of diverse interface concepts of modularity. That is, 'component swapping modularity' to relate an overall function to suitable logical entities and 'combinatorial modularity' to combine different logical entities on the same hierarchical level.

Pahl et al. (2007) represent functions as discrete modular entities with specified inputs and outputs. Based on the IDEF0 methodology, *Esdras and Liscouet-Hanke (2015)* additionally assign controls and mechanisms at the entity’s parent and child level respectively. Controls in our case can be functions that require a logical entity and mechanisms can be sub-functions that are specific to the logical entity at hand. For our current task of structuring and (re-)combining logical systems, we consequently propose the representation shown in Fig.8.

Whether a secondary system should be modeled as an input (combinatorial modularity) or sub-system (component swapping modularity), is determined by whether it can be seen as part of the system of interest or not: Assume that our current system of interest was one that provides rotational power to a propeller. We choose an electric engine as a module to provide this energy as output to the propeller. In this case, we would need a system to provide electric power to the engine. It is easiest to model the system as an input system, since it does not directly constitute the electric engine. Rather, the electric engine is fairly flexible with respect to where the electric energy comes from. Many options are conceivable and could be investigated. By modeling a battery as an input system, we ease the systematic combination of logical systems, as it is the intention of a design catalog.

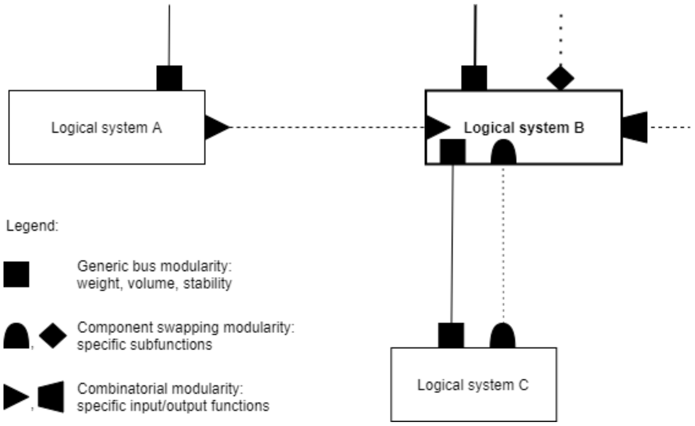


Fig.8: Representation and combination of logical systems

So far, we have illustrated our extended use of modularity to build up ‘logical system’ structures. Our logical system topology is now ‘modifiable’ (modifiable and scalable according to *Ross et al. (2008)*. The design task however is to come up with a specification of an artifact. Hence, we need to map our logical entities to concrete, ‘physical systems’. We can achieve the mapping to physical specification by means of ‘scalable’ modules: Scalable modules contain a parametric description, whose parameter values can be adapted for each design case. The idea of scalability is also covered by SBSD and the DBB approach.

4.3 Summary

Our combined synthesis model formalizes system interactions by different types of modularity. In addition to ‘bus modularity’ aspects as used by SBSD and the DBB approach, we propose using ‘component swapping’ and ‘combinatorial modularity’ as a synthesis concept. Component swapping modularity enables exchanging (sub-)systems and combinatorial modularity facilitates combining different systems on the same hierarchical level. Alike in SBSD and the DBB, scalable modules can help making our knowledge operable and - as opposed to design catalogs - allow case-based reasoning.

So far, the outline of our combined synthesis model has been rather theory-laden. We will therefore illustrate how it can be applied by means of object-oriented programming. Also, we will explain how the implementation helps to realize our initial goal of systematic systems combination together with a case-based assessment.

5. Implementation and application of a modular synthesis model

We have seen that interfaces are important to facilitate a systematic combination of logical entities. Relying on interfaces makes a type-safe, class-based object-oriented programming language particularly suitable for implementation. In this way, we can capture our logical module interactions (bus modularity, component swapping modularity and combinatorial modularity) by means of an abstract class' interface. By deriving abstract classes (or abstract interfaces, depending on the programming language), we can assign a parametric, scalable system description to this interface. Once instantiated and scaled, the instance of a concrete class represents a mapping into the physical form space. The following figure depicts the basic object structure:

We can assign different spatial architectures to the same system topology. Certain functions (such as stability) will be largely dependent on the ship's architecture. We have already formalized these simple interactions numerically be means of the generic bus. A 3-dimensional architectural representation however, such as the DBB's implementation in Paramarine, can be much more revelatory than only providing numerical feedback. Due to the lack of completeness when stating requirements a-priori, a 3-dimensional representation can help to unveil and elucidate requirements.

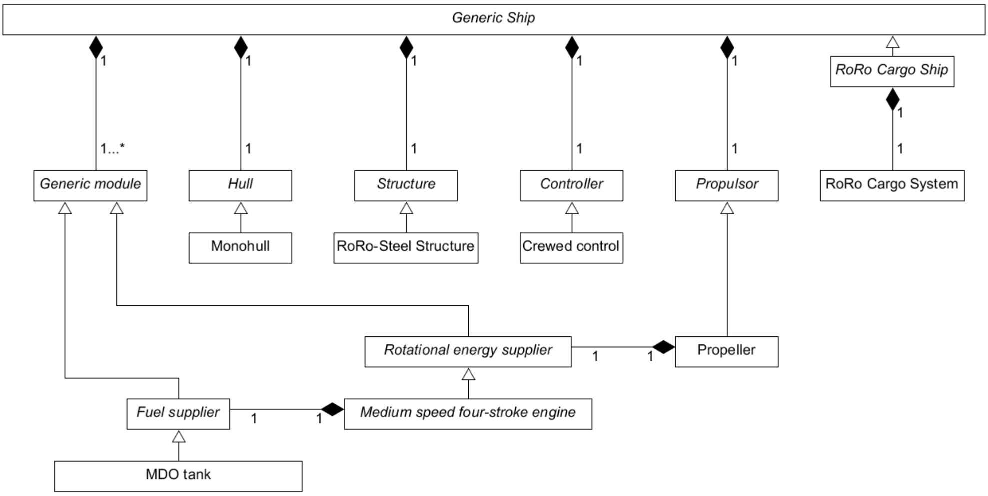


Fig.9: UML representation of proposed synthesis model

For our illustrative implementation, we have chosen to implement our logical system model in Java and couple it with the open-source JavaScript library vessel.JS, *Gaspar (2018)*, to address the architectural aspect with a 3-dimensional representation. The mapping between the two is achieved by serializing the Java system configuration to JSON which is read by vessel.JS. As shown by Figs.10 and 11, we thus have a system view (logical entities and respective topology) and an architectural view on our configuration.

5.1 Illustrative ship mission

When defining our functional breakdown structure in Section 4.1, we have taken a generic ship RoRo transport mission as an example. The generic functional breakdown is still valid. We now define a specific ship mission for our example:

- Transport 5500 cars on a bi-weekly schedule from Rotterdam to Halifax.

The distance between the two ports of call is assumed to be 2800nm, which results in an average speed of about 17 knots. This ship mission assigns numerical values to some if its functions (speed for moving and the cargo capacity). Hence, we can use our predefined function-systems mapping, implemented within the class structure, and turn towards synthesizing two ship configurations that fulfill our mission.

5.2 Ship synthesis

When synthesizing a ship configuration, we start with instantiating a ship. For our RoRo ship case, the RoRo ship class implements the functional breakdown shown in Fig.6 and provides component swapping slots for corresponding logical modules. Next, we instantiate our logical systems and integrate them into an overall topology. The manual input required for instantiation is relatively limited as shown in the Table II. As proposed by *Levander (1991)*, experience data is used for implementation of both design and analysis.

Table II: Module implementation

ship module slot	selected module type	required input parameters	design knowledge and experience data used for implementation
cargo system	RoRo cargo system	position, number of cars	per car: mass 2 t, 2.3 m width, 5 m length; 2.5 m height from deck to deck
structure	steel structure for RoRo monohull	total displacement, cargo system height	weight estimated acc. to Papanikolaou (2014), $VCG = 40\%\ of\ side\ depth$
propulsor	single-screw propeller	position	$\eta_D = 0.67, diameter\ =\ 2 \cdot VCG$
control system	crewed control	position	$12\ pers$ $1000\ USD/day * person$, $3\ t/pers$, $75\ m3/pers$
generic	four-stroke engine	position	$b_e \triangleq 250\ gMDO/kWh$, $3.2\ tCO2/tMDO$, $15\%\ MCR$ at max power
generic	MDO tank	position	$42.7\ MJ/kg$, $\rho_{MDO} = 890\ kg/m^3$, 5% margin on volume and weight for systems, $300\ USD/tMDO$
generic	pressurized ammonia tank	position	$18.6\ MJ/kg$, $\rho_{Ammonia} = 610.3$ kg/m3, 20% margin on tank weight, 27% margin on tank space, $850\ USD/tNH3$, exhaust heat used for ammonia evaporation
hull	monohull	L, B, T, C_B, C_P	Holtrop and Mennen (1982) for calm water resistance, STawave-1 (ITTC 2014) for R_{AW}, 15% sea margin for power sizing

One can recognize that we have not used any advanced analysis method and our design experience data can be termed (very) rough. It is therefore easy to come up with more accurate analysis methods or better data. The point here is not to propose any specific analysis method or design data, but rather to see them as a complementary part for the synthesis model. Yet, more advanced methods will not fundamentally change the modules' interfaces. They may require a more detailed description of the hull form, but the function of a hull is still to provide a vertical force, stability and low resistance. The goal of these simplistic implementations is to focus on the most important decisions to be made ("major feature selection" according to *Andrews and Dicks (1997)* in the preliminary design phase.

Sizing and balancing can be triggered once our system topology is established, Figs.10 and 11. As outlined in Table II, the manual input for sizing is rather simple: The cargo system is directly sized according to our requirements specification; the hull requires a few main particulars; similarly, the structure. In order to size the remaining systems correspondingly, we can make use of van der Nat's idea of sizing functions which we assign to an abstract class's interface. For the propulsor slot, the methods 'sizeForEndurance(SailingLeg)' and 'sizeForPower(SailingLeg)' have thus been added to the class interface. The argument for both methods is a sailing leg, a concatenation of discrete events.

Since all systems communicate through the main bus in terms of weight, volume and COG, one can easily check the ship's balance after sizing and positioning the systems. That being said, we can position the objects before assigning a hull ('wrapping' strategy, *Andrews (1986)*) or place them inside a given envelope ('packing' strategy, *van Oers (2011)*). Those systems that rely on information of the hull (the propulsor with all connected systems), will not be able to size automatically until a hull is instantiated. If we alter or exchange the hull module, we can update the size of the propulsion-related systems directly. Most importantly, this procedure is responsive to changes in both requirements and system configuration. In order to synthesize diverse configurations, we can

- assign different input parameters to the same logical entity, see *van Oers (2011)*, for exploration of alternative arrangements)
- exchange the logical entity against another one (if compatible), keeping the overall topology equal
- change the logical system topology

For our illustrative case, we will stick to the same spatial concept and similar system topology, but exchange the diesel oil fuel tank against an ammonia fuel tank (option 2). The system topology and ship architecture of our configurations is depicted in Figs.10 and 11.

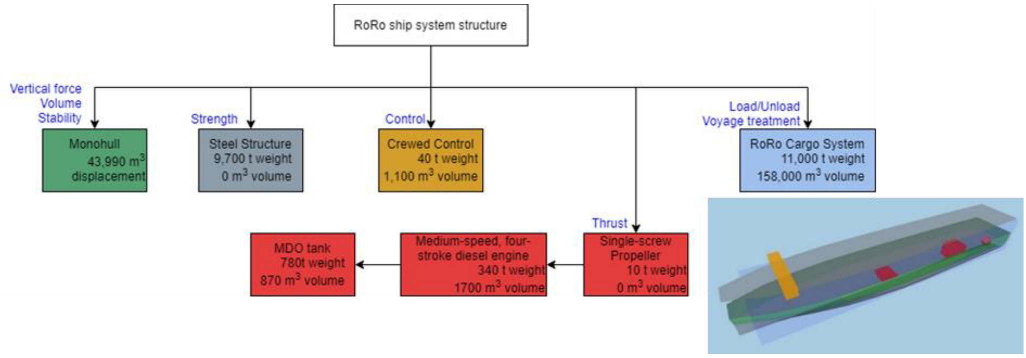


Fig.10: Systems engineering and architectural representation for MDO-driven configuration

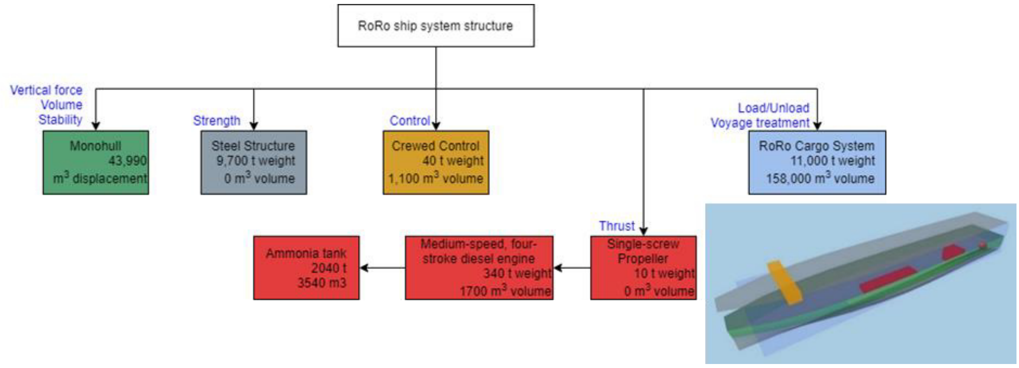


Fig.11: Systems engineering and architectural representation for ammonia-driven configuration

5.3 Simple analysis and evaluation

Once all systems are sized and the configuration is deemed to be balanced, we can analyze our system with a discrete event simulation. Not only is this method increasingly used to simulate more realistic conditions, *Sandvik et al. (2018)*, but also a necessity if we wish to analyze the response of wind- or wave-propelled configurations in the future, *van der Kolk et al. (2019)*. In order to create a sample concatenation of discrete events, we employ the wave scatter diagram, *DNVGL (2018)*, and divide the voyage into discrete events that represent the proportional time spent in each sea state. This is most likely is not a realistic voyage simulation, as a captain would certainly avoid extreme sea states and will alter the route along the way. We shall only use it for our simple illustration.

Our generated sample sailing leg from Rotterdam to Halifax contains approximately 2500 discrete events. The complete sailing leg is handed over to the ship that will execute the voyage and forward information to its sub-modules. The ship controls communication between its slot modules which themselves can communicate with their corresponding inputs, outputs and submodules: For each discrete event, the ship requests the hull to compute its resistance. The propulsor slot will then receive this information and request required rotational power from the engine etc. Throughout the course of discrete events, all modules can post relevant information, such as instantaneous power, fuel consumption or CO2 emissions.

Table III shows a compilation of posted data for one voyage in our illustrative design case.

Table III: Compiled results for one voyage

	economics			environmental impact	
ship configuration	crew costs [USD]	fuel costs [USD]	total costs [USD]	consumed fuel [t]	tank-to-wake CO2 emissions [t]
MDO-driven	91 000	209 000	300 000	700	2 240
ammonia-driven	91 000	639 000	730 000	1 600	0

With our rough and simplified experience data in mind, we clearly cannot claim the produced data to be accurate. Nevertheless, we can see a clear trend: With today's fuel prices, ammonia is not likely to the preferred economical choice. The cost relations indicate similar magnitudes as found by *de Vries (2019)* for today's fuel prices. On the other hand, if we limited ourselves to these two options only, ammonia would be the only viable way to reduce tank-to-wake emissions. For this reason, order-of-magnitude estimations are likely to be sufficient in the preliminary design phase. With a computational time well below 0.1s, we may consider the effort to see the implications of our decisions appropriate.

Our goal is not to argue in favor or against ammonia- or MDO-propelled ships here. We only use these technologies to highlight the need of a quick ship synthesis model as a necessity for a wide exploration in combination with a holistic analysis to find truly optimal solutions – or rather dismiss inferior ones before spending many resources in subsequent design stages. If we wish to reduce emissions significantly, we need to be able to predict their magnitudes at least approximately from the very beginning of the design phase.

Getting back to our illustrative case, one may justifiably raise the question 'what will happen if we were obliged to pay a certain carbon tax and ammonia prices drop significantly?'. In such a scenario, an ammonia-propelled option could come within reach. ‘But what if we relaxed our speed requirement, would that render a wind-powered ship feasible? Alternatively, what if we retrofit the vessel in 8 years from now? What would be the most energy-efficient solutions if we considered different synthetic e-fuels?' This discussion directly relates to the process of requirements elucidation, *Andrews (2011),* and is one that will likely be required for future-proof ships. We subscribe to *van Oers' (2011)* notion, that the feedback time between making a decision and seeing its implications needs to be as short as possible. Our modular synthesis model shall help to predict the implications of our decisions. It is responsive to changes in requirements and choice of systems and can thus support the preliminary, explorative design phase of low-emission ships.

6. Conclusion

By reviewing a set of ship synthesis models, we have seen the difficulty of efficiently and systematically synthesizing low-emission ships. Hence the need for a more flexible yet systematic approach to investigate the various options for low-emission shipping. Our proposed modular synthesis model in many ways resembles ideas of established synthesis models; most importantly SBSD and the DBB methodology. In addition to these models, our proposed synthesis model formalizes the mapping from functions to logical systems as component swapping modularity and the interaction between different systems as combinatorial modularity. Scalable modules eventually map logical systems to form. These means enable us to flexibly synthesize a wide range of ship system configurations.

To make appropriate decisions, the designer needs to know their implications on the specific design task, *van Oers (2011).* Coupled to a discrete event analysis, our model can predict the consequences of decisions within short time (0.1s). By supporting such direct feedback on decision implications, the model can serve as a conceptual synthesis platform to not only configure different systems, but also elucidate requirements - potentially in an interactive way. Nevertheless, the proposed synthesis model is far away from a describing a complete design model. At best, it could be a small brick within a larger, holistic design process. We thus foresee different research directions for the future:

- Refining the module implementation: Naturally, a balance between accuracy and computational speed needs to be sought. The simulation time indicates that a slight balance shift towards accuracy is reasonable and advantageous to create more believable solutions.
- Adding more logical systems: A necessity if we wish to synthesize more configurations to get closer to global optimum solutions. With a larger component library, coupling to a guided search algorithm, as presented by *van Oers (2011)*, becomes interesting.
- Application to different ship missions: The methodology has been illustrated for a RoRo cargo ship mission. Its applicability and use with different functional breakdowns still needs to be proven.
- A holistic life-cycle perspective: As *Papanikolaou (2010)* argues, a life-cycle perspective is required to understand the full consequences of each design. Future uncertainty could be integrated by means of scenarios.
- Retrofittability and modularity: With a holistic life-cycle perspective in place, we could investigate the impact of changes along the ship's lifetime, *Rehn et al. (2018)*. A relevant, exemplary question is 'should we equip the ship with physical modularity to enable exchanging the power system for instance?'
- Design process integration: Given that we had the ability to synthesize and analyze different ship configurations in different scenarios, how can we best use this in the design process involving different stakeholders? A combination with an interactive evaluation, *Duchateau (2016), Calleya et al. (2016)*, is a promising approach.

We recognize the long way ahead and at the same time acknowledge that fundamental research on most the above-mentioned topics has already been undertaken. For the future, we thus wish to build upon this research and integrate its concepts into a future-proof design process. Being a prescriptive design methodology, we can expect our presented synthesis approach to face obstacles and undergo alterations when applied to real-world problems. We thus appreciate future case studies to correct, adapt and expand the proposed methodology and continuously learn from practitioners.

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Main Paper 2

System alternatives for modular, zero-emission high-speed ferries
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System alternatives for modular, zero-emission high-speed ferries

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Low emission requirements exert increasing influence upon ship design. The large variety of technological options makes selecting systems during the conceptual design phase a difficult endeavor. To compare different solutions, we need to be able to exchange individual systems and directly evaluate their impact on the design's economic and environmental performance. Based on the idea of model-based systems engineering, we present a modular synthesis approach for ship systems. The modules are coupled to a discrete event simulation and allow for a case-based assessment of system configurations. We apply this method to a high-speed passenger ferry and show how it can provide decision support for hydrogen- and battery-based system architectures.

KEY WORDS: modular design; low emission; model-based systems engineering; discrete event simulation; system architecture

INTRODUCTION

Global warming and the threat of climate change require a rapid rethink in many industry sectors. Shipbuilding and the transport industry are also affected, as large quantities of greenhouse gases (GHG) are emitted by these sectors. Passenger ships produce a relevant amount of GHG emissions and are part of a public transport network in many cities. In Stavanger, one use case within the TrAM-Project, the few passenger ferries in use generate about the same quantity of the CO_2 emissions as public buses (Dahle 2020) in Norway. Passenger ferries however only cover about 10 % of passenger kilometers, while buses account for 90 % of passenger kilometers in public transport. It is therefore important to significantly reduce emissions from passenger ferries, as they disproportionately contribute to GHG emissions seen from a person-mile perspective (Dahle 2020). With the first cities planning emissions zones similar to those in place for road transportation, reducing ship emissions is no longer just a moral obligation. It is a concrete requirement that calls for direct action. At the time of the TrAM project proposal there were no feasible alternatives to fossil-powered ferries. Hence the need for developing cost-efficient, low-emission solutions for this transportation task.

Bouman et al. (2017) examined the potential for reducing greenhouse gas emissions in the shipping industry. The outlined CO_2 reduction potential for individual measures shows large variances and applies to shipping in general. To provide better decision-support for a specific design case, the yield and cost-efficiency of individual measures needs to be quantified more precisely. In this paper, we aim to study effects of system alternatives based on a modular design method with the example of the TrAM Stavanger use case. In the light of emission reduction requirements, we will focus on specific powering and fuel options.

PROBLEM ANALYSIS

Ship design is highly complex and involves great effort (Papanikolaou 2014). Product development in shipbuilding is mainly characterized by complex product structures and unique or small series production (Hoffmann 2017). Ship design approaches can be classified according to their novelty, ranging from simple base ship adaptions to radical inventions.

Revolutionary ships that demonstrate the first-time use of a technology are usually developed based on research projects as the risk is too high for individual companies. The research projects are long-planned and sometimes funded by public institutions. Due to the required rapid exchange of conventional against low-emission high speed ferries, establishing a research project for each individual use case does not seem feasible.

As an alternative to research projects, cooperation between the shipowner and shipyard are common. The aim of this cooperation is usually not only the design, but the conclusion of a contract and the construction of the ship. The focus therefore is on economic aspects and innovations play a subordinate role (Vossen et al. 2013). The design spiral (Evans 1959) presents an iterative, sequential model of the ship design process and is often referred as the general procedure when designing ships. It indicates a progression through conceptual, preliminary, contract and detailed design stages. To keep the risk low and to comply with the customer's economic ideas, the developer usually uses reference data from comparable, proven ship designs. Due to the lack of comparable ships for low emission vessels in inland waterways (Hekkenberg 2010), using the design spiral as a conceptual design process does not seem to be viable for enabling the wide use of low emission ships.

Calleya (2014) presents a model for quantifying the yield of individual measures for a given design. Requiring detailed solutions being developed for each individual case results in high development costs and time expenditure before a comparison is possible.

A method is needed that allows rapid generation and comparison of solution alternatives before progressing into time consuming design stages.

Exchanging a few systems of a ship can have large repercussions for its physical structure. This is particularly difficult when considering new energy storage technologies, like hydrogen tanks or batteries, which can have a major impact on the weight of the vessel. Figure 1 illustrates this problem, which is also indicated by the design spiral.

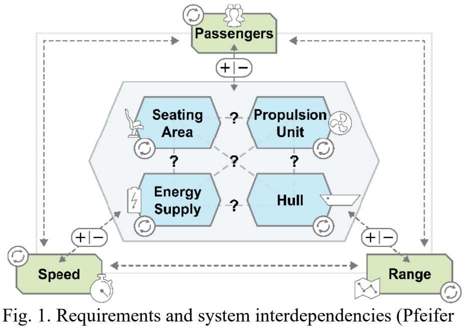

Fig. 1. Requirements and system interdependencies (Pfeifer et al. (2020)

Our method needs to capture these dependencies. However, decisions in the conceptual design phase comprise more than merely balancing a ship: Conceptual design is about building up functional architectures which can be embodied by systems. Our method aims to address these decisions and make them explicit.

In order to capture both, the dependencies and the important decisions, we approach the problem from a model-based systems engineering perspective.

STATE OF THE ART

The following section gives an overview of fields of science relevant to the method.

Model-based Systems Engineering (MBSE)

Model-Based Systems Engineering (MBSE) refers to the concept of a consistent description and analysis of the system to be developed based on models, from the early phase of conceptual design throughout the entire product life cycle. The system model is the superordinate system. This consists of partial models, which reflect different ways of looking at a system. The system model thus reflects the requirements definition and the conception. The goal of model-based system engineering is to take the step from a document-centered to a model-based design approach. Three aspects are mentioned in the literature that should contribute to a uniform understanding among the disciplines involved (Alt 2012, Kaiser 2013): requirements, structure and behavior of the system.

A system model consists of the modelling language, a modelling method and a modelling software. With these three components, MBSE leads to effective and efficient use in companies.

The modelling language leads to a formalization of content across different disciplines. A modelling language is defined by its syntax and semantics. Modelling languages can be, for example, SysML or CONSENS (Gausemeier et al. 2019). These model constructs are defined into a meta-model. This is a higher-level set of rules that defines the elements and structure of the modelling language. The modelling method determines the modelling language and specifies how detailed which information is to be considered in the system model at which point in time. The result is then the system model represented by linking different partial diagrams of the system specification. A tool is needed to create the system model, manage different versions and allow evaluation. Therefore, the tool is often software-based. The software support ensures a computer-aided evaluation of the system model. In practice, software-supported modelling is preceded by a workshop in which interdisciplinary teams collect relevant information on a whiteboard with the help of prepared cards that act as template for each element.

Logical Modularization

In order to generate and finally evaluate different options efficiently it is desirable to use the same base-model and adapt it to the use case. Generating a new model for each technology alternative is to time consuming and leads to results that are not direct comparable. A common approach to work with complex systems that have changing functions and systems while still allowing a degree of standardization and keeping the functional principle is modularization. By defining a modular ship architecture on a logical level, we can thus reuse partial models and exchanges others as required by the change in the evolving functional structure.

The automotive and aviation sector are of particular interest when discussing existing modularization methods, as those are widespread in these industries and the general function of the product (transporting people) is similar. The methods allow using the same base product and adapting it to the specific requirements of an individual customer in defined boundaries. At the same time, the reuse of modules allows shortening development and production times. The overall objective is to reduce the internal variety while enlarging the variety from a customer point of view.

Well-known approaches are based on linking partial models from requirements to functions and from functions to entities. Depending on the method, the final entities are described on a physical level or as an intermediate logical element (e.g. Esdras and Liscouet-Hanke 2015). The connections between these different partial models are often visualized with help of tree diagrams (Göpfert 1998) or matrices (Lindemann et al. 2009). The most effective technique to identify connections between requirements and physical elements generally depends on the product and modularization target. Being able to identify and cluster these connections, one can attempt to define modules which are independently exchangeable if the initial requirement changes.

As for ships, we generally see a large number of system options, many of which serve similar functions: e.g. both a battery and a fuel cell may supply electric power, each with its very own characteristics and subsequent requirements.

Discrete Event Simulation

Discrete event simulation is a computational technique for system simulation under time-varying conditions. The long-term time horizon to be simulated is divided into discrete entities. The division can be done in a dynamic or quasi-static fashion. Applied to the simulation of ship voyages, the time horizon to be simulated is the operational profile, consisting of weather conditions and ship speed requirements. A quasi-static discrete event simulation, neglecting the transient phases in the operational profile, has shown to be a fair compromise between required computing power and accuracy for ocean-going ships (Sandvik et al. 2018). Thanks to a complete description of weather conditions, wind-assist propulsion technologies, which gain interest for commercial zero-emission vessels, can be investigated as well (van der Kolk et al. 2019).

METHODOLOGICAL APPROACH AND VALIDATION

The following section presents our approach to generate and evaluate system alternatives based on a modular ship design for high-speed vessels. The validation is based on the Stavanger use case of the TrAM project.

Working Principles and Functions

Our logical modules are intended to represent working principles (Pahl et al. 2007). That is, they do not represent a concrete physical system per se, but instead a principle solution concept for a certain function. For mechanical systems, such working principles have been collected in numerous design catalogs which can be combined into working structures. We see two challenges when applying this approach to ships: First, the working principles must necessarily comprise and be combinable across multiple domains (electric, mechanic, hydrodynamic etc.). Second, the combination and evaluation of suitable working principles from a static catalog is difficult as their respective suitability depends on the design case at hand.

Our logical modules aim to remedy the first issue by assigning functional interfaces to modules (e.g. supply Hydrogen) and an abstraction of existing solutions similar to system-based ship design (Levander 1991). The second challenge is tackled by automatic sizing procedures assigned to module interfaces, combined with their ability to process discrete events (Lagemann and Erikstad 2020). That feature renders the logical modules responsive to overall requirements, relieves the designer from manual sizing and enables a case-based evaluation. Moving away from static design catalogs to dynamic models thus reflects one of the main principles of MBSE.

Development of Modules

The definition of the logical modules in the previous section focuses on the simulation of the different ship variants. In this chapter we describe the development of a modular ship class that leads into physical modules.

Our method is divided in three phases: Requirements, modular platform design and modular system design. In the requirements phase all information needed for the development of the ship class are gathered and structured. To cover all aspects relevant for the ship class several edge use cases are considered which then also describe the boundary conditions of the ship class in speed, range and payload. As a result, a model of different aspects describing the requirements is generated.

The second phase of the method focuses on identifying similarities between the ships that need to be designed for the defined use cases. This is based on the RFLP procedure where the requirements (R) are the input from the first phase and lead to the development of the function (F) needed to fulfill the requirements. Those functions are then fulfilled by logical modules (L). Now the use case-specific manifestation of each logical module in a physical module (P) is carried out. The resulting physical modules are compared and sorted into categories depending on their similarity. Based on this result the product architecture, that can cover all use cases, is defined. For the TrAM project the shared platform modules that have been identified are:

- Hull module, covering the main deck and everything bellow
- Bridge module, including the wheelhouse and possible crew areas
- Supply module, consisting of the energy storage and electrical systems
- Superstructure module, covering the seating areas and roof structure

The third step of the method adapts the general procedure of the second phase but focuses on the systems inside of the defined platform modules. As result, the systems are categorized into e.g. shared systems that are used in all use cases of the ship class or individual systems which always fulfil a similar function but are individually designed for each use case.

Implementation of Modules

By implementation we refer to the inner structure, i.e. the working principle, of a logical module. Having defined clear functional interfaces between modules, their behavior depends on their respective implementation. Table 1 provides a brief overview of the main methods and assumptions that are used for each module's implementation.

As can be seen from Table 1, we have used system-based regression coefficients wherever possible. The rationale for implementing each module was 'as few and generic parameters as possible, but as many as necessary for capturing the working principle sufficiently'. That shall ensure we merely capture the working principle of each logical module, without the specifics of any embodiment solution. Our aim is estimating the ship's environmental performance in the concept design phase, hence we have given the hydrodynamic modules slightly more attention.

The generic software architecture used for the modules' implementation is described by Lagemann and Erikstad (2020). For this case study, the above modules were added, combined with additional, module-specific interfaces such as 'supply pure hydrogen'. The configuration is visualized by means of the vessel.js open-source library (Gaspar 2018).

Generating System Alternatives

We generate two alternative configurations for this case study: The first one is based purely on a battery-electric propulsion and the second one on compressed hydrogen with a proton-exchange membrane fuel cell (PEM FC). While the logical architectures differ, the arrangements of both configurations are kept similar. Figures 2 and 3 depict the logical architectures of both configurations. Note that although hydrogen is the main energy source for the PEM FC configuration, a buffer battery is required for peak load shaving.

Table 1. Methods and assumptions for module implementations

Module slot	selected logical module	methods and assumptions
Payload	'Jet seat' type accommodation	120 kg/m^2, 100 kg/person, 30 m^2 service areas
Control	Bridge	5 t, 250 kg/m^2
Hull	Round-bilge catamaran hull	Parametric description based on Sahoo et al. 2007 and Sahoo et al. 2008, air resistance coefficient
Structure	Small craft catamaran structure	Grubišić (2008) adapted to catamarans
Propulsor	Twin propeller proxy	numerical proxy for combining any two propellers
Generic	Fixed-pitch propeller	B-Series (Oosterveld and van Oossanen 1975), use max. available diameter
	Electric motor	1.6 kW/kg, 500 kW/m^3, 96% efficiency (E-ferry 2020)
	Lithium-ion battery	0.076 kWh/kg, 676 kg/m^3, discharge rate 3 C (based on Corvus Energy 2019), 95% charging efficiency
	Proton Exchange Membrane Fuel Cell	1.7 kg/kW, 330 kW/m^3 (based on PowerCellution 2021), lower bound efficiency 45%
	Type IV hydrogen tank	Type IV compressed hydrogen tank, 700 bar, 0.6 kg/kWh, 1350 kWh/m^3 (based on Taccani et al. 2020)

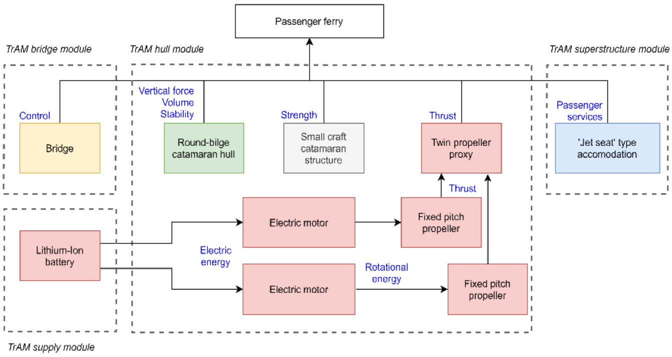

Fig. 2. Logical architecture for the battery-electric configuration

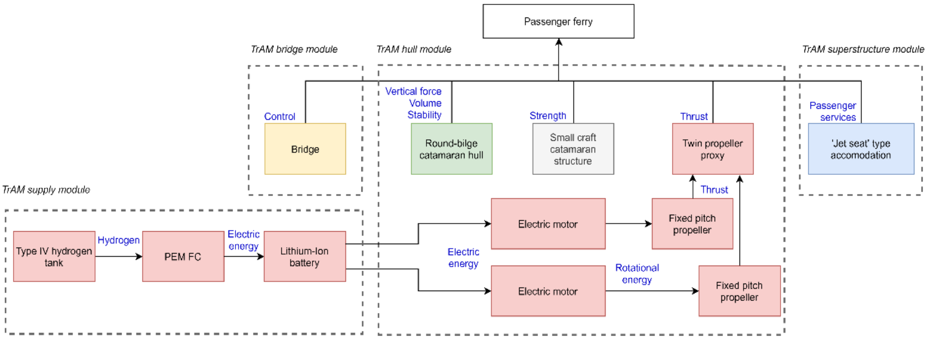

Fig. 3. Logical architecture for the hydrogen-electric configuration

Within the modular conceptual design method, the designer mainly needs to select a logical module, connect it into an overall logical architecture and assign a spatial position. The size of systems is determined based on input requirements propagating through the logical architecture. There is no automatic balancing procedure due to the targeted solution-neutrality. The designer hence needs to align the demand and supply of stability and buoyancy manually to an appropriate level. The few required manual decisions with respect to the modules' inner parameters correspond to the battery's desired lowest state of charge or the choice of structural material for instance. That is, they represent important decisions which affect the concept of configuration. By assigning a spatial position to the modules, we can visualize an approximate arrangement for the configurations (Figure 4).

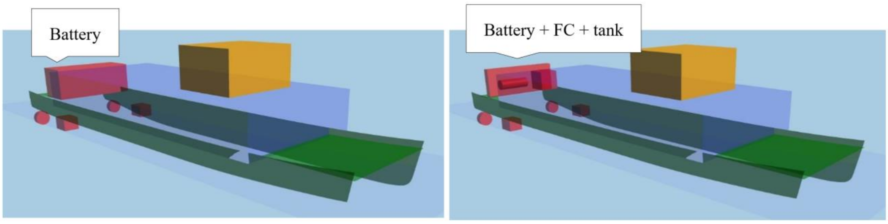

Fig. 4. Arrangements of the battery-electric (left) and single roundtrip hydrogen-electric (right) configuration. Module colors as in Figures 2 and 3

When balancing the buoyancy and weight of the two configurations, we apply a weight margin of about 10%. The hull thus needs to provide more buoyancy than required as we both neglected many auxiliary sub-systems as well as used approximate preliminary formulas. Nevertheless, we clearly see the effects of the spiral dependencies indicated by Evans (1959): exchanging a battery for a fuel cell results in less weight utilization on the same hull. Decreasing, e.g., the demi-hull beam, leads to both less structural weight as well as less resistance, which again requires less power and thereby less system weight. Except for the automated sizing procedures, there is no 'black box'-fashion naval architecture. All decisions with respect to architecture and arrangement need to be made by the designer. The immediate exposure to the implications of these decisions shall help elucidating requirements interactively (Andrews 2011, van Oers 2011).

One example of these requirements is the ship's range: Figure 4 shows both configurations for the same range, that is 21 nm. As for the hydrogen-based configuration, one may prefer bunkering fuel once per day rather than once per roundtrip. Imposing this requirement results in a vessel with similar displacement as the battery-electric configuration. Such decisions are affecting the complete route operation as e.g. more ships are needed for the same service or less cycles can be made per day. From an ecological point of view, it is preferable to only carry as much energy as needed for one roundtrip to minimize displacement. In contrast, the economical preferable decision can be to invest in only one ship with a larger range, leading to higher energy expenditures but lower maintenance and crew costs.

As can be seen from Figures 4 and 5, the arrangement would generally provide sufficient deck area for the batteries and hydrogen tanks. The arrangement sheds light on important safety requirements related to hydrogen and batteries, in particular zoning of hazardous areas. The proposed aft positioning of the hazardous systems (Figure 5) has only one clear boundary in common with passenger areas and therefore may be preferred over a more distributed arrangement. Each of the hazardous systems requires a safety compartment separated by A-60 bulkheads. Ventilation and potential pressure-release/burst walls do not interfere with passenger spaces. The consideration of such aspects is necessary to identify viable system alternatives. For a balanced trim condition, it is desirable to move the relatively heavy power systems further amidships. By computing the center of gravity, the modular design approach can help identifying such conflicting requirements early. Deciding how to resolve them is eventually left to the designer but supported by shifting modules interactively. The TrAM demonstrator as currently under construction hence partly wraps the passenger areas around the batteries.

Evaluation of system alternatives

Once configured, the two alternatives can be evaluated by means of the discrete event simulation. We use exemplary weather data for one day of operation in the Stavanger area. The timespan of 16 hours operation per day is discretized into 323 discrete events which are sequentially processed by each configuration. With the approximate semi-empirical methods referred to in Table 1, computational time for one day of operation is well below one second. Each module posts relevant information (e.g. fuel consumption) throughout the simulation.

Hydrogen production is commonly denoted as 'green' (electrolysis from renewable electricity), 'blue' (steam methane reforming with carbon capture and storage) and 'grey' (steam methane reforming without carbon capture and storage). Out of these both green and blue hydrogen offer significant GHG reductions, albeit not (yet) to zero in practice: blue hydrogen suffers from incomplete carbon capture, while green hydrogen by definition relies on the source of electricity. For our following analysis, we use the average emissions for electricity in the Stavanger area of 25 gCO_{2eq}/kWh (Tomorrow 2021). This is exceptionally low compared to other countries. The worldwide aggregate in 2013 was slightly above 500 gCO_{2eq}/kWh (Ang & Su 2016). For 'blue' hydrogen we assume 131 gCO_{2eq}/kWh (Noussan et al. 2021).

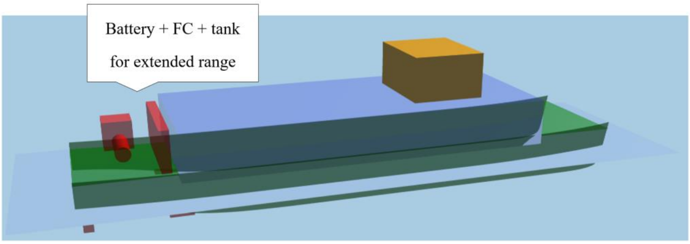

Fig. 5. Arrangement of the hydrogen-based configuration with one day range.

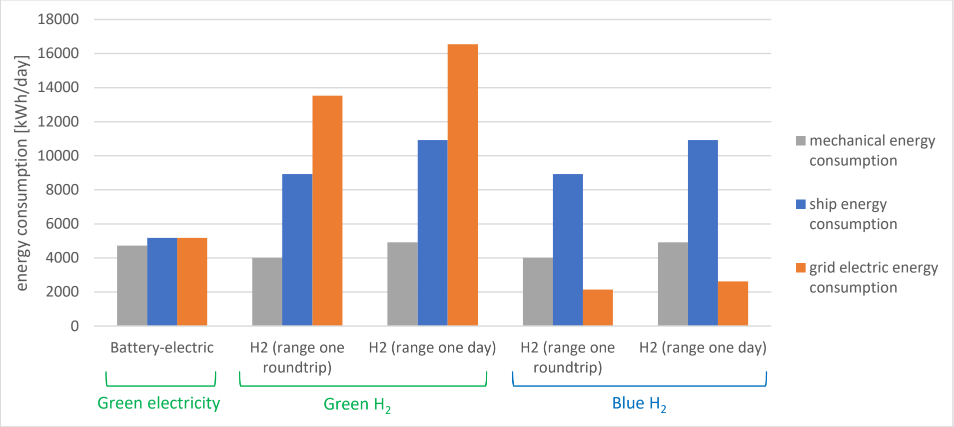

Fig. 6. Energy consumptions for all three configurations.

Figure 6 shows accumulated energy consumptions over one day for each of the three configurations. The mechanical energy consumption corresponds to the energy required by the propeller (brake power). Ship energy consumption denotes the energy that is delivered from shore to ship, either in the form of electric energy or chemical energy. We also plot the total grid electric energy consumption attributed to hydrogen production, assuming 66% efficiency for electrolysis and compression and 8 kWh/kgH_2 (Lloyd's Register and UMAS 2020).

For our further analysis we assume an electricity price of 0.1 €/kWh. Leaving aside costs for hydrogen storage and electrolysis infrastructure, this electricity price corresponds to roughly 5€/kgH_2 for green hydrogen. For blue hydrogen, we assume a price of 2€/kgH_2 (Bartlett and Krupnick 2020). Figure 7 shows the difference in energy or fuel costs over a period of 10 years. Due to greater overall system efficiency, the fuel bill for the battery-electric configuration amounts to approximately 40% of the fuel costs for the single-roundtrip H_2 configuration. The Diesel benchmark case is calculated with a modern diesel engine that would be the alternative power source in a new vessel. Based on data from engine manufactures 199g fuel per kWh (MAN 2019) are needed which costs 1.38€/L in the Stavanger area. The engine efficiency for the Diesel benchmark can hence be considered as a best-case scenario.

We have refrained from including manufacturing costs due to the difficulty of finding prices that are applicable to the marine

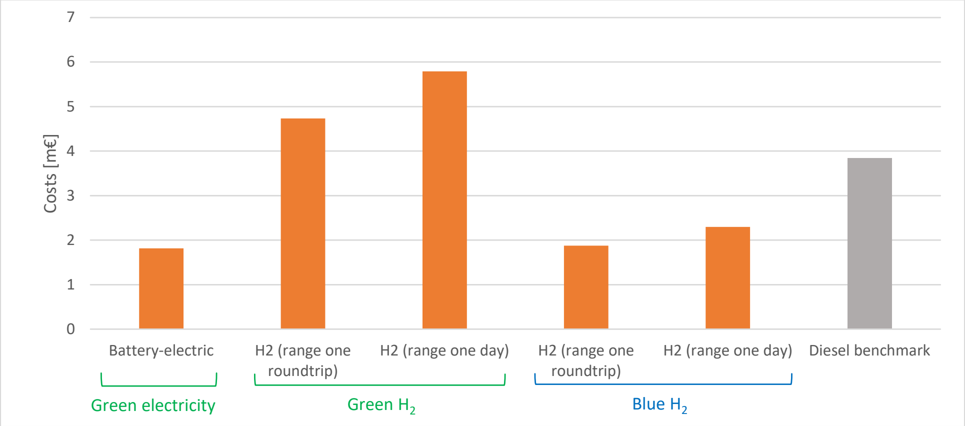

Fig. 7. Estimated energy costs over 10 years.

sector. Prices from literature did by far not reflect the real system procurement costs, which we had access to within this project. Finding reasonable price estimates applicable to the marine environment thus seems to be an issue for new, low-emission technologies, even when leaving aside the costs for system integration.

In contrast, the data for estimating GHG emissions from system manufacturing seemed more consistent. We have used the data shown in Table 2 for our comparison.

Table 2. GWP coefficients for manufacturing phase for each system

Module	unit	coefficient	source
Lio-Ion battery	$kgCO_{2eq}/kWh$	72.9	Ellingsen et al. (2014)
Aluminum hull	$kgCO_{2eq}/kg$	18	World Aluminum (2017)
PEM FC	$kgCO_{2eq}/kW$	112	Stropnik (2019)
Type IV hydrogen tank	$kgCO_{2eq}/kWh$	0.8	Fraunhofer ISE (2019)

These data do not allow a complete estimate of GHG emissions from the manufacturing phase, as not all ship systems are included. They do however allow estimating the differences between configurations which is of main interest when selecting a concept. To further simplify the assessment, we assume a lifetime of 10 years to account for the generally shorter lifetime of batteries and FCs compared to traditional drivetrains. For the diesel benchmark the emissions of the manufacturing phase are not included due to inconsistent data. It can be assumed that the manufacturing emissions are lower than for all other cases though.

CONCLUSION AND DISCUSSION

Applying a design method based on logical modules to the TrAM ferry enabled quickly configuring, exploring and analyzing different system architectures. With the battery-electric solution being the most economic and ecological option compared to the four hydrogen configurations, the final evaluation of alternatives supports the battery-electric choice for the TrAM Stavanger use case. This conclusion may change for different operational requirements (e.g. range or schedule).

The accelerated concept screening process from generation to final evaluation seems to support our method that is based on architectural logical modules. The application of the method was not without challenges though: Our general-purpose hydrodynamic method has shown to give very conservative resistance estimates compared to the thoroughly optimized hull design. Our aim, however, is not to argue in favor or against of specific sub-methods, but rather to evaluate the overarching design method. The method shall facilitate preliminary concept screening rather than optimization. As such, it seems to provide useful decision support in early design phases.

The discussion on the range and operating profile for a potential hydrogen-powered configuration exemplifies the merit of our method: This discussion is likely to be required for a successful extension of system boundaries (Hagen and Grimstad 2010). To engage in such discussions, the designer needs to be able to discuss the requirements, such as infrastructure and operational profile, in the presence of different conceptual solutions. If each of these solutions features potentially innovative components in the form of logical modules, the requirements can be thoroughly elucidated to identify low-emission solutions on a transport system level.

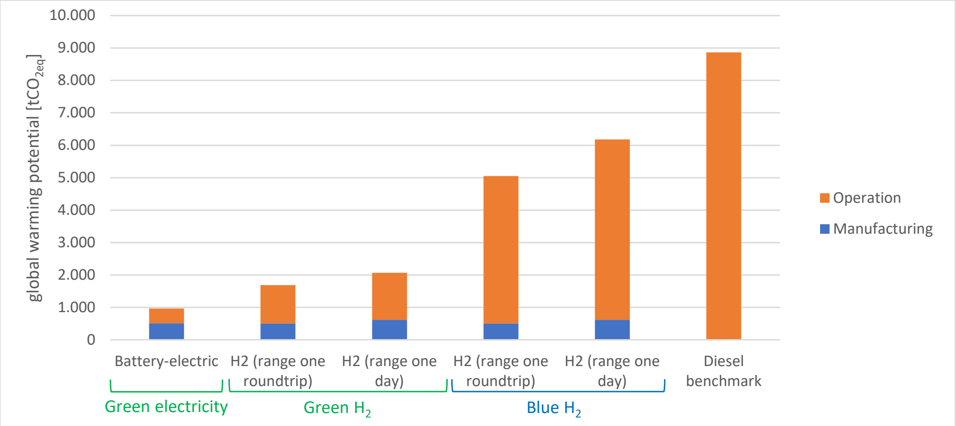

Fig. 8. Estimated GHG emissions from manufacturing and operation over 10 years.

Although our design method is primarily based on logical thought modules, it can additionally provide a useful starting point for physical modularization: Knowing that a hydrogen-powered vessel with extended range would have a displacement similar to the battery-powered, short range solution, one may think about using the Stavanger ferry as a product platform for different use cases. If the physical architecture then allowed for variants either in the building or operational phase, the platform may be configured by exchanging the battery for fuel cells.

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CREDIT AUTHOR CONTRIBUTION

Benjamin Lagemann: Conceptualization, Methodology, Software, Writing – Original Draft, Visualization; **Tobias Seidenberg:** Conceptualization, Methodology, Validation, Writing – Original Draft; **Christoph Jürgenhake:** Project administration, Supervision, Writing - Review & Editing; **Stein Ove Erikstad:** Supervision; **Roman Dumitrescu:** Supervision

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Main Paper 3

Optimal ship lifetime fuel and power system selection
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Optimal ship lifetime fuel and power system selection

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ABSTRACT

Alternative fuels and fuel-flexible ships are often seen as promising solutions for achieving significant greenhouse gas reductions in shipping. We formulate the selection of alternative fuels and corresponding ship power systems as a bi-objective integer optimization problem. We apply our model to a Supramax Dry-bulker and solve it for a lower bound price scenario including a carbon tax. Within this setting, the question whether bio-fuels will be available to shipping has significant effect on the lifetime costs. For the given scenario and case study ship, our model identifies LNG as a robust power system choice today for a broad range of GHG reduction ambitions. For high GHG reduction ambitions, a retrofit to ammonia, produced from renewable electricity, appears to be the most cost-effective option. While these findings are case-specific, the model may be applied to a broad range of cargo ships.

1. Introduction

In April 2018, the International Maritime Organization (IMO, 2018) adopted a strategic plan to align with the Paris Agreement (United Nations, 2015) temperature goals to reduce annual greenhouse gas (GHG) emissions from international shipping. This strategy can be summarized in three points. First, to reduce the carbon intensity of ships through further reductions of the energy efficiency design index (EEDI) for new ships. Second, to reduce CO_2 emissions per transport work by at least 40% by 2030 and pursue efforts for reducing them by 70% by 2050 compared with 2008. Third, to peak international shipping's GHG emissions as soon as possible and to reduce annual GHG emissions by at least 50% by 2050 compared to 2008.

These global preliminary ambitions however are not without debate. Single states or unions may set out additional goals, such as the EU aiming to achieve carbon-neutrality by 2050 (European Commission, 2019; European Community Shipowners' Association). The translation of shipping's global ambition levels into single ship requirements is an ongoing discussion (IMO MEPC, 2021). Consensus on both fleet and ship emission ambitions is dependent not only on technical issues, but further complicated by political debates (Psaraftis and Kontovas, 2020; Psaraftis and Kontovas, 2021). Moreover, there are different pathways conceivable for how shipping's energy demand can be met in the future (Vergara et al., 2012; Smith, 2012; Lindstad and Eskeland, 2016). The uncertainties with respect to both ambitions and energy pathways are exemplified by DNV GL's various scenarios in its Maritime Forecast to 2050 (DNV GL, 2020) or future price range predictions for alternative fuels (Lloyd's Register and UMAS, 2020).

For a ship designer, aiming to develop a competitive ship, there is hence a large uncertainty associated with exogenous and time-

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dependent factors. These factors can be directly linked to the contextual and temporal aspects of ship design, respectively (Gaspar et al., 2012). The exogenous uncertainties need to be handled in addition to the simultaneously increasing structural and behavioral complexities that stem from new, emission-reducing onboard technologies.

Calleya (2014) presents a 'ship impact model' to assess the impact of technical and operational carbon-reducing measures. The model can be applied to a fully developed ship design and represents a leap forward in tackling the behavioral complexities, i.e. the performance assessment of emissions-reducing technologies. Lindstad and Bø (2018) investigate combinations of different engine setups, batteries, alternative fuels, and hull forms to identify EEDI-compliant solutions. The model provides a full evaluation of costs and emissions as functions of vessel operation, abatement option and fuel prices.

Solem et al. (2015), Balland et al. (2013) and Gaspar et al. (2015) present several decision support models for air emission reductions. These models consider the uncertainty and time-dependency of target emission levels, but do not include GHG reduction measures to the extend required by neither IMO nor EU ambitions. In turn, Korberg et al. (2021) investigate a large number of low-emission options, but without explicitly considering retrofits.

Rehn (2018) investigates ways for considering uncertainty in ship design. Generally, this can be done deterministically or stochastically (Erikstad and Rehn, 2015). For ship design, retrofittability has shown to be a promising strategy for mitigating the consequences of uncertainty. This has been shown for both merchant (Buxton and Stephenson, 2001) and naval ships (Andrews, 2001). Choi et al. (2018) find that a modular design can significantly ease system adaptability and retrofittability. However, retrofittability and modularity both come at a cost. Their trade-offs need to be carefully considered (Erikstad, 2019). DNV GL's Maritime Forecast to 2050 (DNV GL, 2020) takes a scenario-based approach to the alternative fuel selection problem. The model's focus is on a global fleet perspective. Similarly, Nair and Acciaro (2018) present a model for optimized fleet composition under economic and environmental constraints. The decisions and recommendations for a specific ship may thus differ. Moreover, only minor retrofits (switch between similar fuels) are considered.

To sum up, studies so far have focused on technical assessment of emission reduction measures (Calleya, 2014; DNV GL, 2019), the timing of air emission abatement options (Solem et al., 2015; Balland et al., 2013; Gaspar et al., 2015; Korberg et al., 2021) or alternative fuels on a fleet perspective (DNV GL, 2020; Vergara et al., 2012; Smith 2012, Nair and Acciaro, 2018). There seems to be a gap when it comes to analyzing a wide range of alternative fuel options from a ship perspective, considering contextual and temporal complexities in combination with changeability. Even though alternative fuels only represent a subset of the emission reduction options for shipping, they are estimated to have high abatement potential (up to 85% CO_2 reduction potential according to Bouman et al., 2017) and thus are of significant interest to ship designers today. This interest, particularly in power system retrofits, is backed by industry examples: The Spirit of British Columbia's retrofit (MarineLink, 2018) from very low sulphur fuel poil (VLSFO) to liquified natural gas (LNG) or the conversion of the Stena Germanica from heavy fuel oil (HFO) to Methanol (Naval Architect, 2015). Further, Maersk (2021) has recently announced to build dual-fuel ships running on both VLSFO and Methanol and ColorLine investigates conversions towards ammonia (Ammonia Energy Association, 2020).

The motivation for this study is to contribute to an individual ship's lifetime perspective on alternative fuel selection, taking into account potential retrofits. We see a gap when it comes to identifying such cost-efficient and robust solutions in a transparent manner. By assuming a certain lifetime that involves a fundamental change of the favored primary energy source from fossil-based to renewable electricity-based, we aim to answer the questions:

1. How would a transition from cheap fossil to cheap electric energy influence the optimal ship power system choice?
2. How do our here-and-now decision, i.e. what power system to invest in, change when considering a large variety of power systems, including retrofits, fuel options and different emission reduction ambitions?
3. Are retrofits included in the optimal solution?

We outline the problem in more detail in Section 2. Section 3 presents a mathematical bi-objective optimization model that shall provide decision support to the problem at hand. Section 4 describes the application and use of the same model to a case study. We conclude and highlight our findings in Section 5.

2. Problem description

Selecting among alternative fuels under uncertain ambitions and cost scenarios is not an easy endeavor. Not only do the exogenous uncertainties obscure a straight-forward solution. Even under known, but changing exogenous conditions, the decision problem is complex due to the ship's long lifetime and hence exposure to potentially very different exogenous conditions. The problem addressed in this paper is thus: "Given a known fuel price scenario, what are the best power system and fuel choices throughout the ship's lifetime with respect to costs and GHG emissions?". We refer to this problem as 'ship fuel and power system selection under certainty'. By certainty, we mean an assumed, known exogenous future fuel price scenario as well as carbon tax development. Approaching this as a compromise selection problem between emissions and costs over time, uncertain long-term ambition levels as seen by an individual ship can be accounted for when selecting compromises.

Our goal is to provide decision support for the selection among a wide range of alternative fuel options and power system options in the early ship design phase, while considering potential switches between power system options (retrofits). These options all come with different emissions and different costs, which change over time. A ship power system option here denotes all required onboard systems for the combustion of VLSFO or LNG for example. That is, machinery, tanks, piping and processing equipment where necessary shall be included in our definition of power system option. Compatibilities between fuel and power system options must be considered as well as their impact on the ship's payload carrying capacity. For a given power system option, switching between compatible fuels, e.g. from fossil LNG to electric LNG (e-LNG), represents an action with no switch cost. Retrofits, e.g. from VLSFO to Methanol, can be accounted for as switching between power system options, which comes at a certain cost. Note that we here refer to 'option' as the choice of fuel and power system at a discrete point in time. This definition is not far away from the term 'recourse options' (King and Wallace, 2012), apart from that we assume a single, deterministic future instead of a stochastic one. The potentially reduced cargo-carrying capacity compared to a baseline vessel, due to additional weight of lower density fuels and power systems, can lead to a loss in income. This potential loss needs to be taken into account, e.g. by means of a lost opportunity cost.

Our goal is to provide decision support for the initial ship investment as well as the choice of fuel, considering potential retrofits in response to changing exogenous conditions. Knowing that a specific retrofit would be worthwhile, a ship designer could design a vessel such that it is prepared for the later retrofit. For our problem, we assume a ship without any further retrofit preparations such as modular machinery or preparations for elongation. Such measures could reduce retrofit costs significantly. In order to evaluate, select and implement such technical options however, it is necessary to know what to prepare for in the first place, which shall be the focus of this study.

3. Model formulation

We start our model formulation by defining the notation and then describe our mathematical model.

Sets

Set	Description	Modeling comment
$\mathbb{T}$	set of discrete ***time periods***, indexed by t	discretization into 10 year periods for example, as for this study
$\mathbb{F}$	set of ***fuel options***, indexed by f	refers to main chemical composition and physical state
$\mathbb{S}$	set of pre-generated ***ship power system options*** for energy storage and power conversion, indexed by s	refers to a ship with an energy storage of a certain type and size, and a power converter of certain type and size

Parameters

Parameter	Description	Modeling comment
C^N_s	***newbuild cost*** of a ship with power system option s	
$C^R_{s'st}$	***retrofit cost*** from option s' to option s in time period t	
C^F_{ft}	***cost of fuel*** f in time period t	
C^{LO}_{st}	***lost opportunity cost*** of a ship with power system s per time period t	
B	***energy consumption*** per time period	assuming the fuel conversion efficiencies do not change over time, equidistant time periods
E^{WTT}_f	***well-to-tank emissions*** of fuel f per time unit	
E^{TTW}_f	***tank-to-wake emissions*** of fuel f per time unit	assuming tank-to-wake emissions do not change over time.
K_{fs}	1 if fuel f and power system s are ***compatible***, 0 otherwise	

Decision variables

x_{ft}	1 if ***fuel*** f is chosen at time t, 0 otherwise
y_{st}	1 if ***power system option*** s is chosen at time t, 0 otherwise

Auxiliary variables (implicit, required for linearization)

$r_{s'st}$	1 if retrofit is to be made from power system option s' to power system option s after period t, 0 otherwise

Objectives

We define our first objective of minimizing the total cost of ownership (TCO) as:

$$minTCO = \sum_{s\in\mathbb{S}}\left[\underbrace{C^N_s \cdot y_{s0}}_{building\ cost} + \sum_{t\in\mathbb{T}}\left(\underbrace{C^{LO}_{st} \cdot y_{st}}_{lost\ opportunity\ costs} + \sum_{f\in\mathbb{F}}\underbrace{B \cdot C^F_{ft} \cdot x_{ft}}_{fuel\ cost} + \sum_{s'\in\mathbb{S}}\underbrace{C^R_{s'st} \cdot r_{s'st}}_{retrofit\ cost}\right)\right] \tag{1}$$

A carbon tax could be included either explicitly in the cost function or be included in the fuel prices. We have chosen the latter for simplicity. The retrofit cost is generally dependent on the power system choice between to two consecutive periods. The purpose of the model identifying differences between solutions. Hence, we have not included pure operational expenditures (OPEX), such as manning, that would apply to all solutions. Within our model, we apply a linear formulation with help of the auxiliary variable r_{ist}

which is constrained by constraints (6)–(8).

Our second objective to be minimized is the global warming potential (GWP) accumulated throughout the entire ship lifetime:

$$minGWP = \sum_{t\in\mathbb{T}}\sum_{f\in\mathbb{F}} Bx_{ft}\left(E_f^{WTT} + E_f^{TTW}\right) \tag{2}$$

The energy consumption per time period can be estimated similar to Ji and El-Halwagi (2020).

subject to:

Constraints (3) and (4) ensure that precisely one fuel and one ship power system option are selected at any time:

$$\sum_{f\in\mathbb{F}} x_{ft} = 1 \quad \forall t \in \mathbb{T} \tag{3}$$

$$\sum_{s\in\mathbb{S}} y_{st} = 1 \quad \forall t \in \mathbb{T} \tag{4}$$

Constraints (5) make sure that fuel *f* and power system *s* can only be selected if they are compatible with each other:

$$x_{ft} + y_{st} \le 1 + K_{fs} \quad \forall t \in \mathbb{T},\ f \in \mathbb{F},\ s \in \mathbb{S} \tag{5}$$

Switching from a power system s' to another power system *s* in consecutive periods implies a retrofit. Our auxiliary retrofit variable r_{ist} are hence constrained by constraints (6)-(8).

$$y_{s'(t-1)} + y_{st} - 1 \le r_{s'st} \quad \forall s', s \in \mathbb{S},\ t \in \mathbb{T}\backslash\{0\} \tag{6}$$

$$y_{s'(t-1)} + y_{st} \ge 2r_{s'st} \quad \forall s', s \in \mathbb{S},\ t \in \mathbb{T}\backslash\{0\} \tag{7}$$

$$r_{s'st} = 0 \quad \forall s', s \in \mathbb{S},\ t = 0 \tag{8}$$

Constraints (9) and (10) ensure that our decision variables are binary variables.

$$x_{ft} \in \{0, 1\} \quad \forall f \in \mathbb{F},\ t \in \mathbb{T} \tag{9}$$

$$y_{st} \in \{0, 1\} \quad \forall s \in \mathbb{S},\ t \in \mathbb{T} \tag{10}$$

Additional constraints for allowed emissions, e.g. an energy efficiency existing ship index (EEXI), could be added to the problem. For this paper, we have deliberately not included such constraints for the sake of clarity and transparency of the model and its results.

The resulting model is a bi-objective binary programming model, which allows using a commercial solver for integer programming problems, such as Gurobi. In order to obtain a Pareto set of solutions, i.e. non-dominated solutions that represent a compromise between the two objectives, constraint (11) applies the epsilon-constraint method to the GWP objective:

$$GWP \le \varepsilon$$

The parameter ε is iteratively increased to the GWP of the cheapest solution found in the last iteration.

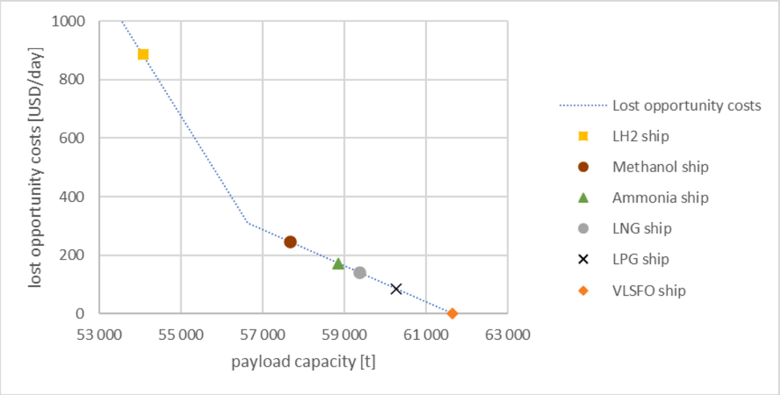

Fig. 1. Daily lost opportunity costs..
Source: own calculation

4. Case study

To test our model proposed in Section 3, we use as a case study a generic dry bulk Supramax vessel for which the ship power system and fuel selection is to be determined throughout the lifetime. A traditional Supramax vessel is designed for maximum cargo-carrying capacity within a maximum length of 200 m, a beam of 32.3 m (the old Panama Canal locks) and a draught of around 13.5 m. This generally yields a cargo capacity between 58,000–65,000 tons. The dry bulk cargo is typically transported in five cargo holds with four slewing cranes for independence of port loading facilities. Supramax bulk carriers constitute approximately 24% of the global dry bulk fleet (Bengtsson, 2018) and perform about 10% percent of the global transport work, measured in ton-miles. The following table shows the data of an exemplary vessel in the Supramax segment, which we use as our reference ship.

We start with a VLSFO ship as a reference and derive alternative ship power system options by replacing the diesel tanks by LNG, liquid hydrogen (LH2), as well as ammonia (NH3), methanol and liquified petrol gas (LPG). We account for the influence of additional fuel tank weight by means of relative factors derived from (Mestemaker, et al., 2020). That is, potential weight in excess of the baseline VLSFO tank configuration is accounted for as a loss of payload capacity (PLC). The loss of payload capacity is consequently converted into a lost opportunity cost C_{st}^{LO} by means of formula (12). Fig. 1 depicts the function values for each of the ship power options.

$$C_{st}^{LO} = \begin{cases} 10y\cdot 300d/y\cdot 13,000USD/d\cdot \dfrac{PLC_s - PLC_{VLSFO}\cdot 25\%}{5000t\cdot 25\% + PLC_{VLSFO}\cdot 90\%}, & PLC_s - PLC_{VLSFO} < 5000t \\ 10y\cdot 300d/y\cdot 13,000USD/d\cdot \dfrac{5000t\cdot 25\% + (PLC_s - PLC_{VLSFO} - 5000t)\cdot 90\%}{5000t\cdot 25\% + PLC_{VLSFO}\cdot 90\%}, & PLC_s - PLC_{VLSFO} \geq 5000t \end{cases} \tag{12}$$

The reasoning behind the lost opportunity cost is as follows: we assume an average utilization of 90% for the first 58,000 dwt and 25% utilization for the last 5,000 dwt. The charter rate of 13,000 USD/day is split proportionally and we assume a piecewise linear contribution to the charter rate. Any loss in charter rate due to additional tank weight contributes to the lost opportunity cost. For a fair comparison we keep speed and endurance constant for all options. In applying this rationale we neglect the influence of lower volumetric density of alternative fuel options. Bulk carriers are traditionally weight-driven ships and hence the designer may have a certain freedom when integrating larger volumes into the arrangement.

The key differences between the ship power system options s and their respective compatibilities K_{fs} to fuels f are listed in Table 2. As for the energy consumption B per time period, we assume the vessel is sailing at 60% of its maximum continuous rating power for 180 days annually.

Compressed hydrogen may be interesting to consider both from a power system as well as a fuel perspective. Compressing hydrogen instead of liquifying may offer less efficiency losses and hence cheaper production costs. Due to the high storage system costs (approx. 170 mUSD according to Rivard et al., 2019) for the given range of the vessel, we have discarded that option though as it would always be an inferior compromise relative to liquid hydrogen. Our set $\mathbb{F}$ of fuel options f comprises the fuels shown in Table 3 with their associated costs per time period t as well as well-to-tank and tank-to-wake emissions. We apply a resolution of 10 years for discretizing the lifetime periods t. For a detailed discussion on fuel and power system options beyond cost-efficiency, we refer to DNV GL (2019) and Mestemaker et al. (2020).

The well-to-tank and tank-to-wake emission factors are based on Lloyd’s Register and UMAS (2020). Fuel prices for the entire lifetime are derived from the same report’s lower bound price scenario and include a linearly increasing carbon tax from $0\$/tCO_2$ in 2020 up to $288\$/tCO_2$ in 2050. The last row in Table 3 indicates the resulting discretized tax values for each period. Both emissions and prices take into account upfront energy losses, e.g. when converting hydrogen to ammonia, within the fuel production chain (Lloyd’s Register and UMAS, 2020). Note that prices for e-fuels are based on lower bound estimates for completely renewable electricity. Hydrogen and ammonia from natural gas are assumed to be produced with carbon capture and storage. Fig. 2 plots the development of fuel prices over time. For each of the three fuel groups (fossil, bio and electric), the proxy fuel, i.e. the fuel from which the remaining prices of the group are derived, is plotted with a bold arc.

Retrofits can be undertaken after each time period t at a cost $C^{R}_{s's\,t}$. The total retrofit costs are shown in Table 4. These costs are based on machinery, tank and piping modifications as well as shipyard labor and lost income during retrofitting. The individual costs per vessel and category are depicted in Fig. 3 (retrofits between conventional power systems) and Fig. 4 (retrofits to ammonia and hydrogen): Each ray indicates a cost category (e.g. machinery), for which the retrofit costs for a specific retrofit (e.g. VLSFO to LNG) are plotted. Cost estimates for individual systems within the shown categories can be retrieved from compiled databases such as MARIN (2021).

Table 1
Data for reference Supramax bulker.

Category	Parameter	Unit	Value
ship	deadweight	dwt	63,000
	range	nm	15,000
	brake power	kW	7,500
	specific fuel consumption (diesel)	kg/kWh	0.17
	design speed	kn	14
	fuel weight	t	1366
operation	average engine power	%	60
	days at sea	days/year	180

Table 2
Ship power system options s and respective fuel consumption.

		Ship power system option, s					
	Parameter	1 VLSFO ship	2 LNG ship	3 LH2 ship	5 Ammonia ship	6 LPG ship	7 Methanol ship
	factor of tank weight (relative to HFO)	1.0	2.7	6.5	3.0	2.0	3.9
	tank weight [t]	1 366	3 629	8 932	4 147	2 732	5 328
C^N_s	newbuilding price [mUSD]	30	37	45	40	35	35
C^{LO}_{st}	lost opportunity costs per 10 years [mUSD]	0	0.4	2.7	0.5	0.3	0.7
K_{fs}	compatible fuels	VLSFO, Bio-diesel, E-diesel	Bio-LNG, E-LNG, fossil LNG	liquid E-hydrogen, liquid NG-hydrogen	E-ammonia, NG-ammonia	fossil LPG	Bio-methanol wood, bio-methanol waste stream, E-methanol

Table 3
Set of fuel options $\mathbb{S}$ with associated costs C^F_{ft}, well-to-tank emissions E^{WTT}_{ft} and tank-to-wake emissions E^{TTW}_f. Based on Lloyd's Register and UMAS (2020).

			2020–2030 C^F_{ft} $[USD/MWh]$	**2030–2040** C^F_{ft} $[USD/MWh]$	**2040–2050** C^F_{ft} $[USD/MWh]$	E^{WTT}_f $[kgCO2/MWh]$	E^{TTW}_f $[kgCO2/MWh]$
f	1	VLSFO	**49.1**	**83.1**	**110.7**	25.2	270.0
	2	Bio-diesel	**91.7**	**117.8**	**143.3**	−136.8	313.2
	3	Bio-methanol wood	**87.9**	**97.8**	**109.5**	−216.0	244.8
	4	Bio-methanol waste stream	**77.6**	**95.7**	**113.3**	−144.0	255.6
	5	Bio-LNG	**76.9**	**88.7**	**97.1**	−158.4	172.8
	6	E-diesel	**439.2**	**383.4**	**327.6**	−262.8	262.8
	7	E-methanol	**282.6**	**244.8**	**207.0**	−262.8	262.8
	8	E-LNG	**232.2**	**199.8**	**167.4**	−180.0	180.0
	9	E-ammonia	**183.6**	**154.8**	**124.2**	0.0	0.0
	10	liquid E-hydrogen	**172.8**	**144.0**	**115.2**	0.0	0.0
	11	NG-ammonia	**100.3**	**99.0**	**99.3**	61.2	0.0
	12	liquid NG-hydrogen	**89.7**	**88.8**	**87.6**	64.8	0.0
	13	fossil LNG	**32.5**	**52.6**	**72.0**	27.0	180.0
	14	fossil LPG	**40.1**	**66.2**	**91.3**	28.8	240.1
		Carbon tax [USD/tCO_2]	**50.5**	**147.5**	**241.0**		

For this case study, we assume an interest rate equal to the discount rate. This simplification enables us to express all time-dependent costs in present cost levels and thus improves transparency by simplifying the problem.

We implement and finally solve our bi-objective linear integer optimization solve our linear integer optimization model in Gurobi 9.1.

4.1. Results

Using the Gurobi solver, the solution time of the mathematical model is below one second on an ordinary PC. By iteratively increasing ε, the solver can identify solutions on the Pareto front, as shown in Fig. 5. The accumulated costs and emissions are computed for a total lifetime of 30 years, split into three discrete time periods of 10 years each as described in Section 3. Based on Table 1, the annual energy consumption of our vessel is 39,200 MWh, corresponding to about 3370 million tonnes of oil equivalent (MTOE). For each solution we indicate the initial power system choice y_{s0}, marked with a number, and the fuel choice at each of the following three time periods, indicated by lowercase letters.

For our given scenario, we see LNG as the most dominant solution on the Pareto front with a retrofit to ammonia at the lower end of lifetime emissions. The most cost-efficient solution for achieving zero well-to-wake emissions is liquid hydrogen without any retrofit.

Many of the indicated Pareto-optimal solutions rely on bio-fuels at one or more periods. In order to show the difference between electro- and bio-fuels, as well as highlighting the cost of making wrong decisions, we compute and plot both objective functions for all permissible combinations. This is done by means of a Python implementation of our mathematical model without any optimization routines. Fig. 6 depicts the solution space for our scenario, excluding solutions over 300 mUSD TCO. The orange and green dots were generated by computing all permissible combinations of decision variables (power system and fuel at each point in time). The dots indicate their respective objective function values, regardless of whether the combination leads to a Pareto-optimal or inferior solution. Green dots indicate solutions which use biofuels at one or more time periods. Orange dots indicate combinations without biofuels at all time periods. The Pareto-fronts are shown for each of the subsets (green for bio- and orange for non-bio) separately. For comparison,

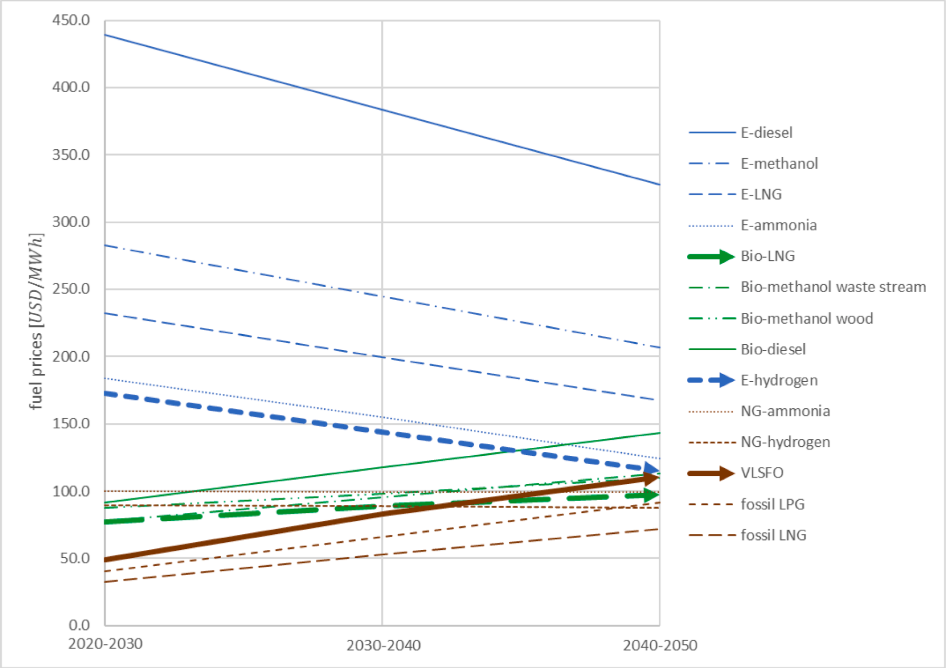

Fig. 2. Fuel prices over time periods. Fuels grouped as fossil, bio- and e-fuels. Fuels are sorted ascendingly according to prices within each group. Based on Lloyd's Register and UMAS (2020).

Table 4
Retrofit costs $C^{R}_{s^{\prime}st}$ in [mUSD]. Green: low cost, red: high cost.

from/to	VLSFO ship	LNG ship	LPG ship	Methanol ship	Ammonia ship	LH2 ship
VLSFO ship	0.0	9.3	9.3	6.0	15.0	24.6
LNG ship	3.5	0.0	2.5	6.7	11.3	22.6
LPG ship	4.0	7.8	0.0	6.7	8.2	22.6
Methanol ship	1.0	9.3	9.3	0.0	15.0	24.6
Ammonia ship					0.0	22.6
LH2 ship					6.7	0.0

Source: various, inhouse calculations.

we note that the TCO for the VLSFO baseline solution without the assumed carbon tax would be about 40% lower.

On the first glance, a large scatter both in terms of emissions and costs can be observed. The cost – environmentally and economically – associated with wrong decisions is hence significant. Within the lower bound carbon tax scenario, bio-fuels yield lower costs for the same emissions level. In our case, bio-fuels can approximately half the cost increase for a given emission level.

The most cost-effective solution (LH2) that yields zero well-to-wake emissions is about 120 mUSD more expensive than the cheapest solution (approx. 120% of the cheapest solution's TCO, in our case using fossil LNG throughout the entire lifetime). However, we could more than half the lifetime emissions when accepting a moderate increase of 50% in TCO. Note that we have not included fixed costs for e.g. crewing in our comparison. The relative cost increase may thus be lower than the one presented here.

We now take a closer at the solutions contained the Pareto set, indicating the choice of power system with the same number as used in Figs. 5–7. We see that the bio-based solutions all involve LNG (1), with a switch to ammonia for the lowest-emission solutions. The Pareto-optimal set for non-bio solutions contains LNG (1 & 2), LPG (4), LH2 (3) and ammonia (2 & 5) as fuels. The more costly low-emission solutions are ships designed directly for LH2 (3) or ammonia (5). Solutions with a TCO below 152 mUSD involve a retrofit from LNG or LPG to ammonia (2 & 4). Within the given scenario, methanol does not appear to be an optimal cost-emission compromise solution.

The following figure illustrates schematically the pathways of Pareto-optimal solutions.

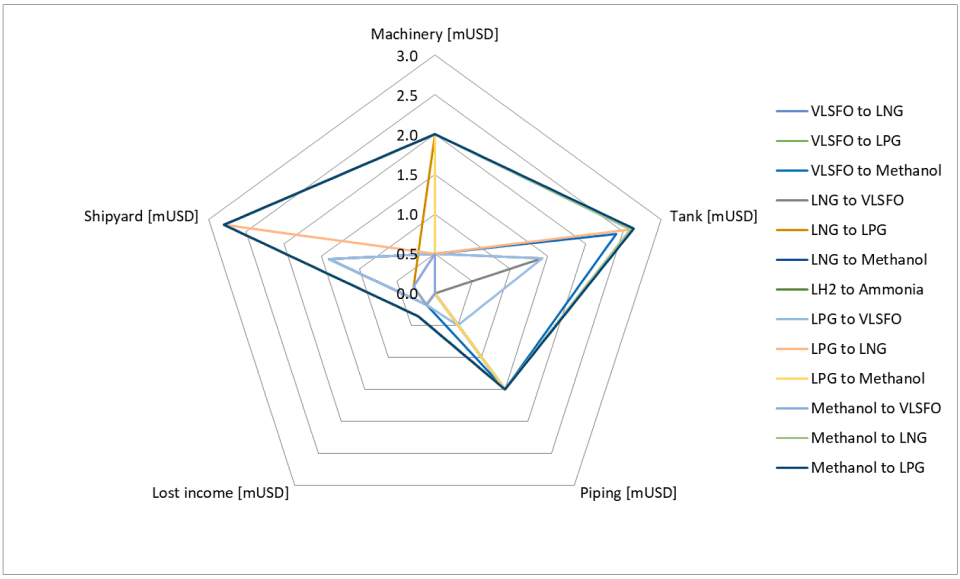

Fig. 3. Retrofit costs per vessel and category. Conventional power systems.
Source: various, inhouse calculations.

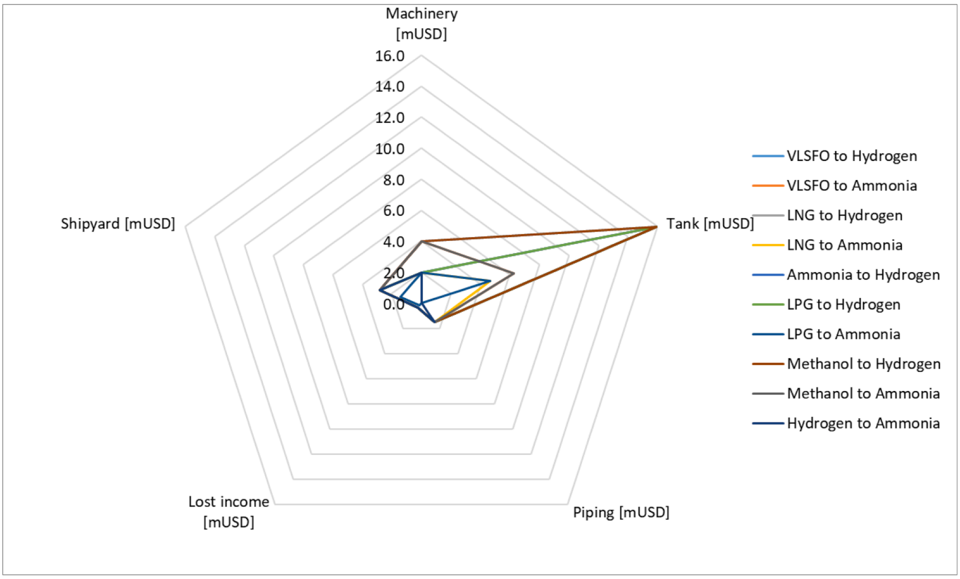

Fig. 4. Retrofit costs per vessel and category. Ammonia and hydrogen.
Source: various, inhouse calculations.

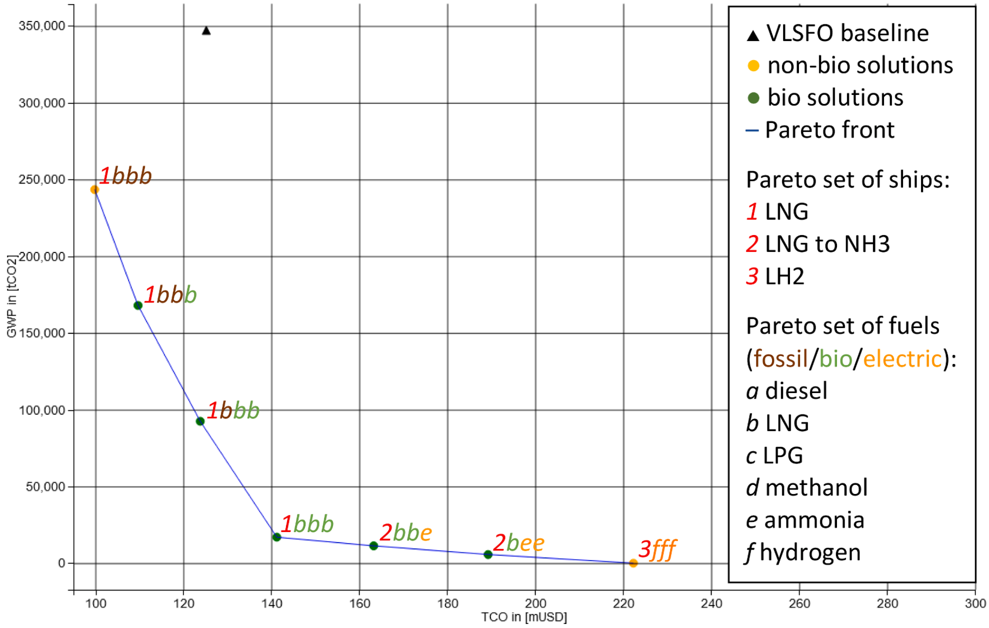

Fig. 5. Lifetime cost and emissions for Pareto-optimal solutions.
Source: own calculations.

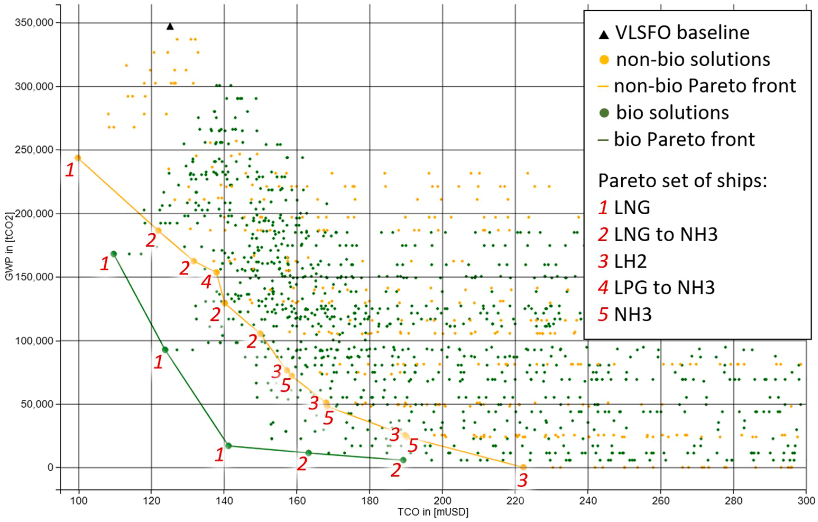

Fig. 6. Lifetime costs and emissions for the entire solution space.
Source: own calculations.

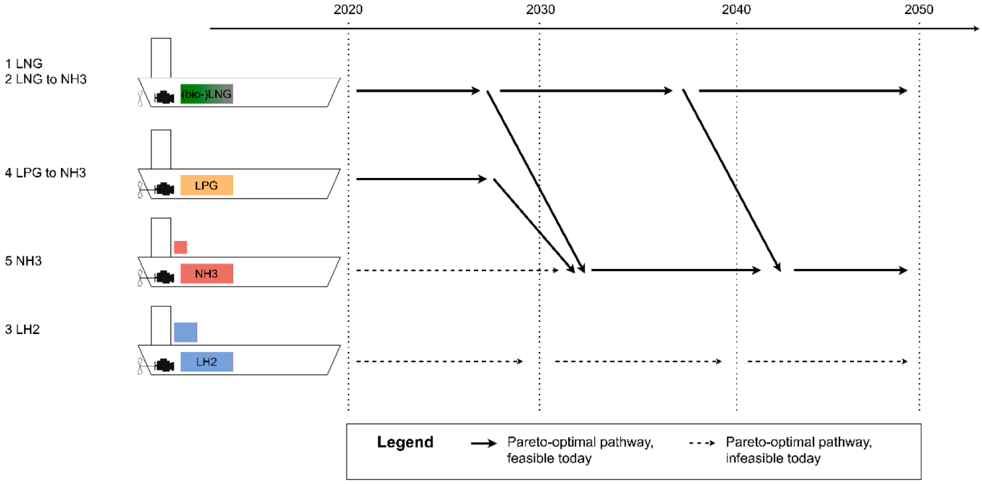

Fig. 7. Schematic timeline illustration of Pareto-optimal solutions.

4.2. Flexibility-bound solution

Relaxing our retrofit cost parameter $C^{R}_{s's t}$ to zero will yield a flexibility-bound solution, i.e. a solution driven by flexibility opportunities rather than flexibility costs. We plot the flexibility-bound Pareto front compared to the initial one in Fig. 8.

The optimal set of solutions to our problem, under the given scenario, is affected by lower retrofit costs. Zero retrofit costs yield a ship power system that is directly responsive to the exogenous scenario. The choice of optimal, alternative low-emission fuels is hence

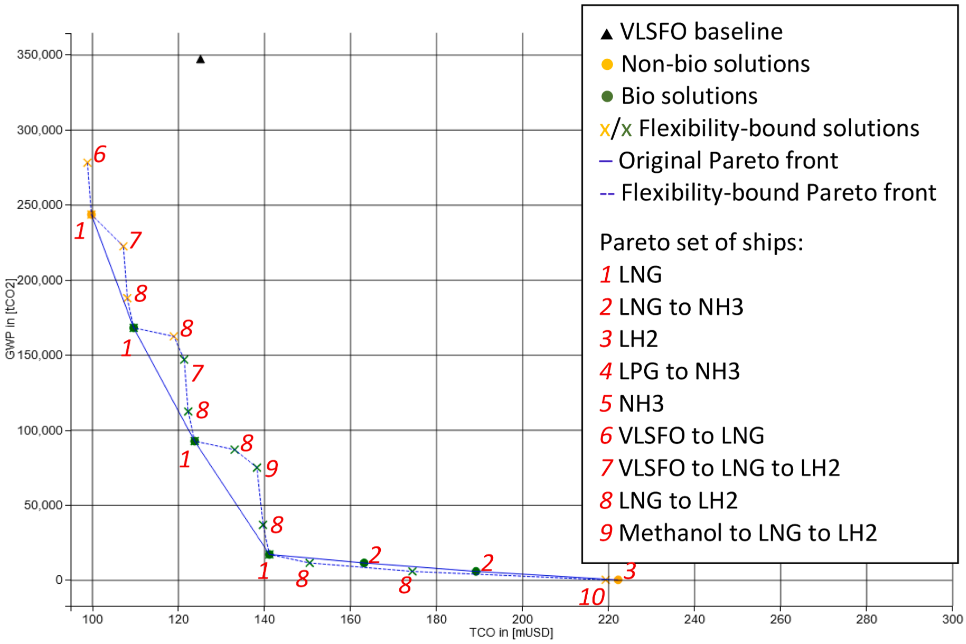

Fig. 8. Pareto front for initial and flexibility-bound problem.

affected by the legacy aspects of a ship. Moreover, we see that two solutions (7 and 9) involve two retrofits along the lifetime. These solutions are a by-product of removing the retrofit costs. The solutions may be less realistic themselves but exemplify that adaptable systems can be beneficial. Solution (6) appears to be slightly cheaper than LNG (1), not the least because of the cheaper building cost of the VLSFO baseline vessel. LNG ships (1) running on bio-LNG have not been superseded; these did not involve any retrofit before. Looking at the more costly, low-emission spectrum of the Pareto front, we see that retrofits from LNG to LH2 are now Pareto-optimal (8), instead of LNG to ammonia (2). The reason for this may be sought in the initially high retrofit costs for LH2 (22.6 mUSD). The high costs to a large extend are due to the expensive tank system. Except for a double retrofit solution (9), methanol does not show to be an optimal cost-emission compromise for the flexibility-bound problem either.

The above results obtained from our optimization model can now help us answering our initial questions:

1. *How would a transition from cheap fossil to cheap electric energy influence the optimal ship power system choice?*

The optimal power system choice would follow the change in primary energy sources from fossil to electro-fuels. Ship legacy aspects, i.e. retrofit costs, affect the optimal choice of power system and thereby choice of fuel.

2. How does our here-and-now decision, i.e. the newbuild's power system choice, change when considering a large variety of power systems, including retrofits, fuel options and different emission reduction ambitions?

If we assume VLSFO as today's preference, our here-and-now decision would change. LNG, with potential retrofits to ammonia or hydrogen, shows to be a rather robust solution for a broad range of emission ambitions.

3. Are retrofits included in the optimal solution?

The answer to this question depends on the availability of bio-fuels: In case bio-fuels were available, no retrofit would be required. In case biofuels were not available and hydrogen- as well as ammonia-powered ships are deemed infeasible today, retrofits would be required for reaching the low end of the emission ambitions.

5. Conclusion and further work

Our chosen deterministic scenario is based on lower bound prices for all fuels combined with a carbon tax. Within this scenario, bio-fuels appear to be more cost-effective than electro-fuels for reducing emissions. Whether and in which quantities bio-fuels should be available to shipping thus seems to be a relevant discussion.

Our here-and-now decision, i.e. what ship to invest in, is affected by the desired emission level as well. Assuming that, from a practical standpoint, ammonia- and hydrogen-powered ships cannot be operated as of tomorrow, the more important question would be when to retrofit from LNG to ammonia rather than if. Retrofits to hydrogen would require a reduction in storage system costs to become attractive. While ammonia also seems to be the most favored solution by Lloyd's Register and UMAS (2020), our proposed model provides additional insight by explicitly considering retrofits and tracing a ship along its lifetime. Although a Supramax bulk carrier may be seen as a representative type of cargo ship, the conclusions drawn from this model are ship- and scenario-specific. More extensive experiments are hence required before generalizing these findings to a broader range of ships.

Within the given scenario our model can provide valuable decision support by considering the ship power system pathway (legacy) of a ship. The model requires only a few generic input parameters and can therefore be applied to other vessel segments too. Thus, the model contributes to transparently identifying robust solutions with respect to unknown ship emission ambitions within one or potentially several individual scenarios.

There is considerable uncertainty with respect to the exogenous factors such as fuel prices and retrofit costs. This could be accounted for by means of a stochastic model (King and Wallace, 2012). The relatively low computational effort for solving our deterministic model should allow for such extensions.

Balland et al. (2015), Andersson et al. (2020) and Mestemaker et al. (2020) show that other factors, such as safety or technical complexity, are important to consider in real-world decision making. From a practical standpoint, these only need to be considered if they would change the solution to our problem. While LNG could be seen as reliable today, experience is yet to be built up for ammonia and hydrogen as marine fuels. Approaching the problem from stochastic standpoint could help answering whether safety and complexity aspects need to be factored in at the earliest decision point.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

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This paper has been subject to a corrigendum, which was submitted to the journal on March 8, 2022. The corrigendum corrects a mistake in lost opportunity costs within the case study data. The mistake did not affect the set of Pareto-opimal solutions and overall conclusion of the paper.

Corrigendum

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The authors would like to submit the following correction to the article “Optimal ship lifetime fuel and power system selection“, published in volume 102, 103145. In Table 2, the tank weight factors and resulting lost opportunity costs for Ammonia and Methanol need to be exchanged. The corrected table now reads as follows:

Table 1: Ship power system options and respective fuel consumption.

		Ship power system option, s					
		1	2	3	5	6	7
	parameter	VLSFO ship	LNG ship	LH2 ship	Ammonia ship	LPG ship	Methanol ship
	cargo loss factor (relative to VLSFO)	1.0	2.3	5.5	3.7	2.0	2.4
	tank weight [t]	1 366	3 629	8 932	5 328	2 732	4 147
C_s^N	newbuilding price [mUSD]	30	37	45	40	35	35
C_{st}^{LO}	lost opportunity costs per 10 years [mUSD]	0.0	0.4	2.7	0.7	0.3	0.5
K_{fs}	compatible fuels	VLSFO, Bio-diesel, E-diesel	Bio-LNG, E-LNG, fossil LNG	liquid E-hydrogen, liquid NG-hydrogen	E-ammonia, NG-ammonia	fossil LPG	Bio-methanol wood, bio-methanol waste stream, E-methanol

Consequently, Figure 1 is to be updated:

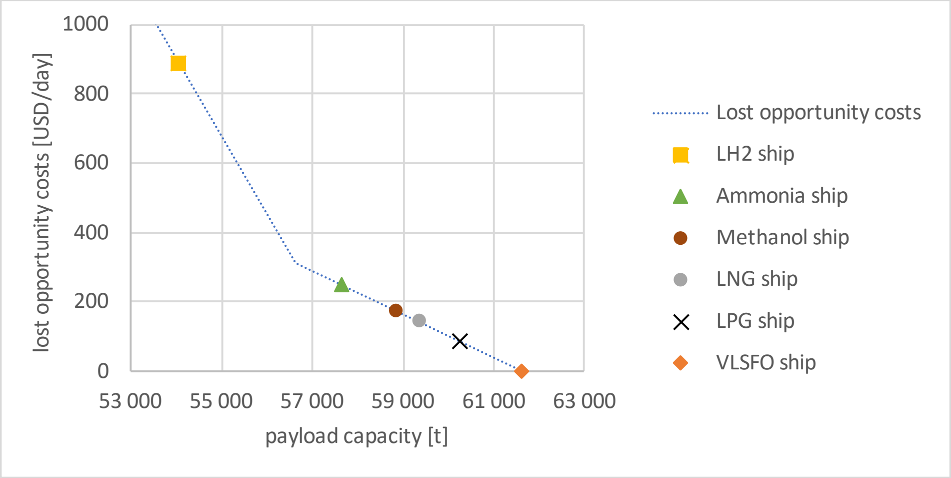

Figure 1: Daily lost opportunity costs (source: own calculation).

The updated values affect neither the set nor the sequence of the Pareto-optimal solutions. That is, albeit there is a small change in costs for different combinations of fuels and power systems, this does not render any of the identified solutions inferior. The conclusions drawn are hence still valid.

Main Paper 4

Understanding agility as a parameter for fuel-flexible ships
Benjamin Lagemann, Stein Ove Erikstad, Per Olaf Brett, Jose Jorge Garcia Agis (2022)
14th International Marine Design Conference; Vancouver, Canada; DOI: 10.5957/IMDC-2022-259

Understanding agility as a parameter for fuel-flexible ships

Benjamin Lagemann[1] and Stein Ove Erikstad[1] and Per Olaf Brett[1] and Jose Jorge Garcia Agis[2]

ABSTRACT

With the need for lower-emission maritime transport solutions, shipowners and designers face uncertainty when it comes to the selection of fuel today and in the future. The effects of this uncertainty can be mitigated to a certain extent by fuel-flexible machinery and containment systems When developing such fuel-flexible designs, capability, changeability and agility are important parameters to be considered. Thus, the required time and cost consumed for conversions or retrofits at a later stage during the vessel's lifetime need to be addressed in the early design phase. We apply and discuss the concept of agility for both existing flexible solutions and new ship design alternatives in this paper.

KEY WORDS

Agility; flexibility; fuel; uncertainty; ship design; greenhouse gas; emission

1 INTRODUCTION

Thriving to contribute to the goals of the Paris Agreement (United Nations 2015), shipping, though not being regulated under the same agreement, is setting tightening greenhouse gas (GHG) emission goals for itself (International Maritime Organization 2018). The translation of these goals into legislative requirements is still ongoing (International Maritime Organization 2021). Individual members of the IMO aim to increase the level of ambition, potentially through regionally stricter requirements (European Commission 2019; European Community Shipowners' Association 2020). Neither the level of ambition nor the concrete per-ship or per-fleet requirements can be seen as cast in stone and introduce significant uncertainty for decision-making today.

Additional uncertainty is brought to the game by various technical solutions at different development stages and with different effects on potential emission reductions (DNV GL 2019). As for alternative fuels, according to CE Delft (2020) with the largest emission reduction potential, the reduction effects hinge on the technological development of their availability and thereby often renewable electricity capacity and its prioritization.

Flexibility as a strategy to meet future unpredictability

The unclear requirements and immature technologies increase the contextual and behavioral complexity (Gaspar et al. 2012), while being additionally coupled with time. Flexibility can, however, be a valuable strategy for dealing with uncertainty, particularly time-dependent, in engineering systems (de Neufville and Scholtes 2019). The value of flexibility for ships has been shown by Buxton for a container ship: rather than investing into the "most generous ship capital can provide", it can be more preferable to design a smaller ship that contains certain options that can be exercised when the market development is known more clearly. Both Choi and Erikstad (2018) and Rehn (2018) have shown similar effects in different merchant vessel design cases.

Flexibility has also been chosen in Navy circles. Hornhaver (1995), Warship Technology (2006) and Volkert (2010), employ flexibility as a response strategy to future uncertainty with respect to mission requirements. Notably, these papers use standard modules to exchange or extend capabilities throughout their service life. In order to be able to exercise these options, the modules and particularly their interfaces need to be considered in the design process from the start (Schank et al. 2016). Andrews (2001) highlights the importance of margins for through-life changes.

In the light of stricter GHG emission requirements, flexibility has recently received a lot of attention in the shipping industry. The Spirit of British Columbia was converted from very low sulphur fuel oil (VLSFO) to liquid natural gas (LNG) (MarineLink 2018). In Europe, the Stena Germanica received capability of running on methanol (Naval Architect 2015). Maersk (2021) announced to build dual-fuel ships VLSFO and methanol and ColorLine investigates conversions to ammonia (Ammonia

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Energy Association 2020). On the engine side, Anglo Belgian Corporation is currently developing retrofittable four-stroke engines (Anglo Belgian Corporation 2021), while MAN Energy Solutions (2019) as well as WinGD (2021) are working on two-stroke combustion engines solutions capable of running on alternative fuels such as ammonia or methanol. Each of these alternative power options come with a certain level of flexibility with respect to fuel compatibility. For a given level of fuel-flexibility, however, the question "how quick and how costly should a fuel switch be?" arises. This question circles around the parameter of agility, which we will discuss in the remainder of this paper.

Agility as a characteristic of flexibility and meeting low-emission goals

In this paper, we investigate agility as an adverb to flexibility in the light of low-emission goals. That is, flexible ship designs at different levels of agility, which shall help meeting future low-emission requirements. We do so by:

1. Establishing an operational definition of agility (grounded in both literature & daily use), Section 2
2. Illustrating design options with different levels of agility, Section 3
3. Discussing these options and their value in Section 4

Section 5 will conclude the paper.

2 LITERATURE REVIEW AND DEFINITIONS

Agility, and -ilities in the broader sense, are system capabilities/attributes in response to changing requirements and contexts. Section 2.1 will provide a short introduction to the -ilities. Section 2.2 aims to review and condense literature on agility in order to establish an operational definition for this paper. Section 2.3 provides some examples, both from general engineering and the maritime domain, for agility.

2.1 -ilities

Ross et al. (2008) provide a comprehensive set of definitions for various -ilities. They suggest that -ilities are system properties that contribute to a system's overall changeability. The purpose of changeability in turn is sustained value-robustness throughout the system's life cycle. Their proposed taxonomy characterizes changeability according to:

- *Change agent:* external (flexible) vs internal (adaptable)
- *Change mechanism:* "the particular path the system must take in order to transition […]" (Ross et al. 2008)
- *Change effect:* no system change (robust), parameter level changed (scalable), parameter set changed (modifiable)

We see this taxonomy as being generally useful, as it enables a systematic discussion of -ilities. However, their suggested definition for flexibility does not necessarily coincide exactly with the everyday use of this term. For this paper, we hence employ the definition "the ability to change to suit new conditions or situations" (Oxford Learner's Dictionaries 2022). We think that this definition better represents the everyday use of the word "flexibility".

2.2 agility

Instead of defining agility explicitly in their -ility framework, Ross et al. (2008) refer to Fricke and Schulz' (2005) definition of agility: "ability to be changed rapidly" indicates that agility is both linked to the duration of change and to an external change agent.

The following table provides a brief overview of alternative definitions of agility in literature and dictionaries:

Table 1: Alternative definitions of agility

Reference	Definition	Limitations
Haberfellner and de Weck (2005)	"flexibility at speed"	Time only
Fricke and Schulz (2005)	"ability to be changed rapidly"	External change agent, time only
Dove and LaBarge (2014)	"Agility is the ability of a system to thrive in an uncertain and unpredictably evolving environment; deploying effective response to both opportunity and threat, within mission. Effective response has four metrics: timely (fast enough to deliver value), affordable (at a cost that can be repeated as often as necessary), predictable (can be counted on to meet the need), and comprehensive (anything and everything within the system mission boundary)."	Uncertain and unpredictable environments
Oxford Dictionary (2022)	*(Business)* "The ability to change rapidly in response to customer needs and market forces; adaptability, flexibility, responsiveness."	Time only
Latin-English Dictionary (2022)	agilis *(latin, adjective)*: "agile, nimble, quick, swift; alert (mind), active; energetic, busy; rousing"	

Being strongly intertwined with concepts such as flexibility or adaptability, agility needs to be seen in relation to its neighboring -ilities (Dove and LaBarge 2014). Apart from flexibility, we employ Ross et al.'s (2008) definitions of -ilities. The limitations in the third column of Table 1 are therefore seen in relation to those definitions. From this viewpoint, Fricke and Schulz' (2005) definitions imply an external change agent. Moreover, Haberfellner and de Weck's (2005) as well as Fricke and Schulz' (2005) concept of agility considers the time of change as the only measure for agility. Dove and LaBarge (2014a) suggest a mixed construct for agility which comprises costs, predictability and comprehensiveness in addition to time. However, their definition is limited to uncertain and unpredictable environments with some associated strong limitations on probabilities.

In order to not limit agility to environments with certain probabilistic attributes, we will employ a definition of agility as "ease to change". This definition is not limited to an external change agent, which means it can be used as an independent modifier for changeability. Within Ross at al.'s (2008) framework, agility thus becomes an attribute of the change mechanism that denotes the ease to change. Most importantly, the "ease to change" is a construct which includes not only time as an important factor, but also further resource expenditures such as cost or personnel. Such ease can be achieved through quick, but also cheap changes. Agility is hence inversely related to effort or resource expenditures: The less effort or cost required for change, the more agile system.

2.3 Engineering examples for different levels of agility

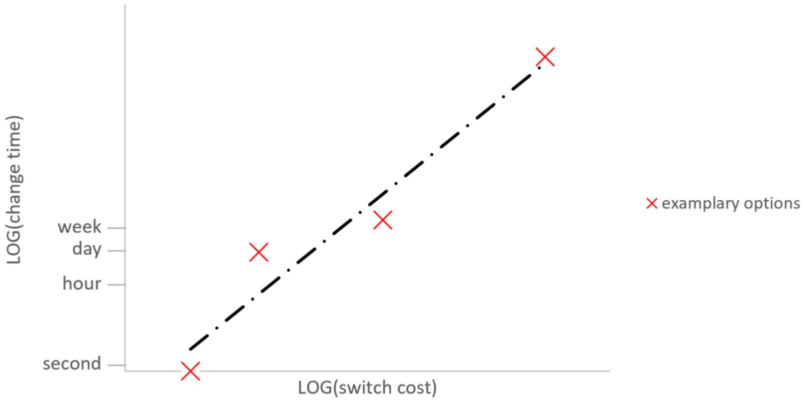
In Section 1, we have already given a few examples of flexibility in ship design. The previous paragraphs have put forward our proposition of agility as an adverb to flexibility. More specifically, an adverb that denotes the "ease to change". The following examples shall help illustrating this point:

Passenger cars are often used by one person at a time. However, there are occasions when many people shall be transported, hence more seats are required. In addition to fixed seats, larger cars sometimes feature foldable rear seats which provide such flexibility. But how easily should these seats be foldable, or perhaps even mountable? Is it better to store spare seats in a garage and mount them when needed? Or should they be folded to the floor and be put up, whenever and wherever necessary? If so, how easily should this be done: is a push-button mechanism required or are manual actions sufficient? These questions all relate to the appropriate or desired level of agility.

In maritime applications, the Danish Standard 300 Flex serves as an example for agility (Hornhaver 1995; Parker and Singer 2012). The ship is reconfigurable by swapping containerized modules in port. In that way, the ship is more agile than if only weight and spaces margins had been set beforehand. As indicated by Figure 1, higher switching costs are generally associated with longer times for switching. The relation does not necessarily be linear though: If the shipowner's contract always spending a certain amount of time in dock per year, there may not be any financial penalties unless the specified period is exceeded. The costs (and in turn cost-savings of agility) will thus be case-specific.

Combination carriers are another example of agility in marine designs (Sødal et al. 2008, Dahm 2022): these enable easy market switches between for example the dry and wet bulk market, a feature which shipowners can capitalize on when the two distinct markets are independently volatile. Additionally, market switches can be used to increase utilization of a ship: If the same cargo category is not available for return voyages, switching to a second market and cargo (which can necessitate cleaning cargo holds) avoids having to sail in ballast. Not only can this increase the shipowner's profit, but also lower GHG emission per ton transport work and thus help complying with tightening GHG emission requirements. The suitable level of agility consequently needs to be discussed.

Figure 1: switch time and costs



3 CASE STUDY: DESIGN OPTIONS WITH DIFFERENT LEVELS OF AGILITY

Flexibility, with different levels of agility, can be implemented in different physical ways. To illustrate the range of options with different levels of agility, we will use a Supramax bulk carrier as an illustrative example. We limit ourselves to VLSFO and LNG as fuels. These definitions shall only refer to the fuels' physical composition (i.e. long-chained hydrocarbons and methane as a primary energy carrier), not the feedstock of these fuels (fossil, bio or electro). Both energy carriers can, primarily in a cleaner form, be derived from biomass or renewable electric energy if available.

The system-level agility is dependent on both the agility of the engine (with the function energy conversion) and the tank (energy storage function), all with their respective sub-systems. We consider the following discrete options for the engine:

- E1: Mono-fuel diesel engine
- E2: Retrofittable diesel engine
- E3: Containerized mono-fuel engine (combined with generators and electric motors)
- E4: Dual-fuel gas engine (diesel cycle, diesel destillates plus LNG)

For the tank system, the following options are considered:

- T1: Diesel only (integrated tanks)
- T2: Diesel integrated plus LNG retrofittable
- T3: Diesel integrated plus LNG containerized
- T4: Diesel integrated plus LNG

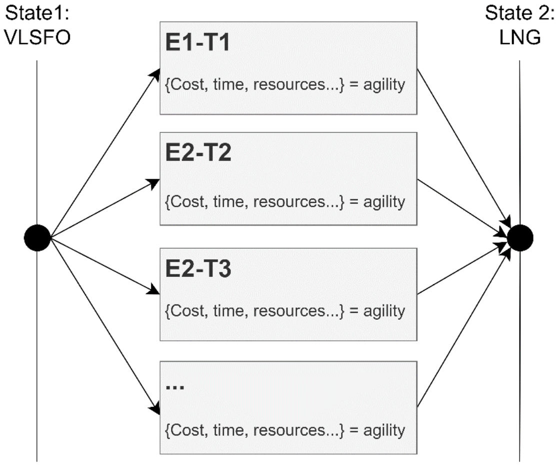
These categories result in the following combinations of engine and tank systems:

Table 3: Combinations of engine and fuel options

		Tank			
		T1 Diesel only	T2 Diesel plus LNG retrofittable	T3 Diesel plus LNG containerized	T4 Diesel plus LNG
Engine	E1 Diesel mono-fuel	X			
	E2 Diesel retrofittable		X	X	X
	E3 Containerized mono-fuel		X	X	X
	E4 Dual-fuel		X	X	X

As can be seen from Table 3, all options except for the pure "diesel only" engine and tank (E1-T1) come with recourse options, i.e. possible changes that be executed as a response to fuel (price) developments. Figure 2 schematically shows the various options for changes between VLSFO and LNG, each with their respective agility level.

Figure 2: Change options with agility levels



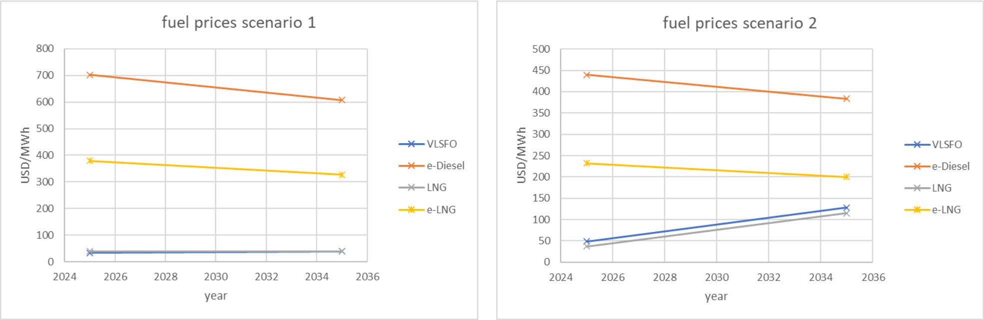
We express the level of agility with a cost function. The conversion time is modelled as a lost opportunity cost that comes in addition to the actual cost of changing the onboard systems. The assumed investment and change costs are displayed in the following table:

Table 4: Investment and change costs

Option	Investment cost [mUSD]	Change time [days]	Change cost [mUSD]
E1-T1	30.0	-	-
E2-T2	32.5	21	2.175
E2-T3	32.9	1	1.175
E2-T4	36.6	0	1.125
E3-T2	34.4	21	3.3
E3-T3	34.8	1	2.3
E3-T4	38.5	0	2.25
E4-T2	31.4	21	1.05
E4-T3	31.8	1	0.05
E4-T4	35.5	0	0

We assume two discrete exogenous scenarios for the fuel prices. The prices are depicted in Figure 3 and are based on cost estimates by Lloyd’s Register and UMAS (2020).

Figure 3: Fuel price developments for scenarios



Scenario 1 is meant to represent a business-as-usual scenario: intermediate fossil fuel prices are combined with high electro-fuel prices. In Scenario 2, fossil fuel prices rise from the lower to upper bound projection, while electro-fuels are comparatively cheap. In addition, a carbon tax increase from 50 USD/tCO2$_{eq}$ is assumed to increase to 300 USD/tCO2$_{eq}$.

3.1 Evaluating the value of agility for different options

Agility as an attribute to flexibility can be valued by means of real-options analysis (Knight and Singer 2012). Combined with stochastic programming (King and Wallace 2012), the problem can be defined as a maximization of an expected performance yield indicator. Such indicators can be of economic nature (useful discussion by Benford 1966) or measure the environmental performance (e.g. Energy Efficiency Design Index, EEDI or Carbon Intensity Indicator, CII). For our case study, we assume the targeted transport work to be constant and minimize the expected total cost of ownership (eTCO) in order to maximize profit. The formulation is based on an optimization model presented by Lagemann et al. (2022). The model applied here incorporates the following simplifications and adaptations:

- The model is single-objective, meaning that GHG emissions are penalized through possible carbon taxes only
- The lost opportunity costs are dropped (since these are comparatively small for this specific narrow range of fuels)
- A scenario formulation is adopted to account for uncertainty and illustrate the value of agility

Availability of fuels is not included explicitly with hard constraints (as it could be the case for a specific route), but rather in a general way by means of the fuel price. The simplified and adapted model reads as follows:

Sets

Set	Description	Modeling comment
$\mathbb{T}$	set of discrete ***time periods***, indexed by t	
$\mathbb{F}$	set of ***fuel options***, indexed by f	refers to main chemical composition and physical state
$\mathbb{S}$	set of pre-generated ***ship system options*** for energy storage and power conversion, indexed by s	refers to a ship with an energy storage of a certain type and size, and a power converter of certain type and size
Ω	set of scenarios, indexed by ω	complete realization of random parameters

Parameters

Parameter	Description	Modeling comment
C_s^N	***newbuild cost*** of ship with system option s	
$C_{s's}^R$	***retrofit cost*** from option s' to option s	
$C_{ft\omega}^F$	***fuel cost*** of fuel *f* at time period *t* in scenario ω	
P_ω	***probability of scenario v***	
B	***energy consumption*** per time period	assuming the fuel conversion efficiencies do not change over time, equidistant time periods
E_f^{WTT}	***well-to-tank emissions*** of fuel f	
E_f^{TTW}	***tank-to-wake emissions*** of fuel f	assuming tank-to-wake emissions do not change over time.
K_{fs}	1 if fuel f and system s are ***compatible***, 0 otherwise	
ε	constraint on global warming potential	ε-constraint method, ε iteratively increased

Decision variables

$x_{ft\omega}$	1 if ***fuel*** f is chosen at time t, 0 otherwise
$y_{s0}, y_{st\omega}$	1 if ***ship system option*** s is chosen at time t, 0 otherwise

Auxiliary variables (implicit, required for linearization)

$r_{s'st\omega}$	1 if retrofit is to be made from system option s' to system option s after period t. 0 otherwise

Objectives

We define our first objective of minimizing the expected total cost of ownership (eTCO) as:

$$min\, eTCO = \tag{1}$$

$$= \sum_{s\in\mathbb{S}} \left[\underbrace{C_s^N \cdot y_{st_0}}_{building\ cost} + \sum_{\omega\in\Omega} P_\omega \left[\sum_{t\in\mathbb{T}} \left(\sum_{s'\in\mathbb{S}} \underbrace{C_{s's}^R \cdot r_{s'st\omega}}_{retrofit\ cost} \right) \right] \right] + \sum_{\omega\in\Omega} \sum_{t\in\mathbb{T}} \sum_{f\in\mathbb{F}} \underbrace{P_\omega \cdot B \cdot x_{ft\omega} \cdot C_{ft\omega}^F}_{fuel\ cost}$$

subject to:

First stage:

$$\sum_{s\in\mathbb{S}} y_{st} = 1, \qquad \forall t = 0 \tag{2}$$

$$y_{st} \in \{0, 1\} \qquad \forall \mathrm{s} \in \mathbb{S},\ t = 0 \tag{3}$$

Constraints (3) ensure that only one ship system option is selected at the first time step. Constraints (3) declare that decision variable y_{st} is of binary type.

Second stage:

$$y_{st\omega} = y_{st} \quad \forall \mathrm{s} \in \mathbb{S}, \forall t = 0, \omega \in \Omega \tag{4}$$

$$\sum_{f\in\mathbb{F}} x_{ft\omega} = 1, \qquad \forall t \in \mathbb{T}, \omega \in \Omega \tag{5}$$

$$\sum_{s\in\mathbb{S}} y_{st\omega} = 1, \qquad \forall t \in \mathbb{T}, \omega \in \Omega \tag{6}$$

$$x_{ft\omega} + y_{st\omega} \leq 1 + K_{fs} \qquad \forall t \in \mathbb{T},\ \forall f \in \mathbb{F},\ \forall s \in \mathbb{S},\ \forall \omega \in \Omega \tag{7}$$

$$y_{s'(t-1)\omega} + y_{st\omega} - 1 \leq r_{s'st\omega} \qquad \forall s', s \in \mathbb{S}, \forall t \in \mathbb{T}\backslash\{0\},\ \forall \omega \in \Omega \tag{8}$$

$$y_{s'(t-1)\omega} + y_{st\omega} \geq 2r_{s'st\omega} \qquad \forall s', s \in \mathbb{S}, \forall t \in \mathbb{T}\backslash\{0\},\ \forall \omega \in \Omega \tag{9}$$

$$r_{s'st\omega} = 0 \qquad \forall s', s \in \mathbb{S}, \forall t = 0,\ \forall \omega \in \Omega \tag{10}$$

$$x_{ft\omega} \in \{0, 1\} \qquad \forall f \in \mathbb{F},\ \forall t \in \mathbb{T},\ \forall \omega \in \Omega \tag{11}$$

$$y_{st\omega} \in \{0, 1\} \qquad \forall s \in \mathbb{S},\ \forall t \in\ \mathbb{T},\ \forall \omega \in \Omega \tag{12}$$

Constraints (4) link the first stage decision variable to the second stage. Constraints (5) and (6) ensure that exactly one fuel and one ship system option are selected at the same time. Constraints (7) imply that a fuel and power conversion system need to be compatible. Constraints (8)-(9) control the auxiliary retrofit variable, which is set to zero for the first time period by constraint (10). Constraints (11) and (12) make sure that also the second stage decision variables are of binary type.

4 RESULTS AND DISCUSSION

The model is implemented and solved with a commercial optimizer (Gurobi 9.1). Table 5 shows the optimal initial system choice for different probability distributions between scenario 1 and 2. Note that $p_1 = 1 - p_2$ in our case.

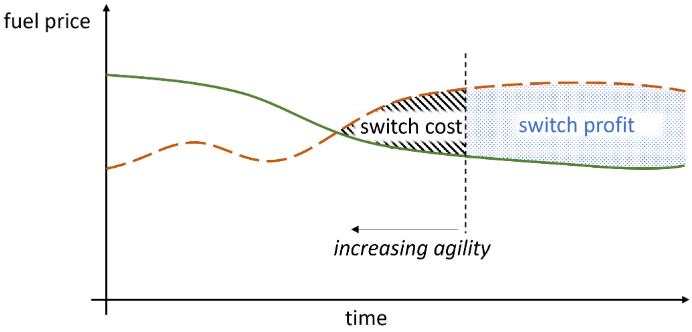
Table 5: Cost-optimal solutions with different levels of agility

p_2	cost-optimal solution	Agility
$0 \leq p_2 \leq 0.34$	E1-T1	inflexible
$0.34 < p_2 \leq 0.4$	E4-T2	↓ increasing agility
$0.4 < p_2 \leq 0.76$	E4-T3	
$0.76 < p_2 \leq 1$	E4-T4	

The results indicate that flexibility pays off for probabilities larger than $p_2 = 0.35$ for scenario 2. The level of desired agility of the system depends as well on the probability distribution. Thus, the probabilities determine the trade-off between upfront investment costs and potential retrofit costs, similar to the one depicted in Figure 1.

The appropriate level of agility, and thereby the cost of change, is hence directly dependent on our expectations with respect to exogenous conditions. This example illustrates that agility, that is easy-to-conduct changes, is valued high under uncertain conditions. In addition, agility can pay off if change is to happen frequently (Sødal et al. 2008; Christensen et al. 2018). This can be seen from equation (1), where the second term is the sum of change costs. Figure 4 illustrates the dependency of worth-while fuel switches on the system's agility, here shown as a switch cost. Lower switch costs facilitate earlier profit from the change. In case the fuel prices cross again, the system's agility determines whether the switch is worthwhile at all or not.

Figure 4: capitalizing on agility



Agility could thus be advantageous if a shipowner wanted to capitalize on frequent fuel switches, i.e. running on LNG whenever that is cheaper than VLSFO. Similarly, agility could be a worthwhile strategy if availability of a certain fuel is restricted on certain trades or in certain scenarios. Both these latter cases have not been investigated in this case study, but could be readily modeled with this approach. Last but not least, the concept of agility is not limited to uncertain conditions: If external conditions are known to change (deterministic future), agility can ease or reduce costs for adaptations to the changing external circumstances (Lagemann et al. 2022).

5 CONCLUSION

Section 2 has reviewed various definitions of agility. For fuel-flexible ships, we have found that a definition for agility as “ease to change” is most appropriate. Sections 3 and 4 have illustrated how this definition can be made operational, i.e. how agile ships can be evaluated. The results indicate that the value we attribute to agile systems is dependent on our expectations for the future: If change is seen to be likely, agile systems can ease this change by bringing down the associated costs and resource expenditures. The presented optimization model can be used to identify the optimal level of agility for a given set of exogenous scenarios.

In addition to the simplifications outlined in Section 3.1, our study has several limitations: Notably, the number of scenarios and the number of fuel options are significantly reduced to analyze agility more closely. For a more comprehensive and systematic study of agility, we see the following challenges:

1. The number of options to be evaluated: The number of options to be evaluated quickly becomes large if multiple fuels and multiple change mechanisms shall be evaluated. That means that matrix sizes increase significantly. Some options may be more flexible (i.e. enable to change between more fuel options), while others may be more agile, but restricted in flexibility.
2. Reliable cost estimates for different options: Reliable cost estimates, both for investment and change costs, are hard to obtain if the set of design options is large. Preferably, such estimates are based on a common methodology to avoid bias. Databases such as MARIN (2021) can help cross-checking multiple sources for cost estimations.
3. Capturing the uncertainty/randomness appropriately: Capturing the uncertain external properties (fuel prices or carbon tax) in an appropriate way is perhaps the most challenging task. Real options analysis is perhaps the most suited technique for this problem (Knight and Singer 2012), but requires probability distributions. For short-term predictions, such as fuel price variation over a year, the properties of the distributions may be more or less well-known (e.g. Christensen et al. 2018), which simplifies quantification of changeability. For long-term fuel price predictions, the data are scarcer. The International Energy Agency’s forecasts have been existent around for about 23 years (International Energy Agency 1999), that is less than the typical service life time of a ship. Capturing different sources and evaluating the effect of different probability distributions seems to be a necessity.

Agility, as put forward in this paper, can be seen as an important adverb to flexibility and changeability and can thereby help mitigating the effects of uncertainty. We see the following links between agility and the 4T’s of risk and loss control management literature (Bird and Germain 1985):

- *Terminate:* Our proposition in this paper has been that the aspect of agility should be considered during the design process. Eventually, the desired level of agility needs to be discussed in the light of technical feasibility (Andrews 2003). Given that the best options for different levels of agility are on the table, terminating (not pursuing a design) as a possible outcome of a design process with thorough requirements elucidation.
- *Treat:* When designing agile systems, risk and uncertainty is treated in a technical way. That is, agility enables responding to risk by adapting the technical system to changing circumstances.
- *Transfer:* Agility does not necessarily transfer risk to others per se. However, leasing or pay-per-use business models can contribute to a ship’s agility.
- *Tolerate:* Uncertainties and risks which can neither be terminated, treated or transferred, need to be tolerated.

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CREDIT AUTHOR STATEMENT

Benjamin Lagemann: Methodology, Software, Validation, Formal analysis, Resources, Writing – Original Draft, Visualization, **Stein Ove Erikstad:** Conceptualization, Methodology, Writing – Review & Editing, Supervision, **Per Olaf Brett:** Writing – Review & Editing, **Jose Jorge Garcia Agis:** Writing – Review & Editing

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Main Paper 5

Optimal ship lifetime fuel and power system selection under uncertainty
Benjamin Lagemann, Sotiria Lagouvardou, Elizabeth Lindstad, Kjetil Fagerholt, Harilaos N. Psaraftis, Stein Ove Erikstad
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Optimal ship lifetime fuel and power system selection under uncertainty

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ABSTRACT

Ship designers face increasing pressure to comply with global emission reduction ambitions. Alternative fuels, potentially derived from bio-feedstock or renewable electricity, provide promising solutions to this problem. The main challenge is to identify a suitable ship power system, given not only uncertain emission requirements but also uncertain fuel and carbon emission prices. We develop a two-stage stochastic optimization model that explicitly considers uncertain fuel and carbon emission prices, as well as potential retrofits along the lifetime. The bi-objective setup of the model shows how the choice of optimal power system changes with reduced emission levels. Methanol and LNG configurations appear to be relatively robust initial choices due to their ability to run on fuel derived from different feedstocks, and their better retrofittability towards ammonia or hydrogen. From a policy perspective, our model provides insight into the effect of the different types of carbon pricing mechanisms on a shipowner's decisions.

1. Introduction

In 2015, the Paris Agreement set out to limit global warming by the end of the century to preferably 1.5 °C (United Nations 2015). The International Maritime Organization (IMO), although not regulated under the same agreement, declared ambitions to contribute this goal by reducing absolute greenhouse gas (GHG) emissions from seaborne transport by at least 50% and relative transport work emissions by at least 70% by 2050 (International Maritime Organization 2018) compared to 2008 levels.

The translation of these high-level ambitions to concrete per-ship requirements is currently still under discussion and the IMO (2018) indicates this may take time. Different regions, e.g., EU (European Commission 2019), and industry associations (e.g., European Community Shipowners' Associations 2020) have recognized that the current IMO ambitions are inconsistent with the overarching goal of limiting global warming and have both declared more ambitious emission reduction targets (European Commission 2019, European Community Shipowners' Associations 2020) to exercise increasing pressure on the IMO to substantiate (Psaraftis et al. 2021) and potentially tighten requirements. This process, accompanied by a lack of transparency (Psaraftis and Kontovas 2020), translates into significant uncertainty for shipowners and designers when it comes to emission requirements along a ship's lifetime.

Alternative fuels are by many seen as a promising technology to substantially reduce emissions from shipping and eventually

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comply with whatever emission target is set (DNV 2021, McKinlay et al. 2021, Nair and Acciaro 2018, CE Delft 2020, DNV GL 2019, Korberg et al. 2021, Lindstad et al. 2021b, Lloyd's Register and UMAS 2020, Wang and Wright 2021, Xing et al. 2021). Each of the fuels comes with its own challenges, be they technical (DNV GL 2019, Wang and Wright 2021), social (Ashrafi et al. 2022), environmental (Lindstad et al. 2021a) or economic (DNV GL 2020, Lloyd's Register and UMAS 2020, Lindstad et al. 2021b). In particular the economic aspects exhibit a high uncertainty, as the long-term costs of the fuels' feedstocks (being fossil, biomass, renewable electricity and captured carbon dioxide) are uncertain (Zwaginga et al. 2022). The aforementioned political negotiations on market-based measures (MBMs), which could potentially map environmental aspects to economic ones, introduce additional economic uncertainty (Psaraftis et al. 2021).

Even reducing the selection of alternative fuels down to techno-economic aspects involves different system complexities (Rhodes and Ross 2010, Gaspar et al. 2012), in particular:

- Structural complexity (the number of fuel and power system options to be studied)
- Contextual complexity (exogenous parameters such as fuel or carbon prices)
- Temporal complexity in combination with the first two complexities (retrofits and development of fuel & carbon prices)

Wang and Wright (2021) have reviewed several studies in this field. These studies, however, either do not consider the whole range of alternative fuel options (Nair and Acciaro 2018, Horvath et al. 2018), do not explicitly consider retrofits (e.g., Lindstad et al. 2021b, Korberg et al. 2021, Zwaginga et al. 2022, Horvath et al. 2018) or employ a deterministic scenario thinking as opposed to across-scenario thinking (DNV 2021, Horvath et al. 2018, Korberg et al. 2021, Lagemann et al. 2022a, Lindstad et al. 2021b, Lloyd's Register and UMAS 2020).

Across-scenario thinking has shown to be useful when dealing with temporal uncertainty, i.e., uncertainty that gradually resolves over time (De Neufville and Scholtes 2019 and King and Wallace 2012 for general engineering systems; Balland et al. 2013 and Pantuso et al. 2016 for ship design). Flexible systems, for example retrofittable ships, are one potential response strategy to handle such uncertainty (De Neufville and Scholtes 2019, Rehn et al. 2018, Parker and Singer 2012). Choi and Erikstad (2017) and Knight and Singer (2012) show how such flexible ships can be evaluated by means of real-options theory in across-scenario thinking.

This article contributes to the existing literature by providing a decision-support model for selecting alternative fuels and power systems that explicitly considers retrofits (similar to Lagemann et al. 2022a) and the prevailing uncertainty with respect to fuel and carbon pricing. Similar to Trivyza (2019), the model considers economic and environmental objectives separately. Uncertainty and across-scenario thinking is accounted for by means of two-stage stochastic programming (e.g., Balland et al. 2013).

The remainder of the article is structured as follows: Section 2 provides a concise description of the problem studied. Section 3 presents the mathematical formulation of the bi-objective two-stage stochastic programming model. Section 4 describes our case study for testing the model and the corresponding results are discussed in Section 5. Section 6 finally concludes our findings.

2. Problem description

This article examines the choice of alternative fuel and power systems from a techno-economic perspective and a shipowner's viewpoint, considering the complexities named in Section 1. Given that the selection among alternative fuels and corresponding systems is a compromise between cost and emission (Trivyza 2019, Lagemann et al. 2022a), the problem can be summarized as: "What are the best ship fuel and power systems today, given significant uncertainty with respect to the development of fuel and carbon prices in the future?". Similar to Balland et al. (2013) we refer to this problem as "ship fuel and power system selection under uncertainty".

Lagemann et al. (2022a) showed that even under an assumed known, deterministic scenario, retrofits can be among the optimal compromises. Considering recourse options (King and Wallace 2012, Pantuso et al. 2016), here in the form of retrofits, may thus be even more important when trying to handle uncertainty. Moreover, fuel switches between compatible fuels, say fossil liquified natural gas (LNG) to its electro counterpart (e-LNG), are recourse options without a switch cost nor option cost, but obviously entailing operational costs for the fuel.

The choice of fuel and respective power system also leads to consequences for the ship's cargo-carrying capacity: Since fuels that are based on different energy carriers, for example very low sulfur fuel oil (VLSFO) and LNG, have different net energy densities (both weight- and volume-wise), a ship with the same engine efficiency needs to be either larger to achieve the same cargo-carrying capacity and increase the installed power or keep the installed power but lose some cargo-carrying capacity. In this article, we choose the second option as we consider this more sensible for retrofits.

The most important decision in the problem outlined is the choice of power system to invest in today. For such urgent here-and-now decisions under uncertainty, two-stage stochastic programming has shown to be a suitable solution technique (King and Wallace 2012, Balland et al. 2013). In two-stage stochastic programming, the uncertainty is accounted for by a set of stochastic scenarios, in the presence of which the program needs to optimize. The next section explains how we map the described problem to a bi-objective two-stage stochastic programming model as well as how the scenario trees unfold.

3. Model formulation

The mathematical formulation of the stochastic programming model is explained in the following subsections. Subsection 3.1 describes the model notation; Subsection 3.2 outlines the mathematical model with objective functions and constraints and Subsection 3.3 aims to visualize the problem formulation by outlining how the here-and-now decisions are connected to the stochastic scenario tree. The model presented herein builds on top of the bi-objective deterministic model presented by Lagemann et al. (2022a) and the single-objective scenario application described by Lagemann et al. (2022b).

3.1. Notation

Sets

Set	Description	Modeling comment
$\mathbb{T}$	set of discrete **time periods**, indexed by t	
$\mathbb{F}$	set of **fuel options**, indexed by f	refers to main chemical composition and physical state
$\mathbb{S}$	set of pre-generated **ship system options** for energy storage and power conversion, indexed by s	refers to a ship with an energy storage of a certain type and size, and a power converter of certain type and size
Ω	set of **scenarios**, indexed by ω	complete realization of random parameters

Parameters

Parameter	Description	Modeling comment
C_s^N	**newbuild cost** of ship with system option s	Static parameter
$C_{s`st}^R$	**retrofit cost** from option s' to option s for period t	Discounted static parameter
$C_{ft\omega}^F$	**fuel cost** of fuel f at time period t in scenario ω	Discounted stochastic parameter
P_ω	**probability of scenario** ω	
C_{st}^{LO}	**lost opportunity cost** of system s per time period t	Discounted static parameter
B	**energy consumption** per time period	assuming the fuel conversion efficiencies do not change over time, equidistant time periods
E_f^{WTT}	**well-to-tank emissions** of fuel f	
E_f^{TTW}	**tank-to-wake emissions** of fuel f	assuming tank-to-wake emissions do not change over time.
K_{fs}	1 if fuel f and system s are **compatible**, 0 otherwise	Required since fuel and power system are modelled as separate decisions
ε	constraint on global warming potential	ε-constraint method, ε iteratively increased

Decision variables

$x_{ft\omega}$	1 if **fuel** f is chosen at time t in scenario ω, 0 otherwise
x_{f1}	1 if **fuel** f is chosen in period 1, 0 otherwise
$y_{st\omega}$	1 if **ship system option** s is chosen at time t in scenario ω, 0 otherwise
y_{s1}	1 if **ship system option** s is chosen in period 1, 0 otherwise
$r_{s`st\omega}$	1 if **retrofit** is to be made from system option s' to system option s at the beginning period t in scenario ω, 0 otherwise

3.2. Mathematical model

Objectives

Our first objective, minimizing the expected total cost of ownership (ETCO), is defined as:

$$\min\ ETCO = \sum_{s\in\mathbb{S}}\left[\underbrace{C_s^N \cdot y_{s1}}_{building\ cost} + \sum_{\omega\in\Omega} P_\omega \left[\sum_{t\in\mathbb{T}}\left(\underbrace{C_{st}^{LO} \cdot y_{st\omega}}_{lost\ \ opportunity\ \ costs} + \sum_{s`\in\mathbb{S}}\underbrace{C_{s`st}^R \cdot r_{s`st\omega}}_{retrofit\ cost}\right)\right]\right] + \sum_{\omega\in\Omega}\sum_{t\in\mathbb{T}}\sum_{f\in\mathbb{F}}\underbrace{P_\omega \cdot B \cdot C_{ft\omega}^F \cdot x_{ft\omega}}_{fuel\ cost} \tag{1}$$

Carbon prices can be included implicitly through the fuel prices. The retrofit cost depends on the selected systems in two consecutive time periods. Since our model is meant to capture differences between solutions, we have excluded pure operational expenditures (OPEX), such as port fees or crewing, which would apply to all alternatives. The lost cargo-carrying capacity under alternative fuels is translated into lost opportunity costs and thus an economic penalty in the objective function. The separation of decision variables into fuel ($x_{f1}, x_{ft\omega}$) and power system ($y_{s1}, y_{st\omega}$) enables considering multi-fuel engines in the model.

We define our second objective as minimizing the expected global warming potential (EGWP) over the entire ship lifetime and weighted by the probability of each scenario:

$$\min\ EGWP = \sum_{\omega\in\Omega} P_\omega \cdot \sum_{t\in\mathbb{T}}\sum_{f\in\mathbb{F}} B \cdot E_f^{WTW} \cdot x_{ft\omega} \tag{2}$$

subject to:

First stage:

$$\sum_{f\in\mathbb{F}} x_{f1} = 1 \tag{3}$$

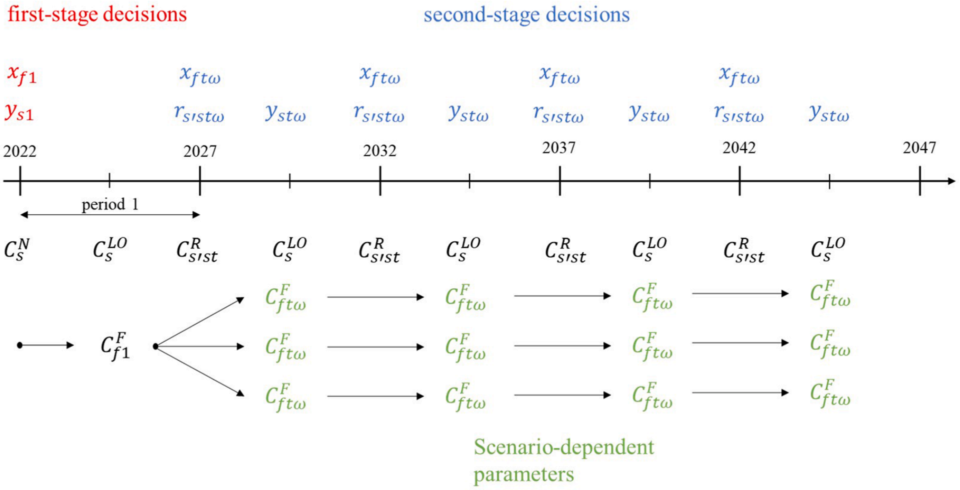


Fig. 1. Connection between decisions and scenario-tree.

$$\sum_{s\in\mathbb{S}} y_{s1} = 1 \tag{4}$$

$$x_{f1} + y_{s1} \leq 1 + K_{fs} \quad f \in \mathbb{F}, s \in \mathbb{S} \tag{5}$$

$$y_{s1} \in \{0,1\} \quad s \in \mathbb{S} \tag{6}$$

$$x_{f1} \in \{0,1\} \quad f \in \mathbb{F} \tag{7}$$

Constraint (3) ensures that only one ship system option is selected at the first time step. Likewise, Constraint (4) enforces only one fuel to be selected for the initial period. Constraints (5) ensure compatibility of the selected fuel and power system. Constraints (6) and (7) declare that the decision variables x_{f1} and y_{s1} are of binary type.

Second stage:

$$y_{s1\omega} = y_{s1} \quad s \in \mathbb{S}, \omega \in \Omega \tag{8}$$

$$x_{f1\omega} = x_{f1} \quad f \in \mathbb{F}, \omega \in \Omega \tag{9}$$

$$\sum_{f\in\mathbb{F}} x_{ft\omega} = 1 \quad t \in \mathbb{T}, \omega \in \Omega \tag{10}$$

$$\sum_{s\in\mathbb{S}} y_{st\omega} = 1 \quad t \in \mathbb{T}, \omega \in \Omega \tag{11}$$

$$x_{ft\omega} + y_{st\omega} \leq 1 + K_{fs} t \in \mathbb{T}, \quad f \in \mathbb{F}, s \in \mathbb{S}, \omega \in \Omega \tag{12}$$

$$y_{s'(t-1)\omega} + y_{st\omega} - 1 \leq r_{s'st\omega} \quad s', s \in \mathbb{S}, t \in \mathbb{T}\backslash\{1\}, \omega \in \Omega \tag{13}$$

$$y_{s'(t-1)\omega} + y_{st\omega} \geq 2r_{s'st\omega} \quad s', s \in \mathbb{S}, t \in \mathbb{T}\backslash\{1\}, \omega \in \Omega \tag{14}$$

$$r_{s'st\omega} = 0 \quad s', s \in \mathbb{S}, t = 0, \omega \in \Omega \tag{15}$$

$$x_{ft\omega} \in \{0,1\} \quad f \in \mathbb{F}, t \in \mathbb{T}, \omega \in \Omega \tag{16}$$

$$y_{st\omega} \in \{0,1\} \quad \mathrm{s} \in \mathbb{S}, t \in \mathbb{T}, \omega \in \Omega \tag{17}$$

$$r_{s'st\omega} \in \{0,1\} \quad \mathrm{s}', \mathrm{s} \in \mathbb{S}, t \in \mathbb{T}, \omega \in \Omega \tag{18}$$

Constraints (8) and (9) link the first stage decision variable to the second stage. Similar to the first stage, constraints (10) and (11)

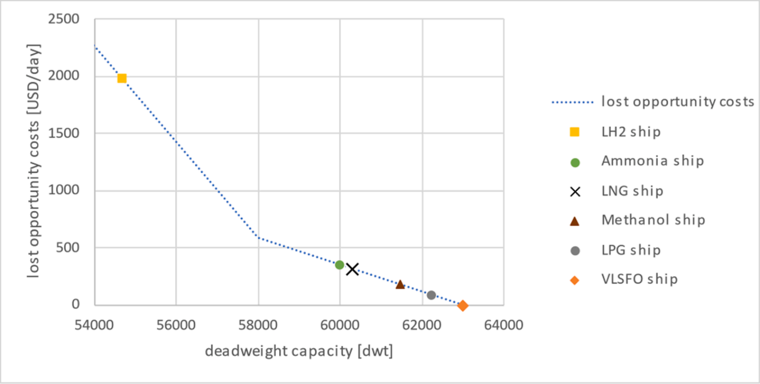


Fig. 2. Daily lost opportunity costs for constant range and energy efficiency.

make sure that exactly one fuel and one ship system option are selected for each time period. Constraints (16) to (18) ensure that also the second stage decision variables are of binary type.

Constraints (12) imply that a fuel and system can only be selected at the same time when compatible. A switch from system s' to another system s in consecutive periods triggers the retrofit variable $r_{s'st\omega}$. This is mathematically defined in constraints (13) to (15).

Additional constraints on emissions, e.g., a Carbon Intensity Indicator (CII), could be added to the problem. This is not done for this paper to maintain simplicity of the model and thus traceability of the results.

The defined model is a two-stage bi-objective binary programming model and can be implemented by means of a commercial solver. The bi-objective nature of the model means that we will obtain Pareto set of non-dominated compromise solutions. To identify this Pareto set, constraint (19) applies the epsilon-constraint method to our second objective:

$$EGWP \leq \varepsilon \tag{19}$$

The parameter ε is iteratively reduced to the EGWP of the cheapest solution found during the previous iteration.

3.3. Scenario trees

We have defined the choice of fuel and power system for the first period as the important here-and-now decisions, because they are most urgent for a shipowner and need to be implemented immediately. The decision variables thus make up the first-stage decisions, as defined in constraints (6) and (7). Fig. 1 aims to explain the relation, in particular the timing, between first-stage decisions to be made and the point when the initial uncertainty resolves. As can be seen in the Figure, this point of resolving uncertainty is after period 1. The main first-stage decision, what ship to invest in, thus needs to be made in the presence of uncertainty, i.e., without knowing which scenario will actually unfold.

As can be seen, the uncertainty resolves after the first time period (period 1), i.e., the further course of fuel prices over time becomes known. The assumption that the fuel prices become known for all consecutive time periods is a modelling feature of two-stage stochastic programming (King and Wallace 2012) and does not affect the outcome of the first-stage decisions. For the first time period, i.e. from 2022 to 2027, fuel prices are assumed to be known, which is certainly a strong assumption. The assumed known price, however, is simply based on the expected value for the stochastic fuel price and likewise is more of a modelling requirement than an additional assumption on top of the probability distributions. The key feature of the model is that is allows accounting for many possible futures, rather than one single deterministic scenario.

4. Case study

This section sketches the case study to which we apply the model developed in Section 3. Subsection 4.1 deals with the general deterministic inputs for our case study, while Subsection 4.2 describes how the uncertainty is accounted for during scenario generation. Again, our goal is not to optimize *within*, but *across* scenarios – we do not know what is going to happen.

4.1. Description of the case

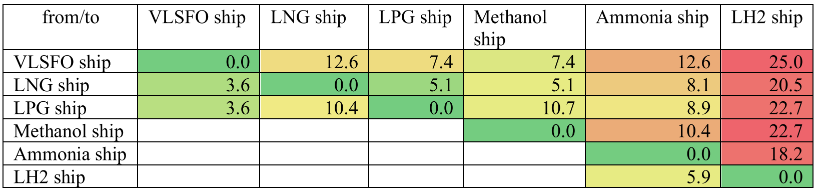
We apply our model to a generic Supramax dry bulk carrier which is to be replaced. The shipowner and designer thus need to select among alternative fuels and power systems for the vessel. Supramax carriers are traditionally designed for maximum cargo-carrying capacity within the beam of the old Panama Canal locks (32.3 m). They typically have a length of about 200 m and a draught around 13.5 m, resulting in 58,000–65,000 tonnes deadweight capacity. Five cargo holds, served by four slewing cranes, accommodate the dry

Table 1
CAPEX and lost opportunity costs.

		Ship power system option, s					
		1	2	3	5	6	7
	parameter	VLSFO ship	LNG ship	LH2 ship	Ammonia ship	LPG ship	Methanol ship
	Engine costs [USD/kW]	400	800	1500	1000	600	600
	Tanks and add-ons [USD/kW]	0	600	1200	400	200	200
C_s^N	newbuilding price [mUSD]	30	37.5	47.5	37.5	33	33
C_{st}^{LO}	lost opportunity costs per 5 years [mUSD]	0	0.5	3.0	0.5	0.1	0.3
K_{fs}	compatible fuels	VLSFO, Bio-diesel, E-diesel	Bio-LNG, E-LNG, fossil LNG	Liquid E-hydrogen, liquid NG-hydrogen	E-ammonia, NG-ammonia	fossil LPG	Bio-methanol wood, bio-methanol waste stream, E-methanol

As for the retrofit costs, we use the same system-based cost factors as for newbuilds (Lindstad et al. 2021b), plus an additional penalty of 3.6 mUSD to account for shipyard costs and lost income during retrofitting. The resulting retrofit costs between options are shown in Table 2. Blank fields indicate no retrofit option when the focus is on reducing GHG, computationally modelled by a very large cost penalty.

Table 2
Retrofit costs, cheap (green) to more expensive (red).



from/to	VLSFO ship	LNG ship	LPG ship	Methanol ship	Ammonia ship	LH2 ship
VLSFO ship	0.0	12.6	7.4	7.4	12.6	25.0
LNG ship	3.6	0.0	5.1	5.1	8.1	20.5
LPG ship	3.6	10.4	0.0	10.7	8.9	22.7
Methanol ship				0.0	10.4	22.7
Ammonia ship					0.0	18.2
LH2 ship					5.9	0.0

bulk cargo. Supramax bulk carriers are a relevant segment in terms of global shipping emissions, as they constitute almost a quarter of the global dry bulk fleet (Bengtsson 2018) and provide about 10% of the global transport work in ton-miles. Due to the generic nature and relatively few ship-specific inputs needed, the model could however easily be applied to other shipping segments.

Conventional Supramax bulk carriers are powered by fuel oil (HFO or VLSFO). We use a VLSFO configuration as a reference for comparison in our case study. As briefly outlined in Section 2, we keep the total displacement constant for all power systems and reduce the cargo-carrying capacity for power systems that require more weight or space than the reference VLSFO configuration. The lost cargo-carrying capacity is accounted for by means of a lost opportunity cost. In order to calculate the lost opportunity cost, we assume an average utilization of 90% for the first 58,000 dwt and 25% utilization for the following 5,000 dwt. We assume a charter rate of 25,000 USD/day (Handybulk 2022), which is split proportionally over the mentioned deadweight ranges weighted with their average utilization. This results in a piecewise linear function for the lost opportunity costs, displayed in Fig. 2. For that figure, we keep the range and energy efficiency constant and only replace the energy carrier.

As compared to Lagemann et al. (2022a), the part of our method for calculating the cargo-carrying capacity has been refined by accounting for potentially lower volumetric power system density. In essence, energy carriers such as methanol that can be integrated into the ship structure are penalized based on excess weight, while energy carriers that cannot be integrated are penalized based on either excess weight or excess volume. Thus, the lost cargo-carrying capacity is now computed by

$$w_s^{lostcargo} = max\left(w_s^{fuelcontained} - w_{VLSFO}^{fuelcontained}; v_s^{excess} \cdot \rho^{cargo}\right) \tag{20}$$

Where $w_s^{fuelcontained}$ is the weight of the contained fuel (including tanks) for each power system s, $w_{VLSFO}^{fuelcontained}$ is the weight of the fuel for the baseline VLSFO configuration and ρ^{cargo} the cargo density, here assumed as simply 1 t/m^3. The required volume for fuel tanks, in excess of what is freely available on the open deck, is calculated as

$$v_s^{fuelexcess} = max\left(0, v_s^{fuelcontained} - v^{free}\right) \tag{21}$$

Where $v_s^{fuelcontained}$ is the contained fuel volume (incl. tanks) and v^{free} the freely available volume, i.e., volume available for fuel storage without any impact on the cargo-carrying capacity. The contained fuel volume $v_s^{fuelcontained}$ is set to zero for integral tanks (e.g., VLSFO, methanol) and the freely available volume is assumed as roughly 1600 m^3, based on the space behind the deckhouse of a typical Supramax carrier.

Over the past years, newbuilding prices for the VLSFO reference configuration have circled around roughly 30 mUSD (Hellenic Shipping News 2022). Deducting the costs of the VLSFO power system yields a cost of roughly 27 mUSD for a vessel without any power system. Using a system-based (Levander 2012) cost estimation approach with cost factors per unit power as proposed by Lindstad et al.

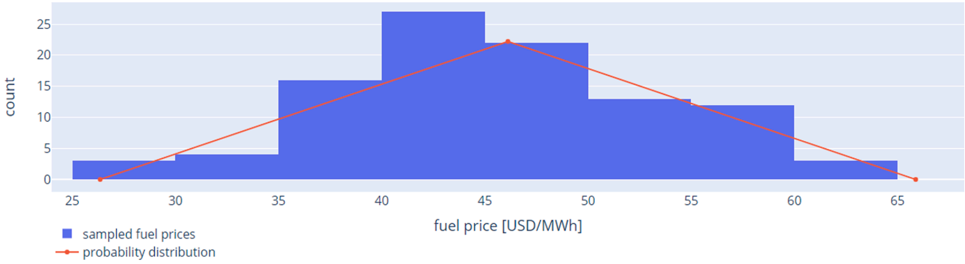


Fig. 3. Sampled and discounted fuel prices for VLSFO in period 1, set with 100 scenarios.

Table 3
Upper and lower bound fuel costs and GWP factors.

			Environmental impact	Economic impact	
Energy carrier	Feed-stock	Fuel label	GWP WTW per fuel energy unit [gCO$_{2eq}$/kWh]	Upper bound cost [USD/MWh]	Lower bound cost [USD/MWh]
Diesel	Fossil	VLSFO	331.6 [1]	95 [2]	38 [2]
	Bio	bio-Diesel	220.0 [5]	128 [3]	93 [3]
	electro	e-Diesel	4.5 [1]	423 [2]	131 [2]
Methane	Fossil	LNG	305.4 [1]	81 [2]	32 [2]
	Bio	bio-LNG	55.7 [1]	119 [3]	89 [3]
	electro	e-LNG	6.0 [1]	358 [2]	115 [2]
LPG	Fossil	LPG	267.5 [1]	98.3 [2]	39.3 [2]
Methanol	Fossil	Methanol	366.1 [1]	210 [2]	90 [2]
	Bio	bio-Methanol	115.9 [1]	97 [3]	66 [3]
	electro	e-Methanol	3.5 [1]	385 [2]	116 [2]
Ammonia	Fossil	Ammonia	106.1 [1], [4]	220 [2], [6]	56 [2], [6]
	electro	e-Ammonia	19.0 [1]	220 [2]	80 [2]
Hydrogen	Fossil	LH2	108.7 [1], [4]	245 [2], [6]	55 [2], [6]
	electro	e-LH2	0.0 [1]	245 [2]	79 [2]

Sources and comments:
[1] Lindstad et al. (2021a).
[2] Lindstad et al. (2021b).
[3] Korberg et al. (2021).
[4] assuming 80% CCS efficiency.
[5] Sustainable Shipping Initiative (2019).
[6] Upper bound 100% of electricity-based pendant, lower bound 70% of electricity-based pendant.

(2021b) and an installed power of 7500 kW, we arrive at the newbuilding cost estimations as shown in Table 1.

Decisions and potential costs lying in the future usually have less of an impact on here-and-now investments, particularly when evaluating flexibility (De Neufville and Scholtes 2019). Costs incurring in the future (i.e., lost opportunity costs, retrofit costs and fuel costs) are thus discounted (Benford 1965) and we assume an annual discount rate of 5% over the entire time horizon.

4.2. Scenario generation

Section 1 described that large uncertainty is related to future fuel prices as well as carbon prices. In order to separate and somewhat isolate the impact of these uncertainties, we generate two scenario sets:

1. A scenario set with stochastic fuel prices
2. A scenario set with stochastic fuel prices and stochastic carbon prices

The mathematical model will then be applied to one set of scenarios at a time, and within this set optimizes across scenarios.

Sampling of fuel prices

Most studies estimating future prices for alternative fuels give high- and low-price scenarios (Lloyd's Register and UMAS 2020, DNV GL 2020, Lindstad et al. 2021b), due to the many uncertain parameters involved in such estimates. This approach is certainly helpful for investigating best- and worst-case scenarios for specific fuels and thus assessing the robustness of different options. However, it is more unlikely that all independent parameters in the estimation are unfavorable (or favorable) than that only some of them are unfavorable (or favorable) for the fuel price. Therefore, a probability distribution, that assigns higher probability to

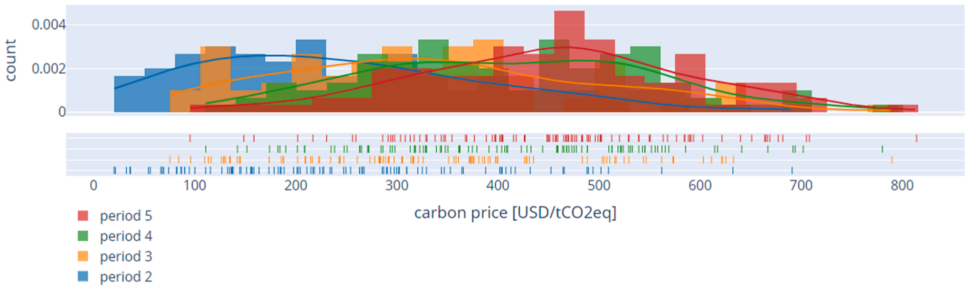


Fig. 4. Sampled carbon prices for 100 scenarios with five time periods.

intermediate values, seems natural. For this study, we assume a simple triangular probability distribution between lower and upper bound fuel prices. This is of course not 100% correct, but we do so on the basis the following argument: It is impossible to accurately know the probability distribution for future, currently non-existing, fuels beforehand. Even in retrospective, this may be hard. One can certainly fit a probability distribution to any historic volatile curve, but it is debatable whether the derived probabilities would be applicable to future developments on the long run. Pantuso et al. (2015), however, argue that it is not always necessary to be right on the probability distribution. It may often be more important that uncertainty is accounted for *at all*.

The main uncertainties affecting fuel costs may have different origins. For example, Lindstad et al. (2021b) show that the cost of electricity is a main determinant for the price of electro-fuels. Similarly, the cost of biomass as a feedstock influences the cost of bio-fuels to a significant extend. Trivyza (2019) finds that prices for conventional fossil fuels have historically been strongly correlated with prices for HFO by around 90%. Keeping in mind that we want to address long-term uncertainty rather than short-term volatility, we take the following approach in this article: We assume that fuel prices within each group of fuels (fossil, bio- and electro-fuels) are perfectly correlated and we draw a random number for each group of fuels and each discrete time period per group of fuel. That is, for generating the first time period for the first scenario, we draw three independent random numbers, based on a triangular probability distribution, which are used to compute the fuel price for fossil, bio- and electro-fuels, respectively. Based on the drawn random number per fuel group, the computation of fuel prices is a simple interpolation between lower and upper bound:

$$C^F_{ft\omega} = C_f^{F,lower\_bound} + \left(C_f^{F,upper\_bound} - C_f^{F,lower\_bound}\right)\cdot random\_number\_per\_group_{t\omega} \tag{22}$$

Thus, the numbers are drawn independently per group of fuel, time period and scenario. Fig. 3 visualizes the probability distribution and sampling of scenarios for VLSFO in period 1.

The numbers used as estimates for the lower and upper bound fuel prices are shown in Table 3. The global warming potentials (GWPs) are primarily based on the life cycle assessment by Lindstad et al. (2021a), complemented with data from Korberg et al. (2021) and Sustainable Shipping Initiative (2019) on biofuels. The GWPs are given for a 100-years period. As for the price estimates in Table 3, we refer to Lindstad et al. (2021b) for fossil as well as electro-fuels and Korberg et al. (2021) for bio-fuels, scaled with a biomass price between 5 and 10€/GJ and finally converted to USD.

It should be noted that different sources can employ different accounting techniques for bio-fuel emissions. Some account for combustion emission already during the production of such fuels. Due to the linear nature of our model though, what matters is only the sum of well-to-tank and tank-to-wake emissions, not the accounting technique. Thus, the GWP factors in Table 3 represent emission per unit energy of the fuel on a well-to-wake basis (WTW). That is, they represent roughly 50% of the GWP factors per unit break power for a large two-stroke engine, with the exact value dependent on the engine's efficiency.

Scenario set generation with and without carbon pricing

To date, there have been multiple discussions on enforcing an MBM in the shipping sector. At the IMO, several member states stand in favor of a carbon levy that will incentivize the stakeholders to opt for low carbon systems onboard their vessels. On the other hand, there have also been proposals in favor of an Emissions Trading System (ETS) that ultimately sets a cap on emissions and lets the market (supply and demand for carbon allowances) to settle on a price for carbon. The implementation of a levy in principle provides certainty on investments as that the level of carbon pricing is pre-decided from the regulators. In this way, stakeholders are able to foresee the increase on their operational expenses and decide whether or not to invest in abatement technology (Lagouvardou et al. 2022). On the other hand, in the case of an ETS, and as indicated from the evolution of carbon pricing from different ETS, the price can be very volatile (Lagouvardou et al. 2020). The certainty on emissions reduction is in practice easily dismissed by grandfathering, e.g., provisions of free allowances, leading to a too low carbon price set by the market to incentivize investments into carbon abatement systems.

Despite the fundamental differences of these two schemes, what is most important for this study is the level of uncertainty that derives from these two most prominent MBMs and the discussion around them. From today's perspective, the carbon price in, say 20 years from now, in practice appears to be uncertain both under an ETS and a levy-based MBM. Our model aims to address this resulting uncertainty on the following three premises: First, the case of no emission pricing can be seen as a special variant with 0 costs for emissions. Second, no matter whether the MBM will be a levy, ETS or any other system, there will be an average price for emissions

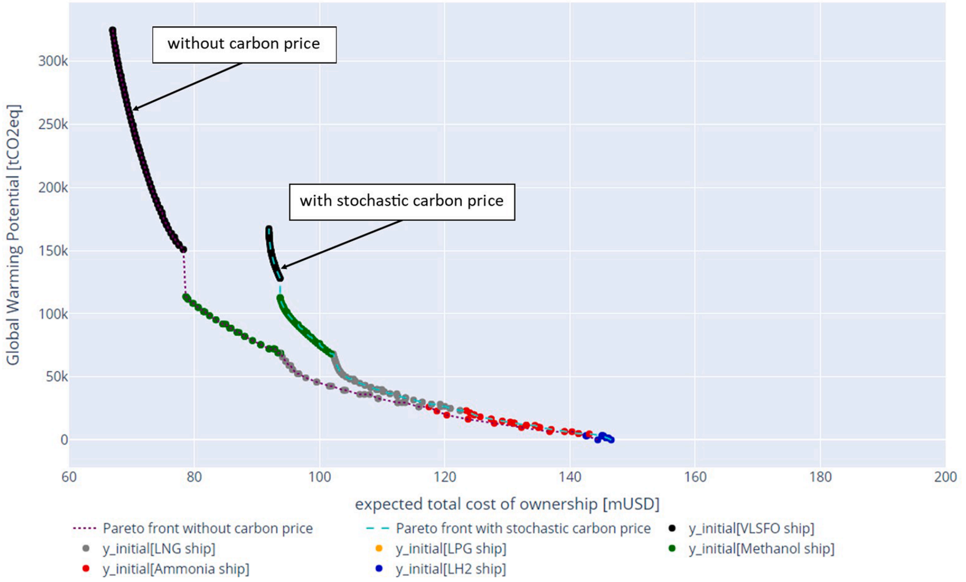


Fig. 5. Pareto front for initial power system configurations with and without carbon price, 100 scenarios.

over any discrete time period. Third, this average long-term development of the emission price level is currently uncertain.

Estimating a long-term probability distribution for carbon prices is thus challenging, as there is currently no global carbon pricing scheme in place and hence a lack of comparative data (Cullinane and Yang 2022). The probability distribution can thus only be based on local carbon pricing systems as well as ongoing discussions and proposals at IMO level (Lagouvardou et al. 2020). The following arguments have led us to apply a beta-variate distribution with alpha = 1.5 and beta = 5, which is scaled to a carbon price range between 0 and 1000 USD/tCO_{2eq}: Currently and historically discussed pricing levels have a large variance, ranging from a few USD/tCO_{2eq} to prices in the order of several hundred USD/tCO_{2eq}. The choice of range is supposed to account for low-probability but high-impact tail effects. The resulting distribution, visualized in Fig. 4, peaks at about 100 USD/tCO_{2eq} which is not far away from current EU ETS levels (Trading Economics 2022) and coincides with a proposal from the Marshall and Salomon Islands (IMO MEPC 2021).

On top of the outlined considerations on ranges and peaks, we apply a path-dependency for carbon prices as follows: Both theory (Center for Climate and Energy Solutions 2013, Mundaca et al. 2021) and historic data for the EU ETS (Trading Economics 2022) suggest that carbon prices should generally increase over time. The same can be said about many proposals discussed at the IMO, which are thought to increase over time (Lagouvardou and Psaraftis 2022). However, effects such as grandfathering have in practice shown to have a lowering effect on carbon prices. We aim to capture both the theoretical and practical considerations in our model, by restricting the carbon price of a consecutive period to not fall below 80% of the previous period. That is, when drawing a random number from the beta-variate probability distribution, the number is simply rejected and a new number drawn, until the carbon price is equal to or higher than 80% of the carbon price of the previous period. Fig. 4 illustrates the resulting sampled carbon prices for the four consecutive time periods. As there is currently now global carbon pricing system in place (zero carbon price for period 1), the random sampling applies from period 2 onwards.

It seems natural and important to question the choice of this probability distribution. It cannot be seen as a probability distribution based on empirical frequency, but rather on belief or expectations (Köhn 2017). Similar to Subsection 4.1 and based on the findings of Pantuso et al. (2015), we deem it more important to account for the uncertainty *at all* – including the mentioned features – than to be absolutely right on the actual distribution. However, in order to separate the effects of random fuel prices from random carbon prices, we use two sets of scenarios, one without carbon price and one with the explained stochastic carbon price features.

Since the stochasticity is dealt with by sampling in the scenario generation, we assign equal probability to each of the generated scenarios:

$$P_\omega = \frac{1}{|\Omega|} \tag{23}$$

Both fuel and carbon prices are discounted with a rate of 5% as in Subsection 4.1. The carbon price is added to the fuel price per unit energy based on the WTW GWP potential. The sampled scenarios with corresponding fuel prices over time are stored as dictionaries in Python.

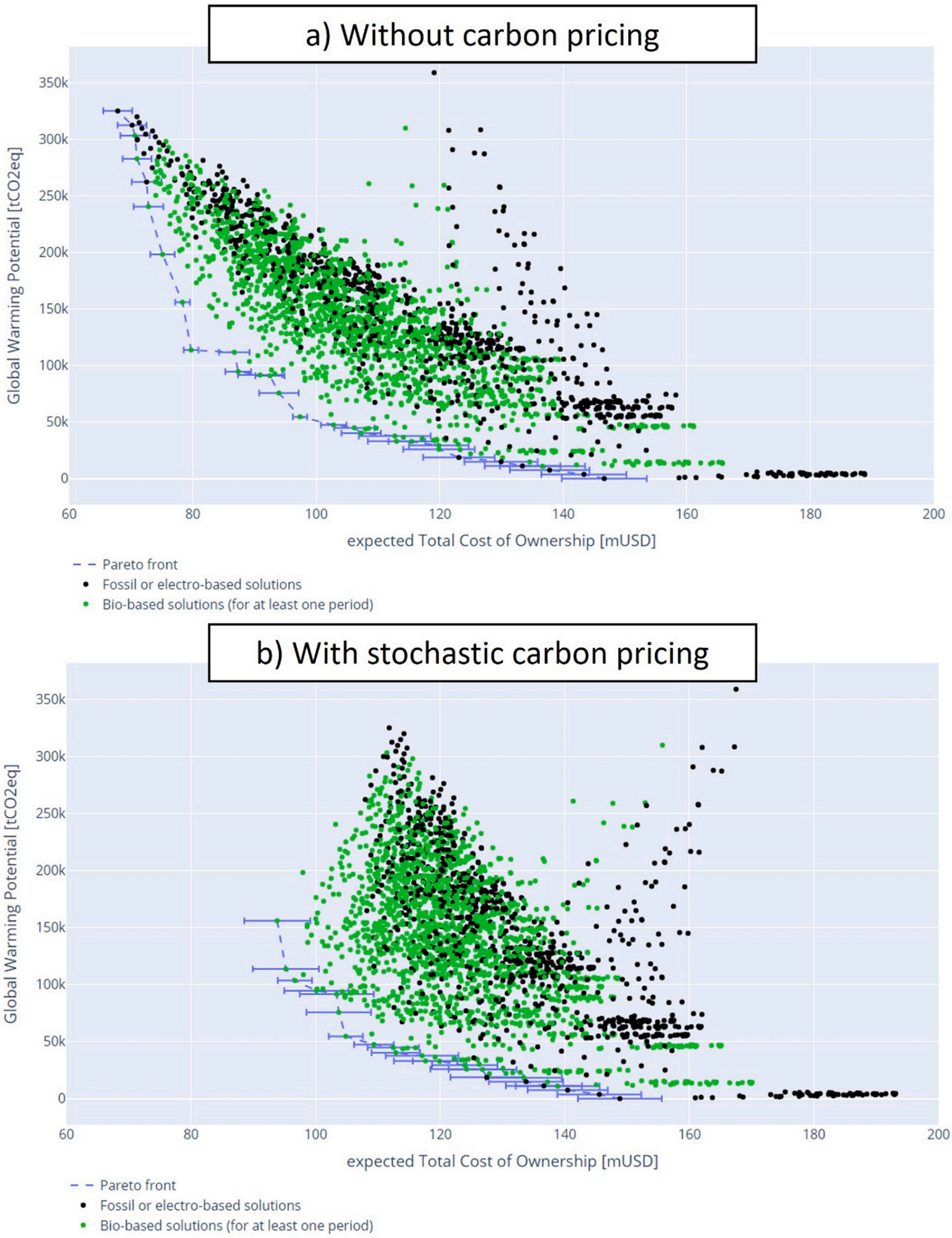
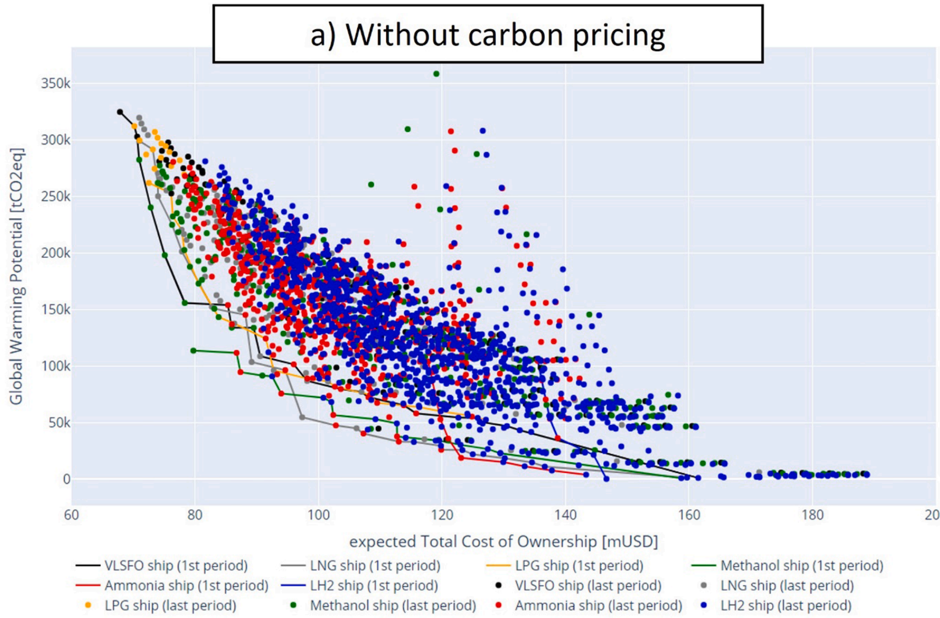


Fig. 6. Permissible combinations of fuels and power systems without (a) and with stochastic carbon price (b).

5. Results and discussion

We present and discuss the results of our case study in Subsection 5.1. Subsection 5.2 touches on the effect of alternative carbon price trajectories, which can be relevant from a policy perspective.



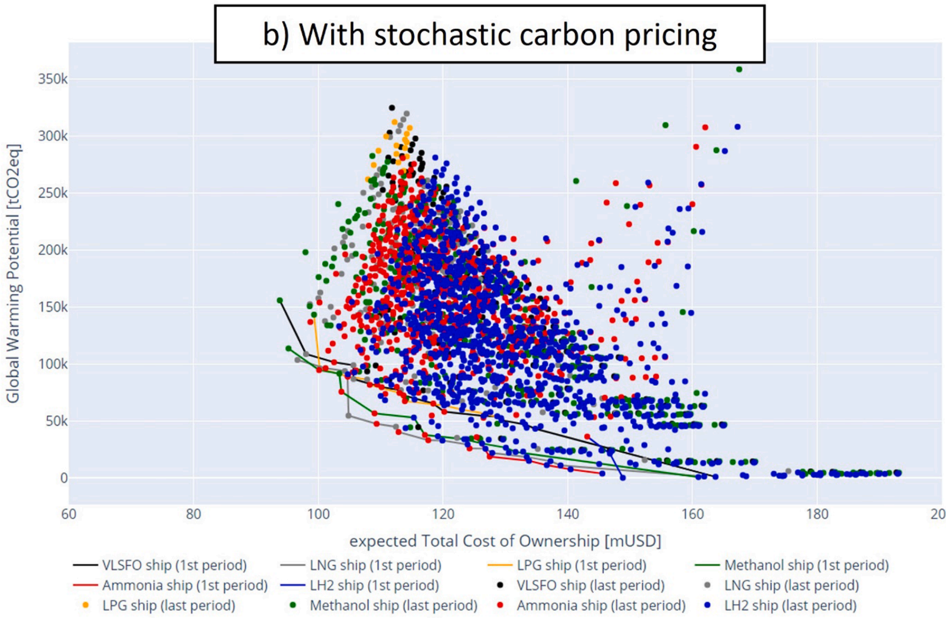


Fig. 7. Permissible combinations showing power system transitions, without (a) and with stochastic carbon price (b). Lines indicating Pareto solution departing from initial power system, dots indicating the power system in the last period.

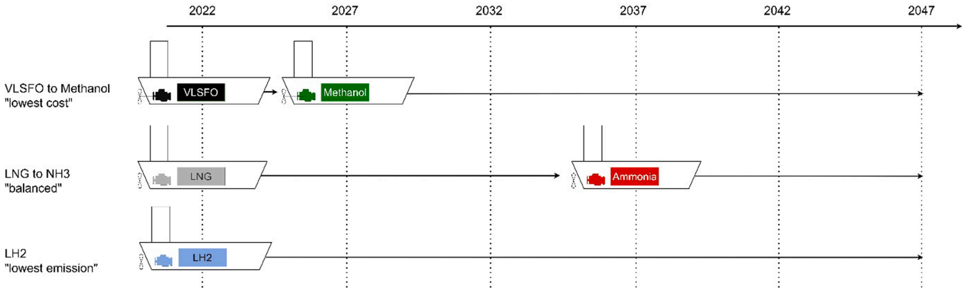


Fig. 8. Lifetime illustration of three Pareto-optimal configurations under stochastic carbon pricing.

5.1. *Case study results*

The stochastic model is implemented in Python and solved with the commercial optimizer Gurobi 9.5. We have investigated the in-sample stability of our stochastic model by tracing the objective values of Pareto-optimal fuel-system combinations over 10 sampled scenario sets with a size of 20, 100 and 500 scenarios respectively. The results showed a decrease in the objective functions' relative standard deviation from 1.0% (20 scenarios) to 0.2% (500 scenarios). Recall that one scenario represents one complete realization of uncertain external parameters, i.e., fuel and carbon prices. In order to avoid excessive runtime, we have selected 100 as an appropriate scenario set size throughout this paper. On an ordinary laptop computer it takes approximately 70 min to solve the model for 100 scenarios.

Fig. 5 shows the Pareto-optimal solutions for both a scenario set without and with carbon pricing, as described in the previous section. We focus on the first-stage decisions. Therefore, the color of each dot denotes the identified optimal power system.

The commercial optimizer helps finding solutions on the Pareto front, but does not provide much insight beyond the Pareto front. For this particular problem - and in contrast to many other cases - we can also use brute force to generate all feasible solutions in order to obtain additional insight. We therefore implement the model in way that it computes the costs and emissions within each and finally across all scenarios for all permissible combinations of power systems and fuels, similar to Lagemann et al. (2022a). This results in a cloud of points, which allows viewing solutions that might be interesting albeit not directly on the Pareto front. Fig. 6 displays the results of this brute force approach, again for a scenario set without (6a) and with (6b) carbon pricing. Each dot denotes a specific combination of fuel and power system for each period, and the dot's color signals whether a bio-fuel is used in one or more periods (green) or not (black). In addition, we show the standard deviation for the Pareto-optimal combinations.

We see that without carbon pricing, fossil fuels are among the Pareto-optimal combinations in the upper left corner. For reduced lifetime GHG emissions, bio-fuels become Pareto-optimal due to their lower cost compared to electro-fuels at only slightly higher emissions on average. For the very low end of lifetime emissions, bio-fuels do not seem suitable. Comparing these general findings with the scenario set for a stochastic carbon price, we observe that high-emission combinations with fossil fuels are penalized to an extent which makes them roughly equally expensive as low-emission combinations with electro-fuels. With stochastic carbon prices, the cheapest solution with bio-fuels reduces emission by 50%. Most Pareto-optimal solutions make use of bio-fuels at one or more periods. The question around availability of bio-fuels thus is important as it affects a shipowner's decision-making.

The brute force computation also allows tracing the specific power systems, see Fig. 7. The dot's color now denotes the system in the last period, while a line is generated for all Pareto-optimal combinations that start from a specific power system configuration. Both lines and dots have the same color for a specific power system (e.g., red = ammonia). This plot thus allows tracing power system transitions, i.e., potential retrofits after the first-stage decision for the initial power system is made. This can be valuable information for designer who aims to design an "future-energy-carrier-ready" ship. What energy carrier to be ready for thus becomes a relevant question.

Fig. 7 shows that the low-emission combinations on the Pareto front in many cases involve retrofits to ammonia or hydrogen. When comparing the sets without and with carbon pricing, we observe that methanol and LNG power systems remain in the absolute Pareto front, while LPG and VLSFO are rendered inferior by the stochastic carbon pricing for lower emission targets. This is an important observation and, if today's baseline is VLSFO, would signal a departure from status quo. We also note that the cheapest combination with methanol or LNG in the initial period does not include any retrofit, while Pareto-optimal combinations with lower GHG impact do. This could potentially mean that even if shipowners depart from status quo and invest in methanol or LNG, they may be required to retrofit. This depends on the development of future emission reduction legislation.

Although both the two-stage optimization and the brute force model are applied to exactly the same sets of scenarios, we recall their slight difference in perspective: While the two-stage optimization model solely focuses on the first-stage decisions, the brute force implementation traces fixed combinations of fuel and systems over time and across all scenarios. Both these perspectives suggest flexible solutions that enable low-cost retrofits (i.e., methanol and LNG power systems) along large portions of the Pareto front, which shows the value of flexibility under the current uncertainty. Fig. 8 illustrates three Pareto-optimal configurations under stochastic carbon pricing. The solutions displayed are the cheapest, the one with lowest emissions, as well as an intermediate one.

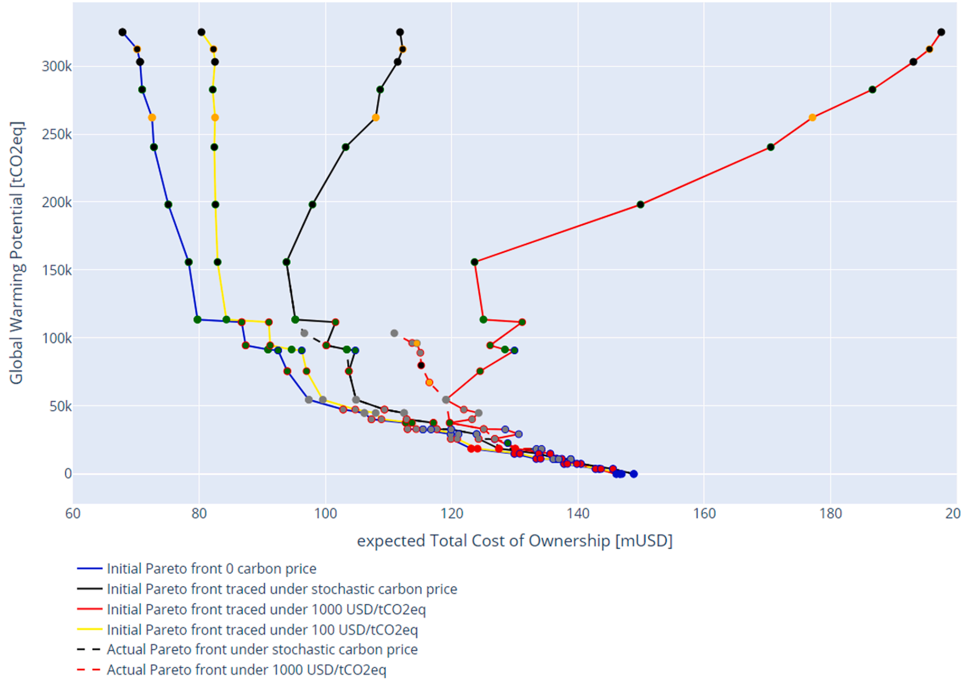


Fig. 9. Tracing the Pareto solutions for 0 carbon pricing (blue) under different conditions (yellow = 100 USD/tCO$_{2eq}$, black = beta-variate distribution for carbon prices, red = 1000 USD/tCO$_{2eq}$). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 4
Pareto set of initial power system configurations.

	a) without carbon pricing		b) with stochastic carbon pricing	
Initial power system	TCO, relative to VLSFO without carbon pricing	GWP, relative to VLSFO in all periods	TCO, relative to VLSFO without carbon pricing	GWP, relative to VLSFO in all periods
VLSFO	**100%** – 115%	**100%** – 48%	138%	48%
Methanol	117% – 138%	35% – 23%	140% – 153%	35% – 23%
LNG	143% – 176%	17% – 8%	143% – 182%	32% – 8%
Ammonia	182% – 212%	6% – 1%	187% – 215%	6% – 1%
LH2	216%	0%	219%	0%

Figs. 6 to 8 only present an excerpt of insight that can be gained from looking at solutions beyond the general Pareto front. The brute force computation technique thus not only helps to trace optimal solutions, but even more to identify the bad ones. The latter is particularly relevant for shipowners who simply aim to stay in business. Additional insight, among others from a policy-maker perspective, can be gained by plots such as Fig. 9 in Subsection 5.2. We supplement the online version of this article with interactive graphs, such that for each dot the combination of power system and fuel can be viewed on hovering. Additionally, Table 4 summarizes the Pareto set of initial power systems as shown in Fig. 9.

All TCO and GWP values in Table 4 are normalized by a ship running on VLSFO for all periods and without carbon pricing, such that relative GHG reductions and additional expenditures can be read.

For stochastic programs, it is common to compute the value of stochastic solution (VSS, Birge 1982). For our case study, the monetary VSS is generally found to be low. The value of solving the more complex stochastic program instead of a simpler deterministic expected value program, lies mainly in the clearer insight provided by the stochastic model. For the interested reader we have enclosed more information in the appendix.

Table 5
Alternative carbon price trajectories.

Scenario set label	Sampled scenarios	Fuel prices	Carbon prices	Color in Figure 9
0 carbon price	100	Stochastic	Deterministic 0 USD/tCO_{2eq}	Blue
100 USD/tCO_{2eq}	100	Stochastic	Deterministic 100 USD/tCO_{2eq}	Yellow
Stochastic carbon price	100	Stochastic	Stochastic beta-variate distribution	Black
1000 USD/tCO_{2eq}	100	Stochastic	Deterministic 1000 USD/tCO_{2eq}	Red

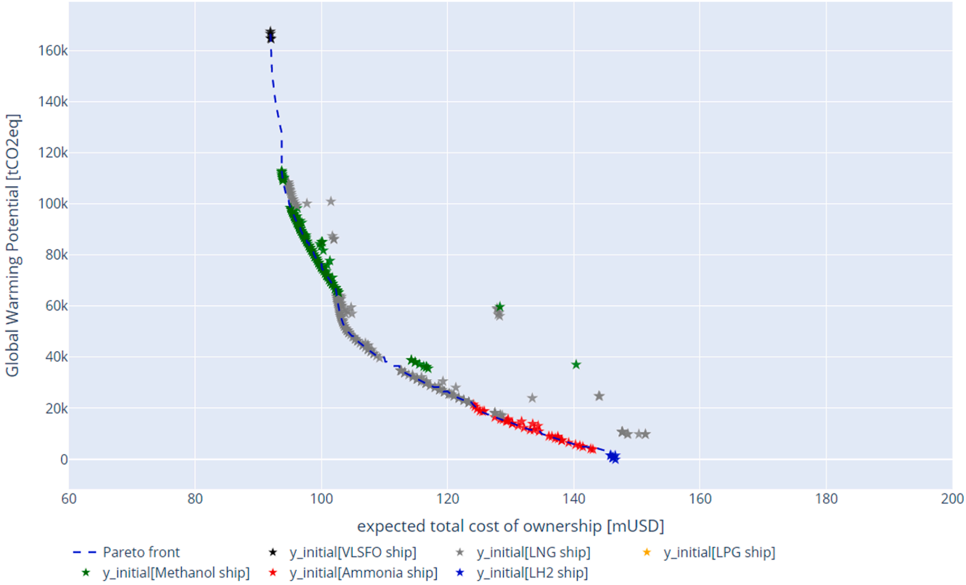


Fig. A1. Value of stochastic solution. Graphical comparison of first-stage solutions from deterministic and stochastic problem.

5.2. *Alternative carbon pricing policies*

In the previous sections, we have examined the effect the assumed carbon price distribution has on the problem of fuel selection. This distribution is based on expectations, grounded in anecdotal empirical support. For a shipowner, however, it may be sensible to investigate the effects of alternative carbon price trajectories on the choice of fuel and power system. From a policy perspective, this can provide additional insight into the incentive that a certain carbon price trajectory may have on a shipowner's decisions and thus the expectable emission reductions.

The generic formulation of the model enables a simple replacement of the scenarios and thus carbon prices. In order to assess the effect of different carbon price trajectories, we test the model with the scenario sets as shown in Table 5.

We use the brute force computation for tracing specific solutions. Fig. 8 shows the results of these computations. The blue continuous line indicates the Pareto front in the absence of any carbon price. The remaining continuous lines trace these so-derived Pareto-optimal combinations under different carbon price policies. The stippled lines indicate the actual Pareto front under the alternative carbon price policies as opposed to the initial Pareto front evaluated under the same scenario.

Besides of the different Pareto-optimal power system configurations, Fig. 9 shows that a fixed carbon price of 100 USD/tCO_{2eq} (yellow line) can render 60% emission reductions cost-competitive with fossil fuels. This may be interesting input from a policy-

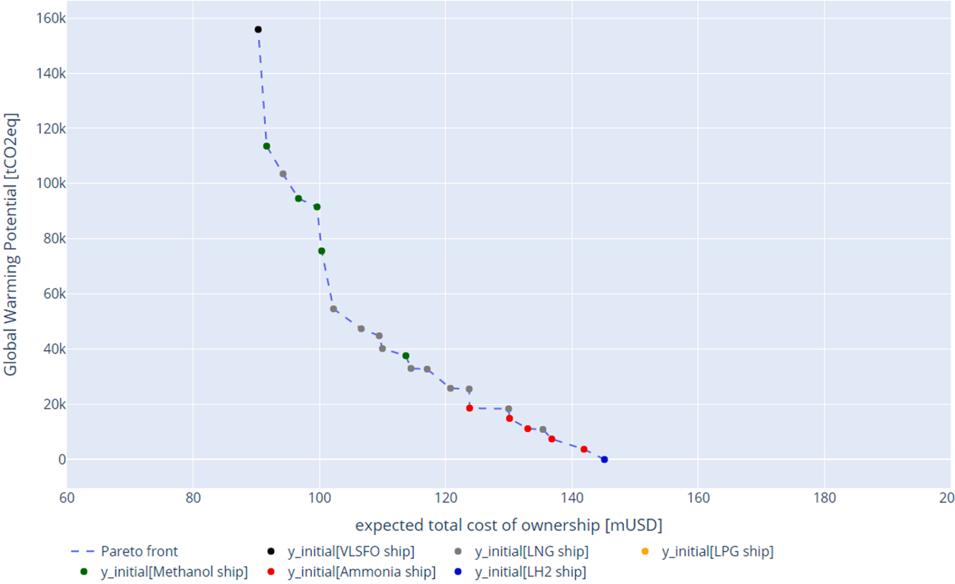


Fig. A2. Pareto front of the expected value-problem, one scenario.

perspective and shows that the model may be used to simulate a single shipowner's behavior, as far as techno-economic aspects are concerned, under different policy-schemes. Also, the actual Pareto front for the stochastic carbon price (black line) does not differ significantly from the initial Pareto front traced under the same conditions. This indicates that the introduction of a carbon price mechanism does not necessarily render completely different solutions optimal. Indeed, the Pareto-optimal solutions may be almost the same, except for the higher end of the emission spectrum. This point is underpinned by the actual Pareto front for the very high carbon price (red line), which coincides with the initial Pareto front in the very low end of the lifetime emission spectrum. Thus, low-emission configurations appear to be robust with respect to carbon prices, but this comes at cost penalty.

The strong similarity of Pareto fronts for 0, 100 and a stochastic carbon price also implies that, as long as the WTW scope is concerned, the optimal decisions are little dependent on whether the IMO opts for any market-based or a command-and-control policy: Both policies incentivize low-emission solutions, for which our Pareto fronts show little difference. From a practical perspective, it is thus almost indifferent which of these policies will be adopted as long as their ultimate reduction ambition is roughly 50% or more. The optimal solutions in that case will be in the lower end of the target emission spectrum, for which there is little difference in terms of here-and-now decisions. This does not apply to the scenarios with 1000 USD/tCO_{2eq} carbon price, for which the Pareto-optimal solutions contain a higher share of LNG ships and in addition LPG configurations with subsequent retrofits.

We have already pointed out that our model as is can provide additional insight from a policy perspective. Specific command-and-control trajectories, i.e., the effect of specific annual reduction goals, could easily be added to the model as hard constraints.

6. Conclusion

In this paper, we have outlined the use of a bi-objective stochastic programming model for the techno-economic selection of ship fuel and power systems. The model is meant to support the requirements elucidation phase (Andrews 2003), i.e., the working out of a new design's requirements specification.

The proposed model gave insight as to how the targeted lifetime global warming potential affects the choice of initial system configurations and the expected total cost of ownership both with and without carbon pricing and considering potential retrofits and fuel switches. The brute force implementation gave additional insight by showing that retrofits are not unlikely for Pareto-optimal solutions. From a shipowner perspective, both methanol and LNG appear to be relatively robust initial power system choices for a broad range of emission reduction ambitions. Both power systems enable low-cost fuel switches to bio- or electro-fuels, while LNG potentially also enables low-cost retrofits to, e.g., ammonia. These findings coincide with the current orderbook indicating that LNG and lately methanol engines are preferred options by shipowners (Chryssakis et al. 2023). From a policy perspective, our model can provide additional insight into a shipowner's decision-making under either uncertainty or specific carbon pricing policies. Our model can thus be used to inform about expected emission reductions under different policies.

The conclusions drawn from this case study are tightly connected to the input parameters and distributions used. Recent years have shown a decoupling of gas prices from oil prices. The fuel price distributions have been compiled from several sources based on available knowledge on production costs. However, they do not account for market effects which, as exemplified by the spiking gas price.

Using fuel production cost data, as opposed to market-pricing data, thus represents a weakness of the current study. This weakness however is not easy to come by from a general standpoint: Adjusting the distribution range for LNG based on hindsight does not prevent such foresight prediction errors from happening for other fuels in the future. The model thus enforces discussing one's expectations on the future explicitly. Combined with the ability to consider uncertainty by means of stochastic distributions, we see this as a significant advantage over ignoring uncertainty and just optimizing for one future scenario. That is, even though the model does not capture so-called Knightian uncertainty (Knight 1921) with unknown probabilities and sometimes even possibilities ("Black Swans", Taleb 2010), it represents an improvement over just using one scenario. Pantuso et al. (2015) show that considering uncertainty can lead to more robust decisions, even though exact probability distributions may be uncertain. After all, "one cannot change what can be predicted perfectly" (Ackoff 1979).

Andersson et al. (2020) and Ashrafi et al. (2022) suggest that factors beyond cost-efficiency play a significant role in the decision-making process. Further studies could thus aim to account for these factors in a consistent and quantifiable way. In addition to continuously updating the cost and emission data set, an expansion of the fuels used by bio-e-fuels (Grahn et al. 2022) could be interesting. As an expansion of real-options theory as used in this article, Knight (2014) suggests prospect theory (Kahneman and Tversky 1979) or game theory (see e.g., DNV 2022) for a better alignment of quantifiable metrics and risk perception.

CRediT authorship contribution statement

Benjamin Lagemann: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **Sotiria Lagouvardou:** Conceptualization, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **Elizabeth Lindstad:** Conceptualization, Validation, Investigation, Resources, Writing – review & editing. **Kjetil Fagerholt:** Conceptualization, Methodology, Formal analysis, Investigation, Writing – review & editing. **Harilaos N. Psaraftis:** Investigation, Writing – review & editing, Supervision. **Stein Ove Erikstad:** Conceptualization, Methodology, Investigation, Writing – review & editing, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We would like to share our data as interactive plots. The files are attached to this submission.

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Appendix A

The following section on the value of stochastic solution (VSS) may provide additional insight, but is not necessary for the understanding of the paper.

The stochasticity adds significant complexity to the problem, compared to its deterministic counterpart (Lagemann et al., 2022a). It may be appropriate to ask: "Is it worth adding this complexity? What is the value of implementing the stochastic solution compared to the deterministic one?" In order to compute the VSS, the same input data as for the stochastic model is used, except for the fact that we only optimize for one scenario which is based on the expected value of each stochastic parameter. For the fuel prices, this is therefore the mean fuel price, discounted for each period. For the stochastic carbon price, which is dependent on the previous time-period, these prices become 200, 300, 360 and 390 USD/tCO$_{2eq}$ for the second to fifth time period respectively.

As we have set up a bi-objective problem, the value of stochastic solution could be expressed in terms of either objective. We choose to compare the cost difference of a solution to achieve a given GWP. This corresponds to our formulation of the epsilon constraint degradation (Eq. (19)). We thus ask: "If we compare solutions that are supposed to achieve the same target GWP, what is the cost difference between implementing the deterministic solution for the first stage vs the stochastic one?" Implementing the deterministic solution hence fixes the first stage decision, but leaves open all further recourse options. Due to the bi-objective nature of the problem as well as for better clarity, we compare the solutions and show the VSS graphically in Fig. A1. The blue line indicates the Pareto front of the stochastic model, while the stars in different colors indicate the initial solutions suggested by the deterministic expected value-problem.

As can be seen, the value of the stochastic solution is generally low as most solutions suggested by the deterministic program coincide with the stochastic program. However, while the stochastic program provides relatively clear ranges in terms EGWP for the optimal systems, the deterministic solution alternates more often. LNG and methanol power systems for example alternate, which is shown by the sudden deviations/spikes in the Pareto front. Thus, the deterministic problem suggests an alternation and thereby chaos of optimal solution that is not present in the stochastic solution. Fig. A2 shows the Pareto front for the deterministic expected value-problem only, which illustrates the alternations of Pareto-optimal solutions.

It can be seen that with decreasing global warming potential, the Pareto-optimal solutions frequently alternate between different initial configurations. This effect is not seen in the corresponding stochastic model (Fig. 5). Possibly, these alterations are due to the sparsity of the problem and discreteness of solutions: The stochastic program has a much higher option density and therefore much smoother Pareto fronts. Although the monetary VSS may not be large, we see substantial value in the stochastic program as it avoids artificial alternation of solution and thereby ultimately contributes to a better understanding and clarity.

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Main Paper 6

Optimal ship fuel selection under life cycle uncertainty
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Optimal ship fuel selection under life cycle uncertainty

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Abstract

Shipowners need to prepare for low emission fuel alternatives to meet the IMO 2050 goals. This is a complex problem due to conflicting objectives and a high degree of uncertainty. To help navigate this problem, this paper investigates how methods that take uncertainty into account, like robust optimization and stochastic optimization, could be used to address uncertainty while taking into account multiple objectives. Robust optimization incorporates uncertainty using a scalable measure of conservativeness, while stochastic programming adds an expected value to the objective function that represents uncertain scenarios. The methods are compared by applying them to the same dataset for a Supramax bulk carrier and taking fuel prices and market-based measures as uncertain factors. It is found that both offer important insights into the impact of uncertainty, which is an improvement when compared to deterministic optimization, that does not take uncertainty into account. From a practical standpoint both methods show that methanol and LNG ships allow a cheap but large reduction in emissions through the use of biofuels. More importantly, even though there are limitations due to the parameter range assumptions, ignoring uncertainty with respect to future fuels is worse as a starting point for discussions.

Keywords: Ship Design; Alternative Fuel; Energy System selection; Uncertainty; Optimization; Robust; Stochastic

1. Introduction

Maritime emissions accounted for roughly 3% of global anthropogenic GHG emissions in 2018 (CE Delft, 2020). However, given global GHG neutrality ambitions (United Nations, 2015), this share may increase substantially in the coming years if no action is taken. Furthermore, even though a maritime emission reductions target of 50% below 2008 levels has been set by the International maritime organization (IMO, 2018), it is expected that the pressure on the maritime industry to decarbonize will increase (Serra & Fancello, 2020).

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According to many studies (CE Delft, 2020; Bouman, Lindstad, Rialland, & Strømman, 2017; DNV, 2022), alternative fuels are the only technical option to drastically reduce emissions from shipping. Depending on the fuel and feedstock, reductions are deemed to be substantial and reach close to zero emissions on a well-to-wake basis (Lindstad, Elizabeth; Gamlem, Gunnar; Rialland, Agathe; Valland, Anders, 2021). Nevertheless, each alternative fuel has distinct advantages and disadvantages in aspects such as safety, combustibility, availability, storage density etc. (DNV GL, 2019). Depending on the preference for these aspects, the choice of the 'best' fuel may hence differ between stakeholders.

Even when reducing the range of aspects to be considered down to techno-economic criteria, the choice of fuel may not be obvious. Multiple studies (DNV, 2022; Korberg, Brynolf, Grahn, & Skov, 2021; Lloyd's Register and UMAS, 2020) show that the choice is strongly dependent on cost assumptions, in particular on relative differences between the different feedstocks. These feedstocks can be fossil, bio or renewable energy sources and open up a large range of conceivable price trajectories which can be viewed as scenarios.

Most studies (DNV, 2022; Lloyd's Register and UMAS, 2020) evaluate alternative fuels *within* multiple scenarios. Less frequently, the fuels are evaluated *across* all possible scenarios, i.e., taking the large range of uncertainty with respect to fuel and carbon prices into account explicitly. Fuel prices are impacted by many external factors, like logistics, regulation, supply and demand, and are therefore subject to change and difficult to forecast. Excluding this in energy system selection could result in future economic infeasibility. The reality of fuel price uncertainty is exemplified by the recent fluctuations in LNG prices. Substantially different fuel prices are even plausible when considering the impact of long-term political development and thereby emission reduction requirements or incentives. Last but not least, flexibility is seldom valued within fixed scenarios, as it is difficult to do so. In the presence of uncertainty, however, flexibility can be a suitable design strategy (De Neufville & Scholtes, 2019).

In this paper, we aim to research how including uncertainty in different ways can provide important insights by comparing two different methods, namely robust and stochastic optimization (Klein Haneveld, van der Vlerk, & Romeijnders, 2020) (Bertsimas & den Hertog, 2022). Robust optimization includes uncertainty by adding it as a constraint and having the decision maker select an uncertainty level to be robust against. Stochastic optimization approaches uncertainty in a probabilistic manner in the objective function by assigning probabilities to possible scenarios. The methods are tested on their ability to investigate a techno-economic selection of alternative fuels under fuel price and carbon price uncertainty. As these methods are relatively new in this field, the paper addresses multiple questions. First, it aims to investigate how solutions that include uncertainty differ versus a deterministic solution. Second, the methods are compared to understand if the difference in their approach also results in a difference in recommendations. Third, further insights from each method for ship designers is examined. Lastly, it is investigated if the methods are sensitive to assumptions and if the amount of work to implement these methods is compensated by the insights they provide.

2. Methodology

As a basis, this paper uses the mixed integer linear program (MILP) setup from (Lagemann, Lindstad, Fagerholt, Rialland, & Erikstad, 2022). Below, the setup of the deterministic model is reiterated and the extensions toward the robust and stochastic optimizations are further explained.

2.1 Deterministic model setup

The variables and parameters used for the deterministic problem setup are shown below:

Table 1. Variables and Parameters for the Linear Programming Setup

Set	Description	Modelling comment
$\mathbb{T}$	set of discrete ***time periods***, indexed by t	set of discrete ***time periods***, indexed by t
$\mathbb{F}$	set of ***fuel options***, indexed by sf	set of ***fuel options***, indexed by sf

Parameter	Description	Modelling Comment
C^N_{sf}	***newbuild cost*** of ship with system option sf	
$C^R_{sf'sft}$	***retrofit cost*** from option sf' to option sf for period t	
C^{CF}_{sft}	***fuel and carbon cost*** of fuel *sf* at time period *t* in	
C^{LO}_{sft}	***lost opportunity cost*** of system sf per time period *t*	
B	***energy consumption*** per time period	assumed fuel conversion efficiencies do not change over time, equidistant time periods
E_{sf}	***Emissions*** of fuel *sf* per time period	
Decision variable	**Description**	
X_{sft}	1 if ***fuel*** sf is chosen at time t in scenario ω, 0 otherwise	
X_{sf0}	1 if fuel sf is chosen in period 1, 0 otherwise	
$r_{sf'sft}$	retrofit from fuel sf' to fuel sf after period t	

The problem consists of two objective functions, cost of ownership;

$$\min \sum_{sf}\left(C^N_{sf}X_{sf0} + \sum_t\left(\sum_{sf}\left(C^R_{sf'sft}\, r_{sf'sft}\right) + \left(C^{LO}_{sft} + B\left(C^F_{sft} + C^C_{sft}\right)\right)X_{sft}\right)\right), \tag{1}$$

and global warming potential (GWP) in tonne CO2 equivalent;

$$\min \sum_{sf}\sum_t BX_{sft}\,E_{sf}, \tag{2}$$

where the cost consists of a newbuild, lost opportunity and operational element. While the GWP objective consists of an emission factor E_{sf} which is calculated with emission data estimates for each fuel. The following constraints are added:

$$\begin{gathered} s.t. \sum_{sf} X_{sft} = 1, \qquad \forall t \in T, \\ X_{sf'(t-1)} + X_{sft} - 1 \leq r_{sf'sft} \qquad \forall sf', sf \in \mathbb{S}, \forall t \in \mathbb{T}\backslash\{0\}, \\ X_{sf'(t-1)} + X_{sft} \geq 2r_{sf'sft} \qquad \forall sf', sf \in \mathbb{S}, \forall t \in \mathbb{T}\backslash\{0\}, \\ and\ r_{sf'sft} = 0 \qquad \forall sf', sf \in \mathbb{S}, \forall t = 0. \end{gathered} \tag{3}$$

To be able to solve the multi-objective problem and create a proper front, the GWP objective is rewritten to a constraint that is stepwise (n) relaxed.

$$\min GWP$$

$$\sum_f \sum_t BX_{sft}\,E_f \leq GWP_n \tag{4}$$

2.2 Robust Optimization

Robust optimization focuses on finding solutions that are insensitive to changes in parameter values due to uncertainty. It does so by including the bounds of a parameter as a constraint in the optimization problem. As we consider the uncertain variables to be fuel and carbon price, the objective function for cost is rewritten to be a constraint and the uncertain variable C^{CF}_{sft} is located in red.

$$\min \theta$$

$$s.t. \sum_{sf} \left(C^{N}_{sf} X_{sf0} + \sum_{t} \left(\sum_{sf} \left(C^{R}_{sf'sft}\, r_{sf'sft} \right) + \left(C^{LO}_{sft} + B\left(C^{CF}_{sft} \right) \right) X_{sft} \right) \right) \geq \theta, \qquad \forall\, C^{CF}_{sft} \in U \tag{5}$$

The uncertainty is a combination of carbon and fuel cost, which can be represented using a mean and deviation $C_{sft} = \bar{C}_{sft} + \hat{C}_{sft} z$. Where the deviation is scaled with uncertain variable z, which is used to guide the solution toward the proper robustness level against the cost deviation. The cost constraint becomes;

$$s.t. \sum_{sf} \left(C^{N}_{sf} X_{sf0} + \sum_{t} \left(\sum_{sf} \left(C^{R}_{sf'sft}\, r_{sf'sft} \right) + \left(\bar{C}_{sft} + B\left(\hat{C}_{sft} z \right) \right) X_{sft} \right) \right) \\ \geq \theta, \qquad \forall C_{sft} \in U. \tag{6}$$

The decision to switch option can be made at each time step t. The next step is to rewrite Equation 6 such that the uncertain variable z is constrained by its uncertainty set. This is done by separating the variable and writing the support function δ^{*},

$$s.t. \sum_{sf} \left(C^{N}_{sf} X_{sf0} + \sum_{t} \left(\sum_{sf} \left(C^{R}_{sf'sft}\, r_{sf'sft} \right) + \bar{C}_{sft} X_{sft} + \delta^{*}\left(B \hat{C}_{sft} X_{sft} | Z \right) \right) \right) \\ \leq \theta, \qquad \forall C_{sft} \in U. \tag{7}$$

2.2.1 Uncertainty Set selection

The next step is to select the uncertainty set that the constraint should satisfy, for which the support function is rewritten accordingly. Multiple sets have been proposed in literature that aim to guide the selection toward a proper level of conservativeness and correlation (Gabrel , Murat, & Thiele, 2014). These include research into flexible sets by (Zhang, Yiping, & Gang, 2017), the connection to risk measures from risk theory (Chen, Melvyn, & Peng, 2007), the addition of stochastics in the form of distributional robust optimization (Ben-Tal, Bertsimas, & Brown, 2010) and robust constraints based on probability (Bertsimas & Goyal, 2010). Such directions show the potential for further developments of robust optimization for ship energy system selection. However, to show the principle and benefits of using robust optimization this comparison uses less complex uncertainty sets.

Figure 1 shows the uncertainty sets that are used in this paper. We use two different uncertainty sets to account for two different types of correlations, namely within a feedstock/fuel group and across feedstock/fuel groups. Within a fuel group, we use a box uncertainty set with fuel prices bounded by ρ_F, shown in red. This reflects the direct correlation within bio, fossil and electro-fuel groups, where each fuel would reach its worst case at the same time. In between feedstock groups, indirect correlation is reproduced by using an ellipsoidal uncertainty set bounded by ρ_{FG}, shown in green. In this way, either feedstock can be worst-case, but not both at the same time. On top of these correlations, carbon prices are added with a box uncertainty set bounded by ρ_C.

$$U = \left\{ \begin{array}{c} \|z^C\|_\infty \leq \rho_C \\ \|z^F\|_\infty \leq \rho_F \\ \|z^{FG}\|_2 \leq \rho_{FG} \end{array} \right\}$$

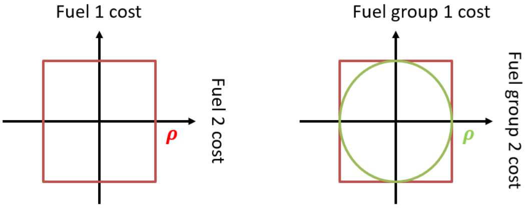

Figure 1. Uncertainty set visualization

The selection of each scaling factor can be done separately to also research relative deviations. The size of the set is typically defined using the central limit theorem (CLT). In effect, the uncertainty set represents all possible combinations of samples of each uncertain variable, but it constrains the extremes. The deviation from the mean can be scaled with ρ to cover a larger space. Therefore, by increasing ρ, the selection can be forced to be more conservative.

2.2.2 Adaptive robust optimization

The most important decision is the selection of a start design while taking future price fluctuations into account. Adaptive robust optimization (ARO) splits the problem into a "here-and-now" decision Y and a "wait-and-see" decision X in the future. By accounting for uncertainty in the future, the initial decision can be made more robust.

$$s.t. \sum_{sf}\left(C^N_{sf} Y_{sf} + \sum_t \left(\sum_{sf} \left(C^R_{sf'sft}\, r_{sf'sft} \right) + \bar{C}_{sft} X_{sft} + \delta^*\left(B\hat{C}_{sft} X_{sft} \middle| Z \right) \right) \right) \leq \theta, \qquad \forall C_{sft} \in U. \tag{8}$$

Which results in the following equation when the ellipsoidal uncertainty set is substituted for the support function;

$$s.t.\ \ \rho \left\| B\hat{C}_{sft} X_{sft} \right\|_2 + \sum_{sf}\left(C^N_{sf} Y_{sf} + \sum_t \left(\sum_{sf} \left(C^R_{sf'sft}\, r_{sf'sft} \right) + \bar{C}_{sft} X_{sft} \right) \right) \leq \theta, \qquad \forall C_{sft} \in U, \tag{9}$$

2.3 Stochastic Optimization

The stochastic programming model is a bi-objective two-stage optimization model. The full model including all constraints is described in detail by (Lagemann, et al., 2022). From the deterministic model presented above, two additional steps are required to derive the mathematical formulation for the stochastic programming model. In short, these steps are a split of decision variables into fuel x and system y, plus the introduction of probabilities utilizing sampled scenarios and respective weighting in the objective function.The split of the decision variable X_{sft} into x_{ft} and y_{st}, i.e., into the fuel and systems for each time period, is made to better distinguish the most urgent decision of the choice of a system from the slightly less pressing decision of the fuel, which in practice can be substituted by any fuel compatible with the selected system. With this step, the objective function reads as

$$min\sum_{s\in\mathbb{S}}\left[\underbrace{C_s^N\cdot y_{st_0}}_{building\ cost}+\sum_{t\in\mathbb{T}}\left(\underbrace{C_{st}^{LO}\cdot y_{st}}_{lost\ opportunity\ costs}+\sum_{s\prime\in\mathbb{S}}\underbrace{C_{s\prime st}^{R}\cdot r_{s\prime st}}_{retrofit\ cost}\right)\right]+\sum_{t\in\mathbb{T}}\sum_{f\in\mathbb{F}}\underbrace{B\cdot x_{ft}\cdot\left(C_{ft}^{F}+C_{ft}^{C}\right)}_{fuel\ cost} \tag{10}$$

As the second step, the uncertainty is accounted for by means of a set of scenarios the model optimizes *across*. That is, the model applies a risk-neutral expected value formulation. The scenarios are sampled based on the probability distributions discussed in (Lagemann, et al., 2022). Sampling scenarios from probability distributions implies that probabilities are implicit in the scenario set. Each sampled scenario ω, therefore, obtains the probability $p_\omega=\frac{1}{|\Omega|}$. The resulting formulation of the objective function thus becomes:

$$\begin{gathered}min\sum_{s\in\mathbb{S}}\left[\underbrace{C_s^N\cdot y_{s0}}_{building\ cost}+\sum_{\omega\in\Omega}P_\omega\left[\sum_{t\in\mathbb{T}}\left(\underbrace{C_{st}^{LO}\cdot y_{st\omega}}_{lost\ opportunity\ costs}+\sum_{s\prime\in\mathbb{S}}\underbrace{C_{s\prime st}^{R}\cdot r_{s\prime st\omega}}_{retrofit\ cost}\right)\right]\right]\\+\sum_{\omega\in\Omega}\sum_{t\in\mathbb{T}}\sum_{f\in\mathbb{F}}\underbrace{P_\omega\cdot B\cdot x_{ft\omega}\cdot C_{ft\omega}^{F}}_{fuel\ cost}\end{gathered} \tag{11}$$

Scenario sampling applies probability distributions for both fuel and carbon prices. The sampled prices are then stored for each fuel as $C_{ft\omega}^F$. Hence, there is no explicit distinction between fuel and carbon price contributions in the mathematical formulation. As for the second objective, the global warming potential, the formulation becomes

$$min\sum_{\omega\in\Omega}P_\omega\cdot\sum_{t\in\mathbb{T}}\sum_{f\in\mathbb{F}}B\cdot E_f^{WTW}\cdot x_{ft\omega} \tag{12}$$

By changing the decision variables and introducing the scenario sampling concept. For the implementation in the commercial solver, this objective is rewritten as a constraint with the right-hand side subsequently lowered in order to identify solutions on the front, i.e. solutions with a lower expected GWP but higher expected TCO.

3. Case study

For the setup of the comparison, the considerations with regard to the uncertain parameter selection is discussed first. Second, the input data, that is kept equal for both methods, is presented in Table 3. Lastly, the aspects that are compared are specified.

3.1 Uncertain parameter selection

The comparison of methods has been limited to two parameters that, when changing, could highly impact the optimal selection. This provides a good basis to test the ability of robust and stochastic optimization. However, besides carbon pricing and fuel price, multiple other parameters are uncertain for alternative fuels. We would like to stress that uncertainties outside of the scope of this research can still impact and skew the results in various ways. To highlight important uncertainties, several categorized parameters are included in Table 2 below.

Table 2. Uncertain parameter categorization and impact factor overview

Category	Parameter	Impacted by	Perceived impact	References
Market	Lost opportunity	Market, capability reduction, safety measures	Medium	(Ramsay, Fridell, & Michan, 2022)
	Mission requirements	Endurance, speed, cargo requirements	Medium	(Kouzelis, Koos, & van Hassel, 2022)
Input	Retrofit cost	Timeframe, lost revenue, component costs	Medium	(Zhao, Ye, & Zhou, 2019)
	Fuel price	Logistics, market supply and demand, availability	High	(Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021)
	Newbuild cost	Timeframe, manhour & material cost, inflation	Low	(Haehl & Spinler, 2020)
Technology	Energy converter	Novel system development, public perception	High	(Bergsma, Pruyn, & van de Kaa, 2021)
	Maintenance	Crew ability, degradation, system complexity	Medium	(Wahl & Kallo, 2022)
	Energy carrier	New storage mediums and feedstock	High	(Grahn, et al., 2022)
	Exhaust treatment	Development, costs	High	(Ros & et al., 2022)
Process	Production (WTT)	Supply chain emission accounting, feedstock availability, supplier	High	(Prussi, et al., 2022)
	Conversion (TTW)	Energy system losses, treatment	Medium	(Wang & Wright, 2021)
Regulations	Scope	WTT/TTW, CO2(eq)?, SOX & NOX	High	(Serra & Fancello, 2020)
	Magnitude	Penalty cost, enforcement	Medium	(Lagouvardou, Psaraftis, & Zis, 2020)
	Lost opportunity	Market, capability reduction, safety measures	Medium	(Kass, Sluder, & Kaul, 2021)

Table 2 identifies possible reasons that parameters could shift and what its perceived impact would be on the final selection. References that discuss the impacts that are mentioned for each parameter are also included. Nevertheless, not all of the factors mentioned are covered by the references. From the perspective of the model, input factors, like costs, will directly influence the results. On the other side, market factors reflect the ability of generating revenue, which could be impacted in different ways by alternative fuels, e.g., generally higher freight rates or different speeds. Furthermore, the development and availability of technology, like energy conversion, carrier and exhaust treatment systems will only become clear over time and could therefore highly impact the fuel selection and ability to reach emission targets. More importantly, other fuels and systems could develop besides the current options that are included in the comparison. The potential emission reduction of a fuel also greatly depends on the process and ability to decrease the environmental impact in the production and transport (WTT) and conversion (TTW) stages. Finally, the focus and magnitude of regulatory measures can stimulate or deter the use of a fuel. These uncertainties should be addressed when applying any of the methods in practice.

3.2 Input data

Table 3 shows the different fuels that were considered and their respective feedstock groups (fossil, bio or electro). The environmental impact in GWP100 has been split into a production and conversion equivalent. The economic impact has an operational part which includes an uncertain range that has been based on estimates from (Lindstad et al) and a fixed capital cost part, which is calculated for a super max bulk carrier. The retrofit cost has been elaborated in (Lagemann, et al., 2022).

Table 3. Model inputs, also showing bounds for uncertain fuel costs

		Environmental impact		Economic impact				
feedstock	Fuel label	GWP WTT per fuel energy unit [gCO2eq/kWh]	GWP TTW per fuel energy unit [gCO2eq/kWh]	Upper bound cost [USD/MWh]	Mean cost [USD/MWh]	Lower bound cost [USD/MWh]	Newbuilding price [mUSD]	Lost opportunity costs per 5 years [mUSD]
Fossil	VLSFO	47.5 [1]	284.1 [1]	95 [2]	66.5	38 [2]	30	0
Bio	bio-Diesel	70.0 [5]	150.0 [5]	128 [3]	110.4	93 [3]	30	0
electro	e-Diesel	0.0 [1]	4.5 [1]	423 [2]	277	131 [2]	30	0
Fossil	LNG	66.6 [1]	238.8 [1]	81 [2]	56.5	32 [2]	37.5	0.5
Bio	bio-LNG	49.7 [1]	6.0 [1]		103.7	89 [3]	37.5	0.5
electro	e-LNG	0.0 [1]	6 [1]	119 [3]	236.5	115 [2]	37.5	0.5
Fossil	LPG	30.0 [1]	237.5 [1]	358 [2]	68.8	39.3 [2]	33	0.1
Fossil	Methanol	112.7 [1]	253.4 [1]	98.3 [2]	150	90 [2]	33	0.3
Bio	bio-Methanol	112.68 [1]	3.24 [1]	210 [2]	81.5	66 [3]	33	0.3
electro	e-Methanol	0.0 [1]	3.5 [1]	97 [3]	250.5	116 [2]	33	0.3
Fossil	Ammonia	87.1 [1], [4]	19.0 [1]	385 [2]	138	56 [2], [6]	37.5	0.5
electro	e-Ammonia	0.0 [1]	19.0 [1]	220 [2], [6]	150	80 [2]	37.5	0.5
Fossil	LH2	108.7 [1], [4]	0.0 [1]	220 [2]	150	55 [2], [6]	47.5	3
electro	e-LH2	0.0 [1]	0.0 [1]	245 [2], [6]	162	79 [2]	47.5	3

[1] (Lindstad, Elizabeth; Gamlem, Gunnar; Rialland, Agathe; Valland, Anders, 2021)
[2] (Lindstad, Lagemann, Rialland, Gamlem, & Valland, 2021)
[3] (Korberg, Brynolf, Grahn, & Skov, 2021)
[4] assuming 80% CCS efficiency
[5] (Sustainable Shipping Initiative, 2019)

[6] Upper bound 100% of electricity-based pendant, lower bound 70% of electricity-based pendant

3.3 Comparison setup

To properly compare both methods, the different manner in which each handles important aspects like time dependency and correlation between fuel prices are examined below in Table 4.

Table 4. Important aspects to compare between robust and stochastic optimization

Aspect	Robust	Stochastic
Within-group fuel price correlation	Independent, box uncertainty set.	Fully correlated
Out-of-group fuel price correlation	Correlated using an ellipsoidal set. Other correlation using other uncertainty sets.	Independent
Carbon pricing	Gamma value could be shifted to examine the impact.	Beta variate probability distribution developing over time

Aspect	Robust	Stochastic
Time-dependency	Discounting, shifting gamma value for different time steps, adaptive robust optimization	Discounting, history-independent fuel prices, history-dependent carbon prices, recourse
Objective function	Edge case performance	Expected performance
Extra criteria	Minimum regret, result deviation	VSS

The value of the comparison can be guaranteed only by being aware of the differences of each approach. Table 5 shows the tests that are designed to highlight the ability of the methods, while remaining able to compare both.

Table 5. Comparison tests

		Robust		Stochastic	
Test	Purpose	Fuel	Carbon	Fuel	Carbon
Deterministic case	Verify code	Mean fuel price	0 carbon price	Mean fuel price	0 carbon price
Uncertain scenarios	Compare direct output of methods	Gamma scenarios, grouped	Gamma scenarios, shifted over time	Triangular fuel price distribution	Beta variate probability distribution developing over time
Measurement criteria	Test evaluation options	Impact of different gamma (min regret)		EVPI, VSS, ECIU	
Impact of mean Change	Sensitivity to assumptions	1/3 of mean	Gamma scenarios	1/3 of mean	Beta variate probability distribution developing over time

The first test serves as a validation and is used for later comparisons. Next, the methods are compared to understand if the difference in their approach also results in different solutions. The third test uses the output and additional measurement criteria to examine what insights could be provided to ship designers. Lastly, the sensitivity of the methods to assumptions is identified. By completing all tests and implementing the methods, the difficulty of implementation versus insights can also be addressed.

4. Results

In this section, the results for the case study from each method are discussed separately. Besides, the insights and methodological approaches of robust optimization and stochastic optimization are further elaborated in a discussion. Lastly, the methods are compared and further discussed along the lines of the questions posed in the introduction.

4.1. Deterministic case

The front for different start ships and pathways is visualized in Figure 2. It shows the total cost of ownership versus the total GWP100 over the lifetime. The figure also includes the performance of non-flexible solutions that stick to a single fuel (colored crosses). The colored fronts identify the total GWP that a pathway from a start ship can reach (line color).

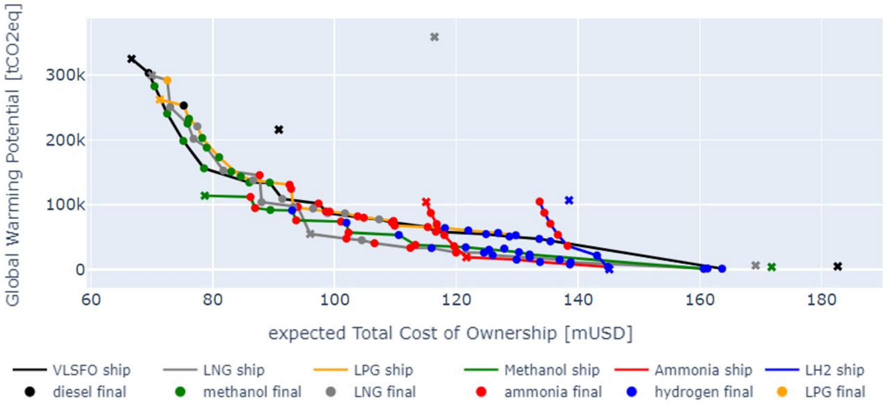

Figure 2. Multi-objective plot for the deterministic case with mean fuel prices and 0 carbon price

The same result was found for both the robust and stochastic optimization codes. By using deterministic optimization, a decision maker can already gain an understanding of the potential price to reduce emissions including the starting ship and pathway that could be followed to meet these targets. However, as values might change, do these results hold under uncertain conditions?

4.2. Robust optimization

Figure 3 shows the multi-objective Pareto fronts for static (crosses) and flexible solutions when the conservativeness level is as large as the identified uncertainty ranges. The deterministic Pareto-fronts are visualized as well.

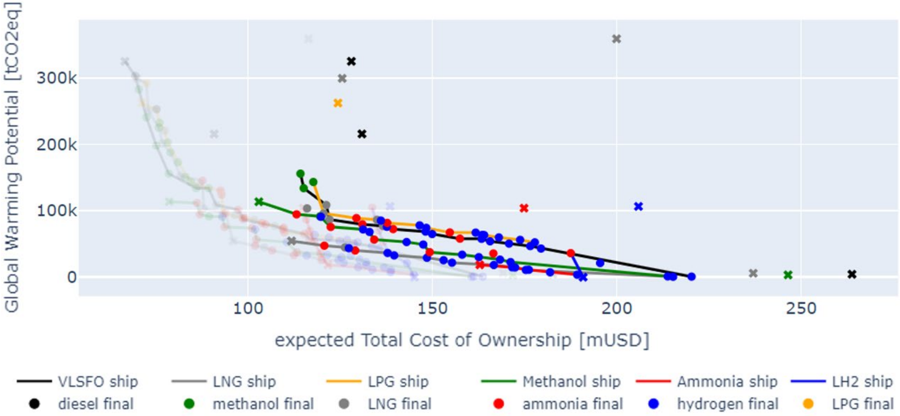

Figure 3. Multi-objective plot for the robust optimization case with high conservativeness level

The large conservativeness against carbon pricing shifts fossil and biofuel options with higher emissions beyond the Pareto front. This shows that robust optimization advocates switching focus toward starting with methanol and LNG ships instead, as other vessels are costly and cannot meet reduction targets or need to switch fuels regardless. To further visualize the impact of fuel price uncertainty, Figure 4 shows results when negating carbon pricing.

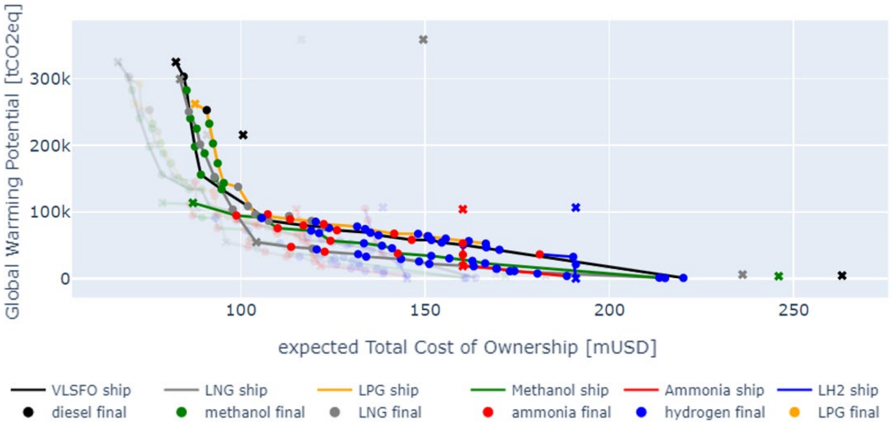

Figure 4. Multi-objective plot for the robust optimization case with zero carbon price and high fuel price conservativeness

When considering only fuel price uncertainty, all options shift to the right. More importantly, the emission reduction slope steepens (reduction becomes cheaper) and the Pareto fronts become more smooth. Furthermore, because there is much uncertainty in the price of ammonia, its TCO shifts to the right, while biofuels like bio-LNG and bio-methanol become more attractive transition options. At medium GWP targets, preference also seems to shift from ammonia toward hydrogen as a final pathway option. This could be explained by the options coming closer together due to high uncertainty, while hydrogen allows initial lenience as it has a higher potential emission reduction. In general, the static options offer cheaper solutions but are not able to adapt toward lower GWP towards the end of the lifecycle. When looking at the least cost pathway toward low or zero emissions, primarily ammonia and hydrogen ships are preferred, as other start options imply more expensive retrofits.

4.2.1 Conservativeness level selection

One of the valuable properties of robust optimization is the addition of the conservativeness factor. It allows the decision maker to select a preferred robustness level. To better understand the impact of conservativeness selection, different values and combinations of ρ_F and ρ_C are explored. However, as the additional dimension makes the multi-objective results more difficult to interpret, the GWP objective is rewritten toward two linearized constraints that represent current reduction targets from the IMO and the EU.

First, for the EU target, increasing carbon pricing conservativeness forces owners to switch toward biofuels, while the impact of fuel price uncertainty on the selected start ship and fuel pathway decreases. At low carbon prices, increased conservativeness against fuel prices shows a preference for flexibility to switch between fossil, bio and e-fuels.

Second, for the IMO target, which represents less strict reduction targets, bio-methanol is selected independently of the conservativeness level. Only when being less conservative for carbon and fuel price, the optimization selects cheaper fossil fuels as a start, which have a higher carbon content but a lower price range. More importantly, only for very high carbon price conservativeness ($\rho_C = 1.5$), the selection is similar to the EU GWP target.

Consequently, carbon pricing primarily affects early pathway decisions, while GWP target is more impactful regardless of carbon pricing. Table 6 shows the robust selections against the deterministic solutions.

4.2.2 Measurement criteria: impact of gamma selection

Selecting a higher robustness level will result in different starting points. Effectively the optimization results in three different ships and 4 different pathways, that are selected dependent on GWP targets and conservatism levels.

Table 6. Single objective robust optimization solutions for different levels of conservativeness for IMO and EU GWP targets

			Pathway				
Design	**Target**	**Start**	2025	2030	2035	2040	2045
0	EU-deterministic	VLSFO ship	VLSFO	Bio-methanol	Bio-methanol	Bio-methanol	E-Ammonia
1	IMO-deterministic	VLSFO ship	VLSFO	Bio-methanol	Bio-methanol	Bio-methanol	Bio-methanol
2	EU-robust	LNG ship	Bio-LNG	Bio-LNG	Bio-LNG	Bio-LNG	Bio-LNG
3	IMO-robust	Methanol ship	Bio-methanol	Bio-methanol	Bio-methanol	Bio-methanol	Bio-methanol

We use the principle of uncertainty quantification (Scarabosio, 2022) to examine the impact of uncertain inputs on the result to see if adaptive robust optimization actually selects robust options. This can be tested by generating a dataset of future scenarios to evaluate the performance of the selections. The sampling is comparable to stochastic optimization, where future prices are sampled from a normal distribution, while carbon price scenarios use a beta-variate distribution. The results of the selected options for 10000 different sampled futures are shown in Figure 5.

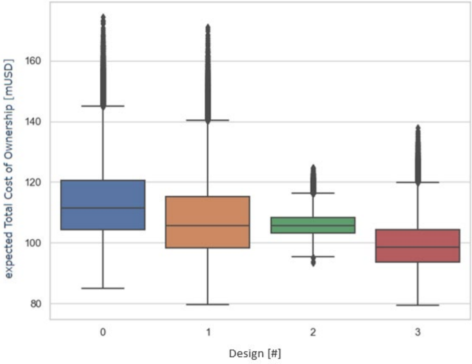

Figure 5. Single objective robust optimization solutions for different levels of conservativeness for IMO and EU GWP targets

In both cases (designs 2 and 3) the method selects options which have low variance, while the deterministic selection has much larger perturbations. Surprisingly, the robust options seem to prefer a static pathway for each GWP strategy. This can be explained by the variance being so low that retrofit cost becomes a significant investment. Therefore, adaptability seems to be neglected, but its benefit is apparent when looking at the multi-objective figures.

4.2.3 Impact of changing variability

Biofuels are found in many pathways on the Pareto fronts. This could be explained by its low variability (15-18%) versus e-fuels (~50%) and fossil fuels (40-60%). However, there are multiple barriers like availability, manufacturing cost and government actions that could increase this variability (Kesieme, Pazouki, Murphy, & Chrysanthou, 2019). Therefore, the variability for biofuels is increased to 50% to examine if the robust optimization selection is impacted. The results for both ranges are presented in Figure 6 for medium carbon price conservativeness ($\rho_C = 0.5$) and high fuel price conservativeness ($\rho_F = 1$).

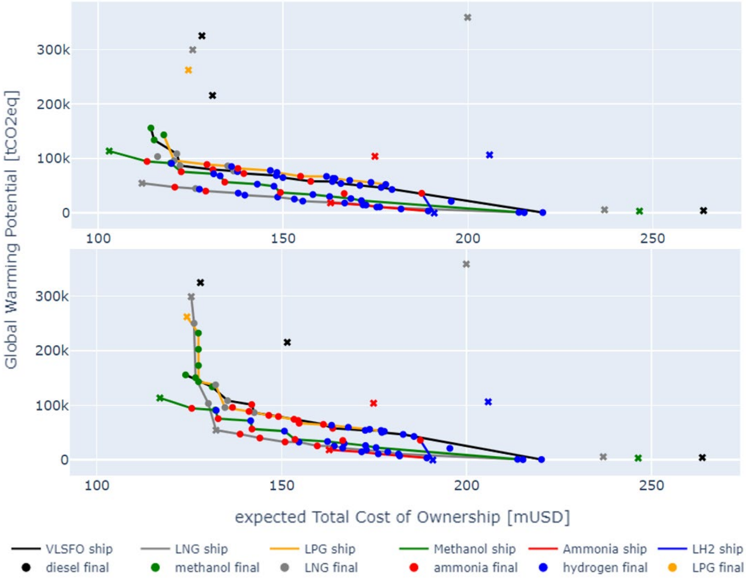

Figure 6. Results for original (above) and increased biofuel prices (below)

There are a few interesting changes due to increased biofuel variability. First, the fronts shift to the right, such that fossil options are in the range of the Pareto fronts, while e-fuel options at lower GWP do not change. More notably, the biofuel shift primarily impacts the mid-range or transition options, where, despite cost increase, biofuels still offer large reduction potential against a low-cost increase versus fossil fuels. Second, the methanol and LNG ship Pareto shift slightly closer, because the LNG front is found to be more dependent on biofuels. This is also apparent from the heavier focus on ammonia, which is switched to earlier instead of balancing out the GWP from cheaper bio-LNG by switching to hydrogen later on. Nevertheless, even though pathways are impacted, start ship decisions (Pareto fronts) seem to be unaffected by variability changes. More importantly, this shows that there is significant value in being able to retrofit to deal with uncertainty after having selected a starting point.

4.2.4 Discussion

Robust optimization was shown to be able to select a set of robust solutions from a large number of options. Furthermore, in the case of alternative fuel selection, switching fuels during the lifetime can be included by using adaptive robust optimization. It can be used to understand the adaptability gap, which is the difference between the static (fixed case) and adaptive robust solution (flexible case). Robust optimization methods shift the focus of a decision-maker from one assumed value towards properly establishing an uncertainty range by adding conservativeness. However, although this allows the decision maker to immunize against the selected uncertainty, the solution can become too conservative. This can be dealt with in two ways, the correlation can be changed using a different uncertainty set, or the conservative factor itself can be reduced. The impact of uncertainty sets has been discussed extensively in literature (Gabrel , Murat, & Thiele, 2014), while this paper primarily discussed the conservativeness factor selection. The impact of these is preferably explored, but this is found to be difficult due to the increased dimensionality. However, a big advantage of robust optimization against other methods is its tractability. This allows the number of uncertain parameters to be increased against low computational cost. Overall, the addition of uncertain parameters for ship design works well with single and multi-objective optimization, but sensitivity exploration is more complex.

4.3. Stochastic optimization

This subsection will briefly present the results obtained from the stochastic model. Subsection 4.3.1 presents the results from the base case as described in Section 3. Subsection 4.3.2 describes the value of a stochastic solution and Subsection 4.3.3 discusses the results when adjusting the bounds for biofuels.

4.3.1 Stochastic optimization base case

The Pareto front of solutions from the stochastic optimization is shown in Figure 7. The plot shows that the expected emissions can be lowered by roughly 50% for a marginal increase in expected costs. Reducing emissions all the way down to zero would result in an approximately 60% increase in the expected costs.

In terms of optimal power system choice for the newbuild, methanol is suggested as a favorable abatement option for up to 60% emission reduction, while an LNG power system would optimal between 60% and 90% reduction. Abating the last 10% of emissions would require ammonia or hydrogen configurations from the beginning.

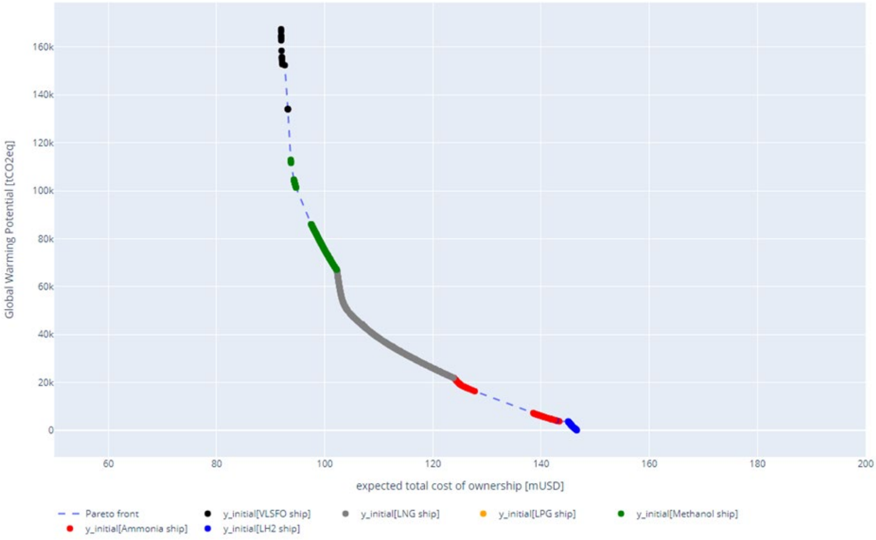

Figure 7. Pareto front for initial power system configurations, 100 scenarios with a stochastic carbon price

4.3.2 Value of stochastic solution

The value of stochastic solution (VSS) characterizes the cost delta between implementing the first-stage decisions of a deterministic program based on expected values vs implementing the first-stage decisions of the stochastic program. That is, the optimal first-stage decisions of the deterministic expected value formulation are simulated under the stochastic setting.

As for this case study, Lagemann et al. (2022) have found that the VSS expressed in monetary terms is generally low. That means, that the first-stage decisions suggested by the deterministic expected value problem do not perform much worse than the first-stage decisions suggested by the stochastic model. However, the suggested first-stage decisions in the deterministic problem alternate frequently with decreasing target GWP. This feature is not present in the stochastic solution. Thus, the deterministic solution suggests artificial chaos, which is not present in the data but rather stems from the discreteness of the problem. More precisely, it is the limited number of possible combinations that generate this alternation of optimal first-stage decisions. The VSS in this case could be better measured as “insight produced”.

4.3.3 Stochastic model with adjusted bounds for biofuels

In Subsection 3.3 we have shown that the results of the base case might be biased due to low variability in bio-fuel prices. In order to investigate a change in bounds, we keep the lower bound as is, and adjust the upper bound such that the difference between the original mean/mode is now 50%, as for most other fuels. As a result, the triangular distribution becomes asymmetric, with the mode assumed as the original mean, and the new mean being higher due to the adjusted upper bound. Pantuso et al. (2015) have shown that stochastic programs are often relatively insensitive to the actual probability distributions while being sensitive to the mean. We will discuss this hypothesis in the light of this case study.

When plotting the suggested first-stage decisions, i.e., what initial system to invest in, there is little difference to observe in the Pareto front. The effect of adjusted upper bounds for biofuels differ, however, when it comes to retrofits. This can be seen from Figure 8 which uses a brute force technique. That is, it traces fixed combinations of fuels and systems over time across the same scenario set as the optimization model. The line’s color indicates the first-stage decision (the initial system), while the dot’s color indicates the final system in the last period. This technique has shown to yield relevant insight (Lagemann, et al., 2022).

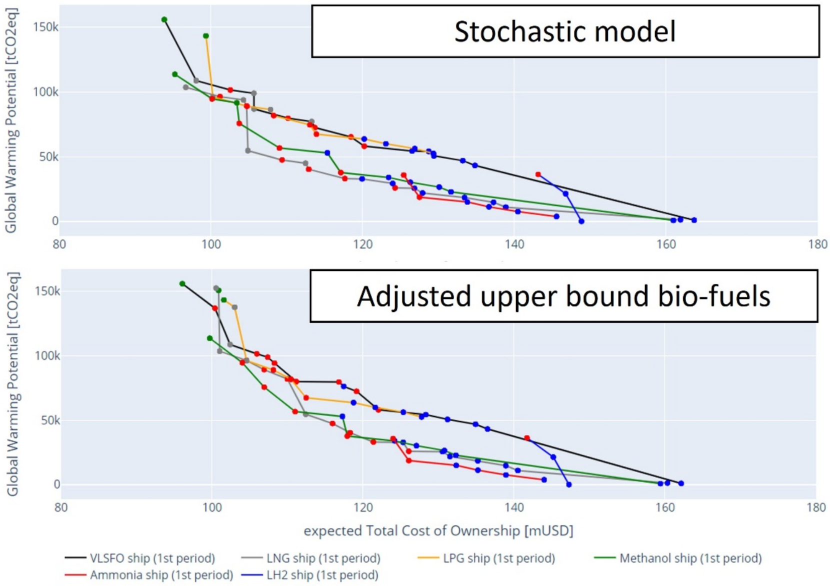

Figure 8. Adjusted upper bound for biofuels, brute force results

Applying the brute force technique to the adjusted biofuels, brings to surface some secondary effects, namely potential retrofits: Retrofits towards ammonia become more frequent along the Pareto front for adjusted biofuel bounds, while retrofits towards hydrogen are less frequent. Our hypothesis for this is, that adjusting the upper bound for biofuels naturally renders them more expensive. The model thus is inclined to switch earlier to e-fuels, for which the retrofit to ammonia is cheaper.

4.3.4 Stochastic optimization discussion

Stochastic optimization offers the ability to balance optimization by weighting uncertain outliers stochastically. In this way, the method allows to select from many options while taking uncertainty into account explicitly. Furthermore, by using two stage stochastic optimization, the method is able to separate the problem into initial (here-and-now) and future (wait-and-see) decisions. This shall reflect the position of a shipowner today, because it models the future to be unfolding only after the initial selection. The use of probability shifts the focus of decision makers toward identifying distributions instead of single values and allows specifying a nuanced believe in the likelihood of scenarios. Nevertheless, one still needs to specify these probability distributions explicitly, which is challenging especially for high uncertainty levels. In the case of additional uncertainties, the probability distributions can possibly lead to non-convexity of the problem. Such potential mathematical limitations must be kept in mind for future extensions and adaptions.

4.4. Discussion across methods

By applying both methods to the same problem, the output, methodological assumptions and impact for this specific use case can be compared. When comparing the methods to the deterministic solution, it is apparent is that taking uncertainty into account results in different selections, which focus on improving robustness, while also incorporating the value of flexibility. The following paragraphs each comment on one of our initially stated aspects for comparison.

Looking at the representation of uncertainty, either conservativeness factors or stochastic distributions are used. However, despite a different approach, the fronts offer very similar insights. On the one hand, for robust optimization, the impact of robustness is clarified when it is compared to the deterministic solution. While on the other hand, stochastic optimization offers smoother Pareto fronts and is less dependent on the initial solution.

Regarding insight for ship designers, it is shown that the gamma values in robust optimization offer much freedom to research different scenarios, even though it increases the dimensionality of the problem. Otherwise, stochastic optimization is more static, but it has several criteria that offer detailed insights on the difference against the deterministic solution.

To research the sensitivity of assumptions, the variability and probability distribution was changed for biofuel. Robust optimization was found to be sensitive to increasing variability, while the selection of the mean is more impactful when using stochastic optimization. Overall, in this case study, these impacts are primarily found at the pathway levels and ending option respectively, while the start selections remain similar. When comparing recommendations from each method, outcomes are very similar, especially regarding the optimal start ship. Table 7 further summarizes the pros and cons of each method, while showing the aspects that are deemed to be of specific importance for this case study in bold.

The setup of the MILP and collecting reliable input was found to be more demanding than subsequently constructing either method. Therefore, in our opinion, the difficulty of implementation primarily depends on the choice to use optimization, rather than the choice between robust and stochastic methods. Nonetheless, for robust optimization, the uncertainty set and conservativeness level selection effort proved significant, while for stochastic optimization, the computational effort, due to the use of probability and sampling is more pressing. Above all, besides the insights from the method output, the knowledge gained through structuring such a problem is deemed to be especially valuable in the face of uncertainty.

Table 7. Advantages and disadvantages of the two optimization methods

Method	Pros	Cons
Robust optimization	Takes uncertainty into account in modelling stage	Can become too conservative
	Immunizes against uncertainty	Uncertainty set and conservativeness selection
	Adaptive robust decision making	**Dimensionality due to added factors**
	Very tractable: low cost extension to multiple uncertainties	
Stochastic optimization	Risk is taken care of explicitly	**Probability distribution difficult to specify reliably**
	Wait-and-see and here-and-now decisions	Probability can make the problem nonconvex and difficult to solve
	Can treat extreme scenarios as unlikely using low probability	Too large to solve with multiple uncertainties

4.5. Conclusion

Robust and stochastic optimization methods are found to present similar solutions for the selected uncertainties under the same assumed input conditions. Specifically, for multi-objective problems, robust optimization offers more extensive scenario research capabilities, while results from stochastic optimization are smoother in the sense that they suggest less alternations along the fronts. By using both methods, it is found that the confidence in final solutions can be improved and additional insights can be gained.

For the selection of alternative fuel and power systems, the success of these methods primarily depends on the level of uncertainty and ability to setup the input for each method. Nevertheless, both methods shift attention toward defining either probabilistic or conservativeness factors and encourage the decision maker to consider uncertainty in the problem explicitly. As demonstrated, many different uncertainties can impact the results in a decision problem such as maritime energy carrier selection. While this paper only looked into two uncertainties, much more are preferably included in the decision problem. An extension of uncertain factors should be covered in further research. For this purpose robust optimization seems to be promising, due to its tractability, but this remains to be proven.

From a more practical standpoint, the methods show that methanol and LNG ships allow a cheap but large reduction in emissions through the use of biofuels. However, flexibility is key for these options to be able to follow possible shifts in fuel or carbon prices as modelled in this paper. The ability to switch toward other fuels during the lifetime was found to become even more important for values that occur outside of the assumed ranges. This was shown for a potential variability change for biofuels, which was still selected as an important intermediate solution for emission reduction, despite the shift of the mean and the increase in price range.

Consequently, under the conditions of the case study, including uncertainty in such a selection problem is more important than the choice of a specific method. Furthermore, applying both methods to the same dataset can increase confidence in the practical results. We have shown, that the suggested decisions of both methods are very similar. Thus, the choice of method, in our case, affects the decisions to a much lesser extent than the assumptions made for the input parameters.

CRediT author statement

Jesper Zwaginga: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Visualization; **Benjamin Lagemann:** Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Data Curation, Writing – Original Draft, Visualization; **Jeroen Pruyn:** Writing – Review & Editing, Supervision, Project administration; **Stein Ove Erikstad:** Conceptualization, Methodology, Writing – Review & Editing, Supervision, Project administration

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Appendix B: supporting papers

Supporting Paper 1

A Method for Evaluating Ship Concepts in Realistic Operational Scenarios using Agent-based Discrete-Event Simulation
Jon S. Dæhlen, Endre Sandvik, Agathe Isabelle Rialland, Benjamin Lagemann (2021)
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A Method for Evaluating Ship Concepts in Realistic Operational Scenarios using Agent-based Discrete-Event Simulation

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Abstract

Meeting IMO's greenhouse gas ambitions generates need for designing low- and zero-emission ships within the maritime industry. Evaluating proposed conceptual ship systems in terms of energy efficiency, exhaust emissions and operability is a task of great complexity, even more under realistic operational profiles and weather conditions. This paper presents a simulation method developed for evaluating a ship concept across several years of realistic operation. The method allows for a user-defined operational scenario and simulates numeric hull, propulsor and machinery models based on agent-based discrete-event simulation in historic oceanographic data. A use case for a tanker is presented, demonstrating how the method, implemented through a simulation software, helps the naval architect in navigating among the various technologies available, being able to assess an early system design in a scenario spanning several years.

1. Introduction

A ship can be identified as a complex system made up from numerous sub-systems, such as main and auxiliary engines, crew and passenger cabins, cargo spaces, cranes, and other handling equipment, as well as the hull itself and the propulsors. Finding the right design and combination of sub-systems for the ship to perform optimally throughout its life time and considering the unknown future, is a difficult multi-objective optimization problem to solve, if not an impossible task, *Bertram and Thiart (2005)*. Notwithstanding, given the urgent need to maintain and improve the cost and carbon competitiveness of waterborne transport, this task is worth trying.

The ship design process has been evolving for several decades since the traditional design spiral was introduced, *Evans (1959)*. Despite the increased availability of computer-aided tools in the 1980s and introduction of system based design method in the 1990s, *Erikstad and Levander (2021)*, which is meant to be an iterative method, ship designers tend to lock the main dimensions of the ship concept early in the design phase, based on experience or tender requirements. Investigations of various energy-saving devices such as wind-assisted, *Lu and Ringsberg (2020), Tillig and Ringsberg (2020),* and wave-assisted propulsion, *Stensvold (2020),* are expected to change how a vessel is designed and operated, *Tillig et al. (2020)*. The current lack of operational experience means risking that the initial ships using such devices may not live up to the expectations compared to the increased investment costs, and such devices may be dismissed on faulty basis. This underlines the importance to uncover the true requirements of the vessel early in the design phase to come up with designs that performs well throughout its lifetime.

Holistic ship design focuses on finding the true functional requirements of the vessel by looking beyond the ship itself and into what the ship is intended to, and maybe just as important, will do throughout the future. Logistics Based Design considers the ship as part of a logistic system with the goal of doing transportation work between two ports, *Brett et al. (2006)*, and extending it into a life cycle approach considering the performance of a design from the keel is laid and eventually including being scrapped, *Papanikolaou (2010)*. Further, moving the scope of the design task to consider all vessels serving as part of a transportation system also including other forms of transportation, such as land-based (multi-modal transport), can help the designer to come even closer to an optimal global solution, *Hagen (2020)*.

Gaspar et al. (2012) identified five aspects of complexity in ship design, namely:

- Structural: How sub-systems of the vessel interacts.
- Behavioural: Analyse how each sub-system performs individually.
- Contextual: The external context the ship is subject to, such as different operational profiles.
- Temporal: The change of all aspects of over time, that is for instance changing operational requirements.
- Perceptual: How advantageous different designs are for various stakeholders, such as owner, operator, and client during different epochs.

A simulation-based evaluation method that can integrate several sub-systems and assess the performance of the ship concept both in an environmental and economic manner seems advantageous for covering several aspects of complexity: the system interactions (behavioural complexity), the effect of operational profiles (contextual complexity), the change of static contexts over time (temporal complexity) as well as to allow the other stakeholders than the designer to do independent evaluations from their point of view in the perceptual aspect. Coupled to a generic ship synthesis model, *Lagemann and Erikstad (2020)* the combination of methods would allow for quick and intuitive way of assembling, analyzing and evaluating a ship designs at a conceptual level.

With increased availability of computational power, simulation of a ship's sub-systems is now a common discipline, and a lot of effort has been put into integrating several sub-systems into a grander ship system model. By defining standard interfaces, dynamic simulation models of various sub-systems developed by their respective vendors can be integrated, *Hassani et al. (2016), Sadjina et al. (2019), Skjong et al. (2018).* The coupled simulation model essentially becoming a large set of differential equations can be accurate, but tends to be computationally demanding to solve, and applying longer simulation horizons than a few days in not practical.

Using simulations to benchmark a a whole ship system in realistic operational conditions over a lifetime period requires a method that allows for simulation horizons on the scale of years. By simplifying the ship model to a quasi-static representation, the number of sampling points can be greatly reduced, still revealing significant performance differences between ship designs, *Fathi et al. (2013)*. The validity of such a method was confirmed by *Sandvik et al. (2018)* through a case study using full-scale measurements from a deep-sea vessel, and also extended to a more complex ship model including a machinery model, *Nielsen et al. (2019)*. The same approach has also been implemented in a software suite and tested by the industry, *Erikstad et al. (2015)*, and applied to use-cases for a RORO-Ferry, passenger ferry and Offshore Supply Vessel to prove its ability to produce operational profiles, *Yrjänäinen et al. (2019)*. The route of a vessel between two harbours are by no means static between voyages due to weather routing and the captains choices, and the effect of such variations were found significant, underlining the importance of modelling realistic scenarios in the simulations, *Sandvik et al. (2020)*.

Based on this work, this study presents a simulation method for early-phase concept evaluation that applies agent-based discrete-event simulation to quasi-static ship models (known as the "Gymir" simulator in the funding project) and demonstrates how it may be used to compare design variations in the design process.

2. Simulation method

Fig. 1 illustrates a high-level sketch of the goal of the simulation method. Inputs to a simulation are:

- A scenario, consisting of waypoints defining a route, speed-policies and timestamps for simulation start and end defines how, where and when the ship will sail.
- Historic oceanographic data, typically from a hindcast/re-analysis model that covers the geographic and time domain of the scenario.

- A numerical ship model that given a sea, -and weather state, calculates the necessary power to maintain a desired speed (i.e., quasi-static)

For an efficient evaluation of these models, the simulation method should only re-evaluate (sample) them when there is a significant change in any of them. Typically, such changes are:

- Reaching a waypoint, triggering a course change for the ship, which consequently changes the encountered wind-, and wave direction.
- There is a significant change in the weather, e.g., the simulation a new cell in the discrete grid of the weather data.
- The speed or power plant setting of the ship is altered.

During the simulation, all the evaluations are logged into a time series, and the performance of the ship model is analysed.

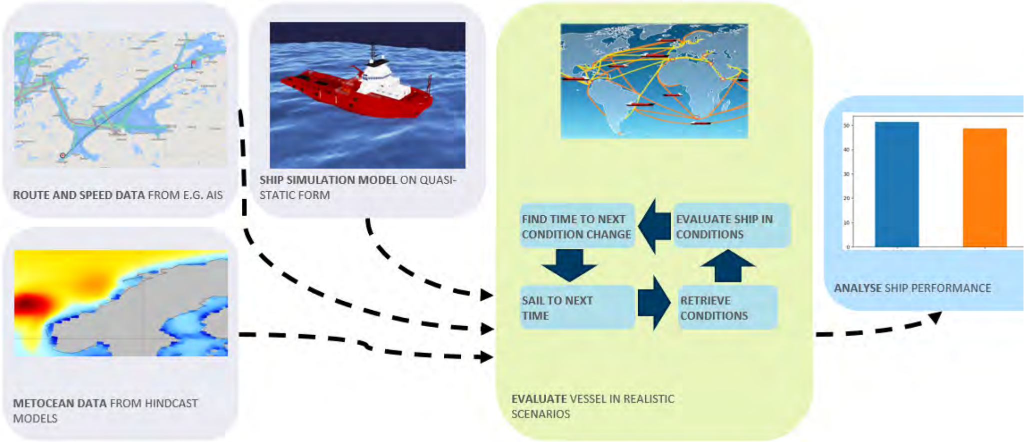

Fig.1: High-level concept sketch of the simulation method

The Agent-based Discrete-Event simulation approach defines parts of the simulation an agent, which at each time step reports back to a central scheduler what should be an appropriate time step to the next sample. The scheduler evaluates the reported time step from all agents, selecting the shortest one. All agents are then evaluated at this time, resulting new time steps are reported to the scheduler.

In this paper, one such agent is the ship, which reports to the scheduler the time required to reach the next waypoint given the current sailing speed, while the weather data is another agent, reporting the next time new data is available. Thus, the relevant changes along the timeline in a simulation scenario are dynamically steering the simulation time step, rather than having to force a significant number of costly samples to ensure that changes in the weather data is covered. Fig.2 illustrates how the simulation method will choose timestamps for sampling.

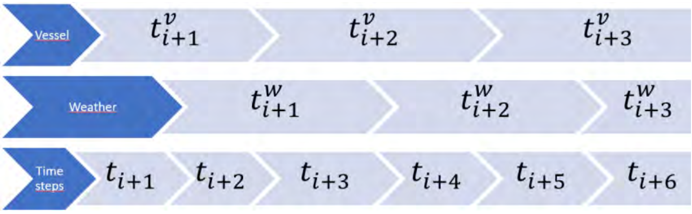

Fig.2: Illustration of the Agent-based Discrete Event Simulation approach used in the ship performance evaluation, *Yrjänäinen et al. (2019)*

3. Ship models

To demonstrate the evaluation method, a case study is constructed by modelling two fictional ships. The first has a typical shape for a Medium-Range tanker of 174 m length (Benchmark), the second is prolonged though slightly slenderer (Slender). Both ships have approximately the same cargo capacity and fit within the old Panamax canal. A ship designer may have a hypothesis that the slender design will outperform the benchmark due to lower wave resistance. This hypothesis can be tested using the simulation method described in Section 2.

Both ships are modelled using the ShipX numerical software package, *Fathi (2018), Fathi and hoff (2017)*, which is based on a 3D-model of the hull and uses potential flow strip theory to compute the residual resistance. Combined with an open water curve for a propulsor, the required power and RPM to attain a speed through water are estimated for any significant height, peak period and mean direction of the waves and average wind speed and direction. Fig.3 shows the hull of the benchmark ship; Table I lists some main particulars for each design.

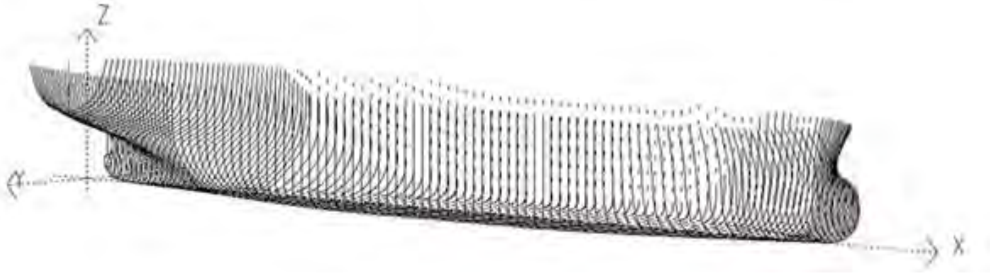

Fig.3: 3D-representation of the hull for the benchmark ship

Table I: Ship model particulars

	Length	Breadth	Draught	Block
Benchmark	174.0 m	32.2 m	11.0 m	0.782
Slender	190.0 m	32.2 m	11.0 m	0.728

The required power to keep a desired speed will vary with the sea- and wind state. As the power plant models in this paper are simplified to deliver a desired power to the propeller shaft, a power control policy more advanced than keeping a constant power is needed to achieve a realistic simulation. Two power policies can be set for the simulation, namely:

- Keep constant speed by varying the power, though if above a limit (e.g., maximum available power), reduce the speed so that power is equal to the limit. This policy may be applicable to ferries, which are required to keep a strict time schedule.
- Vary power (and speed) to keep a constant propeller RPM. This policy is commonly used on deep-sea vessels.

Note that only the power applied to the propeller shaft is considered in this paper. Other consumers such as hotel loads are neglected as they are considered independent of the ship hydrodynamic shape.

4. Scenario

A common transport assignment for a MR Tanker is carrying oil from the east coast of North America to Western Europe. A representative route is constructed from the Gulf of Mexico to the English Channel, and typical waypoints for such a route are visualized in Fig.4, *Admiralty (2018)*. Yellow markers indicating the end points of the route, while the orange markers represent waypoints inserted for navigation.

Fig.4: Visualization of the route used for the simulation

To demonstrate the simulation method, the ships are set up to shuttle this route back and forth, excluding the port entrance and loading / unloading time from the simulation. This pattern is repeated throughout one year from January 1st 2018, until December 31th 2018. The speed policy is set to keep a constant speed of 13 knots and simulate a powerplant by limiting the propulsion power to 8000 kW. Historic weather data from the European Centre for Medium-Range Weather Forecast's ERA5 re-analysis dataset is used, *Hersbach et al. (2018),* p.5.

5. Experimental simulations

Simulating each ship requires approximately 4 minutes running on a relatively standard laptop (Intel i7 8650, 16GB RAM), resulting in 3039 and 3041 sampling points for the benchmark and slender ship simulation, respectively.

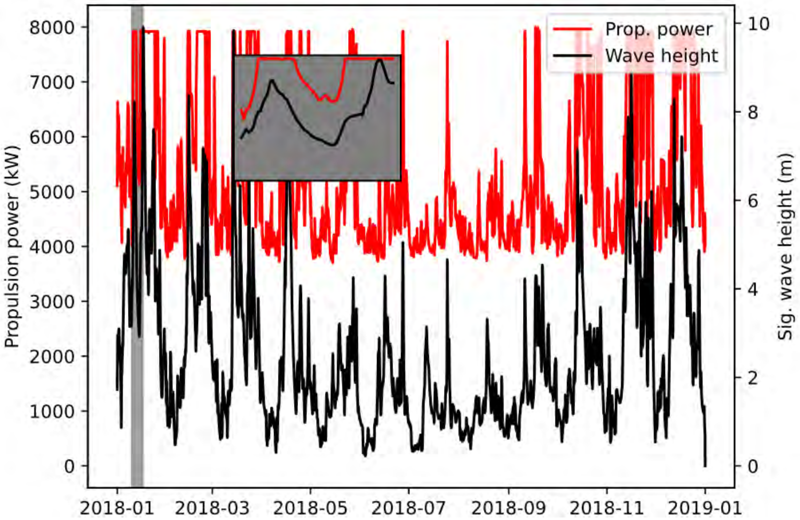

Fig.5: Time series of encountered wave heights and propulsion power for the benchmark ship

Fig.5 shows the encountered significant wave height and resulting power consumption for the benchmark ship during the simulation. It can be noted that on several occasions, when relatively heavy weather is encountered, the power consumption reaches its maximum limit, and the sailing speed is reduced to attain the power limit.

A selection of one week, starting at January 10th, marked in grey on the time-axis, is shown in the grey detail plot to illustrate the level of detail in the simulation.

The effect of the two ships having different added wave resistances is illustrated in Fig.6. Each ship's accumulated sailed distance is subtracted from an "ideal" case sailing at 13 kn for the whole year, regardless of wind and waves. The figure shows that the slender ship is less prone to reaching its power limit due to less added resistance. This in turn results in the slender ship keeping a higher average speed than the benchmark, accumulating a lead as the simulation progresses.

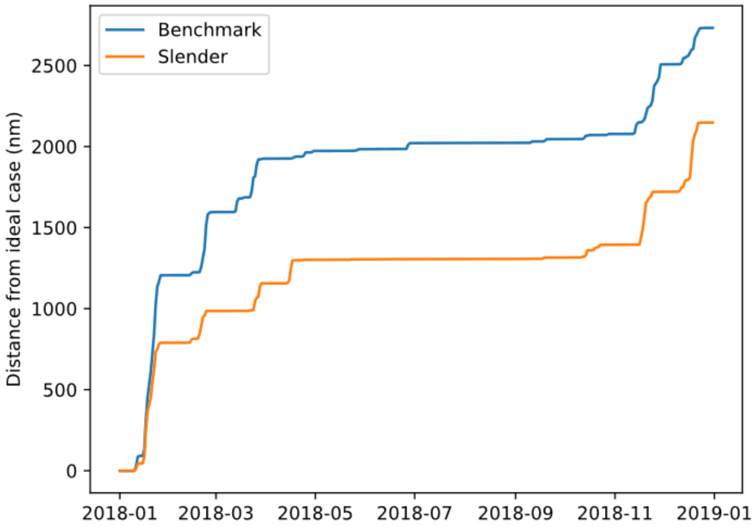

Fig.6: Simulated distance of the two vessels from an "ideal" vessel not exposed to (involuntary) speed loss due to weather

The varying geographical progress of the two simulations inevitably leads to the ships encountering different weather, Fig.7 shows a histogram representation of the waves encountered by the two ships during simulation. The difference may increase due to the lack of active weather routing in the simulation, as the ships will encounter rough weather that the captain in cooperation with weather routing would have avoided by alternate routes and speeds. The highest wave height encountered in this simulation is 10 m significant, which is a rare and undesirable event for a merchant ship, and thus should not have any weight in the design optimization process as it gives the slender vessel an irrelevant advantage. This may be solved by implementing a logic that adapts the speed and route to avoid heavy weather, or simply remove the simulation samples where it occurs. The former method will typically complicate the interpretation of the simulation results, as the two ships may end up sailing very different routes, while great care must be taken using the latter method to avoid removing sample points that have a significance to the design process. As of this, the results are left as-is for the purpose of this study.

The average significant wave height of the encountered sea states is very similar for both vessels. The distribution differs though, highlighting the importance of considering actual sea states rather than averages.

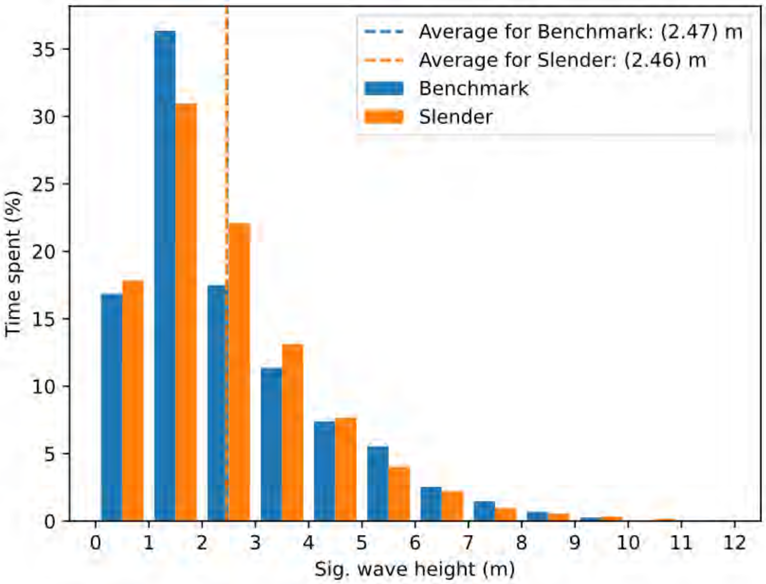

Fig.7: Resulting histogram of encountered significant wave heights

Fig.8 shows a histogram representation of the power consumption for both ships for the whole year. As expected from the lower added resistance, the slender vessel has a reduced accumulated energy consumption, and generally outperforms the benchmark in significant sea states. Such an analysis may form a basis when dimensioning and optimizing the power plant, giving insight into how often a smaller, more efficient power plant will be insufficient to keep the design speed. What load point the power plant should be optimized for, as well the expected variation can be extracted from the data, both factors being desirable to minimize.

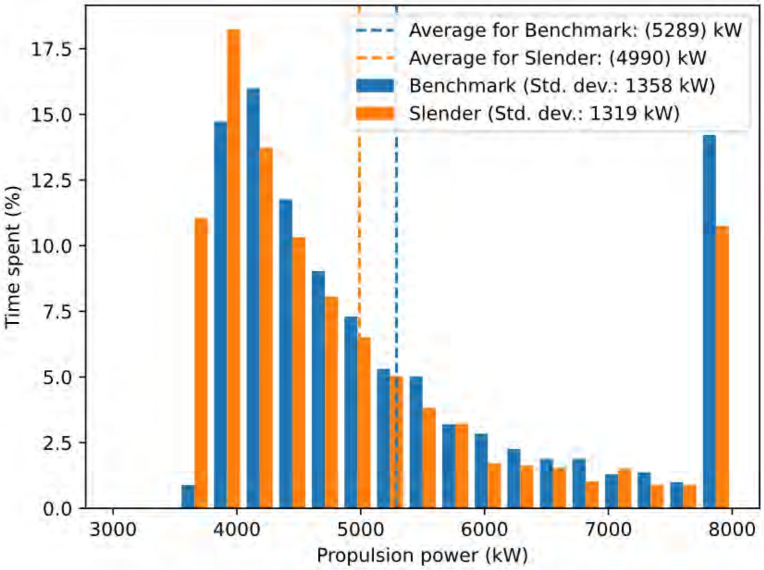

Fig.8: Histogram of propulsion power consumption during simulation

As a last example for what insight a simulation across a long-term horizon can give, Fig.9 shows the wind directions encountered relative to the vessel. This may be used as a basis for optimizing the superstructure with respect to air resistance or, more importantly, to consider the effects of wind-assisted propulsion, and what type of sail that may be the most promising for the scenario that the ship is intended.

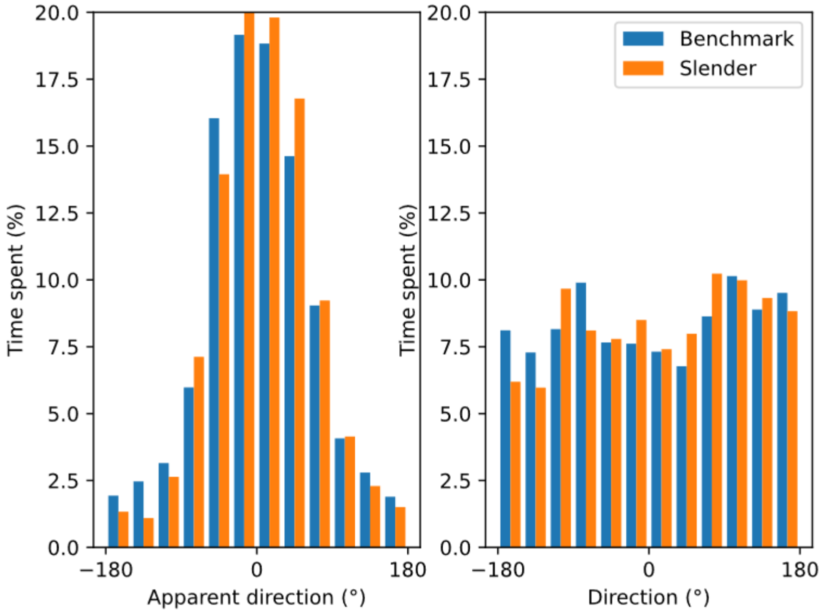

Fig.9: Wind direction relative to the ship. Left plot shows wind direction as apparent to the ship while sailing (left) and wind as apparent to the vessel if standing still (right).

6. Conclusion and further work

A simulation approach for efficient evaluation and benchmarking of a ship concept in a realistic scenario and weather conditions across long-term horizons were presented. Two alternative numerical ship models were introduced, along with a scenario comprising a representative route for the ship class, power plant policies and sailing speeds.

Thanks to the dynamic agent-based discrete-event simulation technique, the long-term simulations (one year) could be carried out efficiently in a matter of minutes. With the speed-up in computational time, our method allows for simulating and exploring further alternatives, whether iteratively or simultaneously.

In general, our method enables moving from calm water evaluations towards real sea states early in the design process. However, it does not come without difficulties: With the ships having different behaviour in similar environmental conditions results in a deviating operational profile as the simulation progresses, complicating the comparison of the results from the ships. Also, the lack of any active weather routing occasionally leads to irrelevant conditions, underlining the need for further work on how the scenario is modelled and simulated.

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Supporting Paper 2

Reduction of maritime GHG emissions and the potential role of E-fuels
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Reduction of maritime GHG emissions and the potential role of E-fuels

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ABSTRACT

Maritime transport accounts for around 3% of global anthropogenic Greenhouse gas (GHG) emissions (Well-to-Wake) and these emissions must be reduced with at least 50% in absolute values by 2050, to contribute to the ambitions of the Paris agreement (2015). Zero carbon fuels made from renewable sources (hydro, wind or solar) are by many seen as the most promising option to deliver the desired GHG reductions. For the maritime sector, these fuels come in two forms: First as E-Hydrogen or E-Ammonia; Second as Hydrocarbon E-fuels in the form of E-Diesel, E-LNG, or E-Methanol. We evaluate emissions, energy use and cost for E-fuels and find that the most robust path to these fuels is through dual-fuel engines and systems to ensure flexibility in fuel selection, to prepare for growing supplies and lower risks. The GHG reduction potential of E-fuels depends entirely on abundant renewable electricity.

1. Introduction

The main source of ships Greenhouse gas (GHG) emissions is the exhaust gas from ships combustion engines which is estimated to be around one billion-ton of carbon dioxide equivalents (CO_{2eq}) annually (Buhaug et al., 2009; Smith et al., 2015; Faber et al., 2020). Such estimates cover what happens on the ship only (Thinkstep, 2019), i.e., the Tank-to-Wake (TTW) emissions. When including the Well-to-Tank (WTT) emissions from producing the fuels (Lindstad et al., 2020), the total Well-to-Wake (WTW) emissions add up to 1.25 – 1.5 billion tons of CO_{2eq}, equal to around 3% of our 50 billion tons of anthropogenic GHG annually emitted (BP 2021).

Assuming continuous annual sea transport growth of 3% and 1% annual energy efficiency improvements as seen from 1970 (Lindstad, 2013; Lindstad et al., 2018), the GHG emissions must then as a minimum be reduced by 75 – 85% per ton-mile up to 2050, to achieve a 50% absolute reduction to contribute to the ambitions of the Paris agreement (2015). The desired GHG reductions can be achieved through: Design and other technical improvements of ships; Operational improvements; Fuels with zero or lower GHG footprint or a combination of these (Bouman et al., 2017).

Zero carbon fuels made from renewable sources (hydro, wind or solar), are by many, for example EU (Fuel EU maritime, 2021), seen as a promising option to deliver the desired GHG reductions. Applied to maritime transport these E-fuels come in two forms: either as E-Hydrogen or E-Ammonia, which requires new vessels and supply infrastructures or conversions of existing ones; Second, as Hydrocarbon E-fuels in the form of E-Diesel or E-LNG, which are fully blend-able (Concawe, 2019) with their fossil counterparts such

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as MGO and LNG and can be used on today's vessels without any modifications or any new infrastructure. In addition to E-Diesel and E-LNG, also E-Methanol has gained interest as a future fuel for the maritime sector. Apart from some of the vessels transporting Methanol, few other ships are using Methanol today. Still, it is seen as a promising future option technically and economically feasible (Andersson and Marquez, 2015; Svanberg et al., 2018; Zincir and Deniz, 2021), either as E-Methanol or from Biomass feedstock as Bio-Methanol. Methanol is a liquid fuel that can be stored in a similar manner to Diesel fuels and for which existing bunkering infrastructure can be converted to Methanol at a low CAPEX (Svanberg et al., 2018). In theory, a vessel's Diesel engine and fuel system can be modified to run on Methanol, while in practice, for most ships, unless the engine and the fuel systems were built to be prepared for a conversion to Methanol, building new ships might be more economical (MAN, 2020; ABS, 2021).

For the scope of this paper, we define all fuels produced by renewable electricity as 'E-fuels' (electro-fuels). That is, E-fuels are low GHG emission fuels considering production (WTT) and combustion (TTW) combined. 'Hydrocarbon E-fuels' is a subset of E-fuels and comprises all hydrocarbon fuels produced by renewable electricity and where the carbon is captured directly from the air, i.e., E-Diesel, E-LNG, and E-Methanol. Moreover, we assume that renewable electricity production does not produce any GHG emissions. Compared to a full Life cycle assessment, the Well-to-Wake approach applied in the present study excludes the production and the setup of the windmills, solar panel parks or hydro power station, the associated supply grid, end-of-production treatment and final disposal. In a future where nearly all the energy for these activities might come from renewables, excluding these emissions makes no large impact on the results and can be justified to make a best-case future estimate for E-fuels. On the contrary, quantifying the impact of these emissions today, which are significant, requires a study on its own.

With conventional fuels, combustion contributes to around 80% of the fuels Well-to-Wake GHG emissions and energy usage, while their production, i.e. Well-to-Tank, accounts for around 20% of their emissions and energy usage (Edwards et al., 2014; Prussi et al., 2020). With so-called zero GHG fuels the picture becomes more complicated: First, with Hydrogen no GHGs are emitted when the power for propulsion is released in the fuel-cell or engine, but large amounts of renewable energy are needed to produce the E-Hydrogen; Second, Ammonia forms no CO_2 when combusted, but higher N_2O emissions (a powerful GHG gas) than with conventional fuels (ABS, 2021); and as for E-Hydrogen, large amounts of renewable energy are needed to produce the E-Ammonia; Third with the Hydrocarbon E-fuels, which release CO_2 in the same amounts as conventional fuels when combusted, their GHG neutrality is based on equivalent volumes of carbon captured directly from the air during their production process. In addition, their production requires large amounts of renewable electricity.

To find the total global warming effects from different greenhouse gases and to compare their relative importance, the various greenhouse gases are weighted according to their global warming potential over a hundred years (Shine, 2009). GWP assigns negative weights to exhaust gases and particles that have a cooling effect, and positive weights to those that have a warming effect. The GWP values as provided by IPCC in their Assessment Reports, the latest being AR5 (IPCC, 2014), which are based on most recent scientific work and therefore recommended as characterization factor of climate impact in LCA studies (Hauschild et al., 2013).

The motivation for this study has been to investigate E-fuels with focus on their feasibility, energy utilization and cost, along with their GHG reduction potential, all compared to the conventional fossil fuels. The paper proceeds as follows. Section 2 reviews the relevant literature, while Section 3 describes the applied Well-to-Wake assessment methodology and section 4 describes the dataset applied. In section 5, we investigate and assess the alternative fuel options with focus on WTW emissions, energy usage and their cost. In section 6 we discuss the results and in section 7 we conclude our work.

2. Litterature review

Studies of marine fuels have used both simplified and more advanced life-cycle assessment (LCA) methodologies to assess environmental impacts from fuel extraction and processing to combustion in ship engines (Bouman et al., 2016; Bouman et al., 2017; Silva, 2017; Lindstad et al., 2020). Previous studies can be grouped into three main categories: Well-to-Tank; Tank-to-Wake; and Well-to-Wake studies.

Well-to-Tank studies focus on the production of the fuel from fossil, bio, or renewable sources. For a conventional fossil fuel, WTT studies include the whole upstream chain from production, processing and transport to the refinery, refining, transport to the ship, and bunkering operations. Edwards et al. (2014), Exergia (2015), GREET (2018), Alvarez et al., 2018, and Prussi et al. (2020) are typical Well-to-Tank studies. These are general studies relevant for all sectors using the fuels, and from which the application of results goes therefore far beyond the maritime sector.

Tank-to-Wake studies focus on the combustion of marine fuels as a function of engine technology and fuel (Campling et al., 2013; Johansson et al., 2013; Brynolf et al., 2014; Jiang et al., 2014; Acciaro, 2014; Lindstad et al., 2015a). Within this scope, there are also more technical studies on how to improve engine energy efficiency and on how to reduce un-combusted methane when Liquid Natural Gas (LNG) is used as the primary fuel (Hiltner et al., 2016; Stenersen and Thonstad, 2017; Hutter et al., 2017; Ushakov et al., 2019a; Ushakov et al., 2019b).

Well-to-Wake studies sum up Well-to-Tank plus Tank-to-Wake for fuels when used to power ships. Compared to full LCA studies, the Well-to-Wake studies exclude construction and decommissioning of the fuel production chain. Thinkstep (2019); Lindstad (2019); ICCT (2020); Lindstad and Rialland (2020); Lindstad et al. 2020; Sphera (2021) are examples of recent studies within this field.

Only a few of these studies consider energy usage when comparing alternative fuels (Edwards et al., 2014; Prussi et al., 2020). On the other hand, cost is frequently included: First, in studies focusing on best fuel options to meet the ECA requirements in North America and North Europe (Jiang et al., 2014; Acciaro, 2014; Lindstad et al., 2015b). Second, for the impact of the 2020 Sulphur cap of 0.5% globally (Lindstad and Eskeland, 2016; Shell, 2016; 2017; Lindstad et al., 2017). Third, in studies assessing alternative zero carbon fuels on their own (IEA, 2019b); Fourth in studies where one zero carbon fuel such as renewable Methanol (Helgason et al.,

2020) is compared against its fossil counterparts and conventional bunker oil; Fifth in studies where alternative zero carbon fuels are assessed and compared with today's conventional fuels (Hansson et al., 2017; Nair and Acciaro, 2018; LR&UMAS, 2020; Prussi et al., 2021).

From a narrow perspective and considering maritime transport as an island on its own, i.e., following the argument that all sectors shall take an equal share of the GHG reductions, one can certainly argue that the way the various zero and low carbon fuels influence global energy usage (consumption) is irrelevant. However, despite that climate change came on the agenda in the 1990′s (UNFCCC, 1997), global energy consumption has increased from 8.8 billion tons oil equivalent (TOE) in 1990 to 14.3 billion TOE in 2018 (IEA, 2019a). This corresponds to an annual increase of 1.7%, which is a tripling compared to the 4.9 billion TOE consumed in 1970 (BP, 2020). Out of this, fossil energy adds up to 81% of the total energy consumed both in 1990 and in 2018 (IEA 2019a). Globally, around 30% of these 14.3 billion TOE are used to produce electricity, of which 60–65% come from fossil, 10% from nuclear and the remaining 25–30% from renewables like wind, solar and hydro (IEA, 2019a; BP, 2021; IEA, 2021a; Shell, 2021). Noting the increased energy consumption and the continued low share of renewables, we would argue that new renewable energy capacity and production must be allocated in a way that achieves the biggest overall emissions reduction.

Making the electricity sector fully renewable will hence give a large GHG reduction on its own and will require a large ramp-up of current renewable energy production. Besides, additional capacity to produce renewable electricity will be needed to fuel an increasing number of electric cars and trucks, and to produce E-fuels if needed for aviation and maritime transport. Therefore, we find it useful to illustrate the amounts of renewable electricity needed under four 2050-scenarios in Table 1. First, with an annual increase of energy consumption of 1.7% as seen from 1990 and that all energy used shall be renewable, a scenario entitled "business-as-usual (BAU) and 100% reduction of CO_2 emissions" (Rialland and Lindstad, 2021); Second, the Shell Sky 1.5degree scenario (Shell, 2021) which assumes 1% annual increase in energy consumption and a gradual decrease of GHG emissions through increased production of renewable energy in combination with carbon capture and storage (CCS) to make us net zero by 2070; Third, assuming zero growth in energy consumption and a cut of global CO_2 emissions by 50% through increased renewable electricity production (Rialland and Lindstad, 2021); Fourth, the Net Zero by 2050 scenario by IEA (2021b) which assumes 0.3% annual reduction in energy consumption and that we will be net zero by 2050 through increased production of renewable energy in combination with carbon capture and storage. Both the Shell and IEA scenarios use CO_2 as a proxy for GHG emissions, where the basic relationship (IPCC, 2014) is that CO_2 accounts for 60–65% of the GHG emissions, methane for around 20%, land use for around 10%, Nitrous oxide for around 5% and fluorinated gasses for 2% (GWP 100). Their assumption is that these other GHG emissions will be reduced proportionally to CO_2 due to a combination of stricter emission rules and the reduced use of fossil fuels.

The main observations from the table are: First, if we combine 2050 BAU increase of energy consumption with net zero GHG emissions in 2050 (Rialland and Lindstad, 2021), we need 731 MTOE of new additional renewable electricity production capacity each year up to 2050 and 384 MTOE reduction of the annual fossil production; Second, with the Shell Sky scenario we need 155 MTOE of new renewable electricity and 28 MTOE of bio annually in addition to a large carbon capture and storage capacity by 2050; Third, with the 2050 Zero growth & 50% reduction of GHG emission (Rialland and Lindstad, 2021) we need 159 MTOE of new annual renewable electricity production. Fourth, with the IEA Net Zero by 2050 scenario we need 150 MTOE of new annual renewable electricity and 57 MTOE of bio in addition to a large carbon capture and storage capacity by 2050. An important observation is that both Shell (2021) with their long track record within the field of making scenarios (Wack, 1985; Shell, 2008) and IEA (2021b) finds that that new renewable electricity production can be increased with around 150 MTOE in average each year up to 2050. Which is significantly less than what is needed to be net zero without carbon capture and storage in 2050 under any of the scenarios presented in Table 1: This implies that renewable electricity will be a scarce resource up to 2050 and beyond.

The contribution of our paper to existing literature is: First, to expand the scope of analysis from covering only emissions or cost and

Table 1
Scenarios for Global energy use and mix in 2050. Source: compiled by the authors; Data sources: IEA 2019a; IEA 2021b; Shell (2021); Rialland and Lindstad (2021).

Global Energy Mix 1990 – 2050	1990	2018	2050 BAU & 100 % GHG reduction	Shell Sky 1.5 degree	2050 Zero Growth & 50% GHG reduction	Net Zero by 2050 IEA
Total energy used (MTOE)	8 791	14 314	25 394	18 741	14 314	12 943
of which renewables (MTOE)	1 127	2 011	25 394	7 876	7 104	8 644
Growth in annual energy use (%)		1.7 %	1.7 %	1.0 %	0 %	−0.3 %
Energy use in percentage of 2018	61 %	100 %	179 %	131 %	100 %	91 %
Anthropogenic CO_2 without CCS	20 416	33 243	0	23 650	16 622	7 600
Carbon Capture and Storage (CCS)			0	5 200	0	7 600
Global anthropogenic CO_2 emissions	20 146	33 243	0	18 450	16 622	0
Annual increase renewable electricity (MTOE)		32	731	155	159	150
Annual increase bio & other renewables (MTOE)			0	28	0	57
Annual increase fossil (MTOE)		166	−384	−45	−173	−250

emissions, to include emissions, cost, and energy use; Second, to perform a transparent WTW assessment of the alternative fuels and their associated engine technologies, including the fuel tank systems. Third, to document that a narrow, solely maritime perspective on both emission ambitions and zero carbon fuels may be counterproductive to a fast, global decarbonization, as it oversees its impact on the global energy supply. In total, this will facilitate increased insight and enable decision makers to avoid sub-optimal solutions where one sector may reduce emissions on the expense of another in a way that do not contribute to reaching the global reduction ambitions set by the Paris agreement (UNFCCC, 2015).

3. Methodology

The present study consists of a transparent Well-to-Wake assessment of alternative E-fuels, considering their GHG reduction potential, cost, and energy use. To do so, we conduct a LCA of alternative power solutions, following the LCA process as defined by ISO LCA guidelines (ISO 14040): goal and scope definition, inventory analysis, impact assessment, and interpretation. This framework is similar to the one applied by Hwang et al. (2019), Dong and Cai (2019) and Lindstad et al. (2020) in their studies of maritime technology solutions. In the present study, the LCA consists of Well-to-Wake GHG emissions, energy usage and cost from the fuels production (WTW) and its combustion (TTW). The Well-to-Wake approach is commonly used for assessing fuels in terms of potential GHG and energy savings (Edwards et al., 2014).

Fig. 1 shows the LCA methodology as applied in this study with the goal of performing a Well-to-Wake assessment of the alternative fuels assessed covering their climate impact, their energy usage, and their cost. The Well-to-Wake assessment is divided into Well-to-Tank (WTT) and Tank-to-Wake (TTW). Emissions, energy usage and cost values are based on a review of studies and inhouse knowledge. All emission assessments are based on a one-hundred-year time horizon (GWP100). The appendixes 1 and 2 contain a compilation of the values used. Compared to a full LCA the construction and decommissioning phases of electricity and fuel production units are not part of the analysis.

4. Dataset

This study investigates alternative E-fuels compared to the conventional fossil fuels, where the purpose of this chapter is: First to introduce the fuels and their associated maritime engine technologies; Second to establish the energy prices for all the fuels assessed;

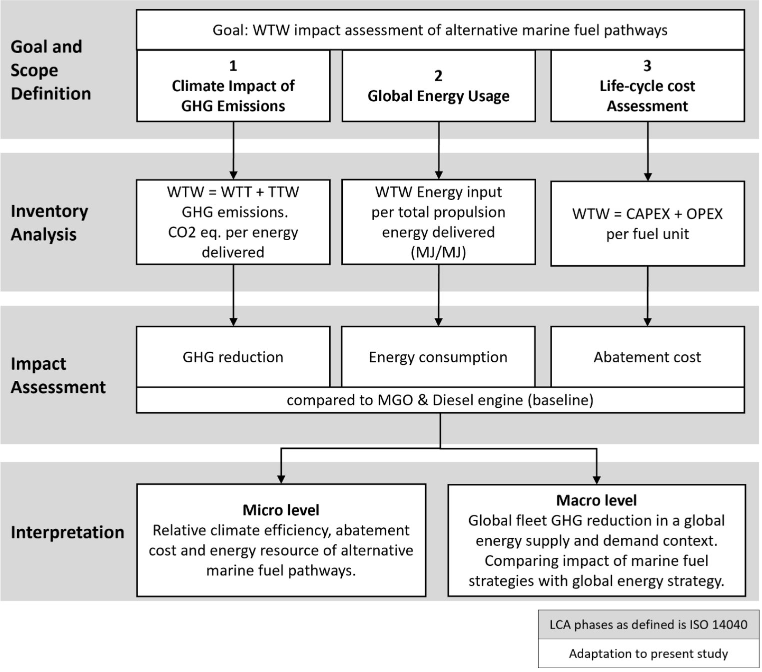

Fig. 1. The applied LCA methodology.

Third to identify ship-specific additional costs of using other fuels than the standard Marine Gas Oil (MGO) or low sulphur bunker oil (VLSFO).

MGO, VLSFO and HFO (Heavy Fuel Oil) represent the conventional fuels. From 2020 onwards HFO can only be used in combination with an exhaust gas scrubber to achieve compliance with the global 0.5% Sulphur cap or the 0.1% Sulphur cap in the North American and North European emission control areas (Lindstad and Eskeland, 2016; Thinkstep, 2019). These conventional fuels are all combusted in Diesel engines. Two-stroke engines dominate when measured by installed power and their share of the total fuel consumption (Thinkstep, 2019; ICCT, 2020). Therefore, all costs, energy usage and emissions for any of the fuels in this study are compared against a two-stroke Diesel engine running on MGO as the basic reference.

LNG (Liquefied Natural Gas) and LPG (Liquefied Petroleum Gas) represent the low carbon fuels, or more precisely, fuels which in the best case give up to 20% GHG reduction measured on a Well-to-Wake basis (Lindstad et al., 2020). These fuels are combusted onboard in pure gas engines or dual-fuel engines (DF-engines) where a small amount of Diesel is used to ignite the fuel when running on LNG or LPG. These engines can also run purely on 100% MGO or VLSFO when LNG or LPG is not available or its cheaper to run on the conventional fuels. The available dual-fuel engines are based on two different combustion cycles, either the Diesel process or the Otto process (Thinkstep, 2019). The advantage of the dual-fuel Diesel engine is that it can be built to burn several fuels such as LNG, ethane, LPG, Methanol and, in the future, Ammonia (Lindstad et al., 2020). Aided by pilot fuel, we get a nearly complete combustion of the fuel in the engines. The disadvantage is a higher CAPEX and OPEX cost than for the Otto option, which in comparison currently only can run on LNG or on the conventional fuels.

When it comes to emissions, un-combusted methane for the Otto option is approximately 10 times larger than for the Diesel option (ICCT, 2020; Lindstad et al., 2020). Un-combusted methane from ship engines is one of many sources to the world's increasing global methane emissions, where the rising atmospheric methane levels represent a major challenge in the effort to limit global warming (Yusuf et al., 2012; Turner et al., 2018; Fletcher and Schaefer, 2019). Methane atmospheric concentration levels have increased by 150% since the industrial revolution (Bloomberg, 2020). In comparison the CO_2 concentration in the atmosphere has increased by 50% and the N_2O with 25% (Mac Farling et al., 2006; CSIRO, 2020). From 2012 to 2018, methane emissions from shipping increased by 150% while the use of LNG increased by only 30% (Faber et al., 2020).

E-fuels, which are an emerging class of carbon–neutral fuels, are made by storing electrical energy from renewable sources in the chemical bonds of liquid or gaseous fuels. Carbon-neutral Hydrogen is produced by means of electrolysis with renewable electricity ($2H_2O$ + renewable energy -> $2H_2 + O_2$). To increase the volumetric density and make Hydrogen and Ammonia feasible for shipping,

Table 2
Fuel specific WTW data (GHG, Energy usage, Fuel cost and CAPEX).

		LCV	WTW Power (Input / Output)	New built cost Engine	Tanks and add-ons such as scrubber	Total Capex	Fuel Cost Low	High	Low	High
		MJ/ kg	*MJ/MJ*	*USD/ kW*			*USD / TOE*		*USD / GJ*	
Electricity			1.5				230	700	5.4	16.3
Natural Gas		49.2					300		7.0	
Crude Oil (60 USD per barrel)		41.9					420		10.0	
HFO & Scrubber	Diesel	40.2	2.3	400	300	700	365		8.8	
VLSFO	Diesel	41.0	2.4	400	0	400	440		11.0	
MGO	Diesel	42.7	2.4	400	0	400	500		12.0	
LNG	Dual Fuel Diesel	49.2	2.4	800	600	1400	380		9.0	
LNG	Dual Fuel Otto	49.2	2.4	400	600	1000	380		9.0	
LPG	Dual Fuel Diesel	46.0	2.2	600	200	800	460		11.0	
Liquid Hydrogen (NG)	Dual Fuel Diesel	120.0	4.5	1500	1200	2700	1 100		26.3	
E-Liquid Hydrogen	Fuel Cell	120.0	5.0	1500	1200	2700	925	1 750	22.0	41.6
Ammonia (NG)	Dual Fuel Diesel	18.6	3.8	800	600	1400	1 100		26.3	
E-Ammonia	Dual Fuel Diesel	18.6	4.2	800	600	1400	940	1 750	22.0	41.0
E-LNG	Dual Fuel Diesel	49.2	6.2	800	600	1400	1 350	3 000	31.2	69.3
E-LNG	Dual Fuel Otto	49.2	6.1	400	600	1000	1 350	3 000	31.2	69.3
E-Methanol	Dual Fuel Diesel	19.9	6.5	600	200	800	1 360	3 235	31.2	74.2
E-Diesel	Dual Fuel Diesel	42.7	7.1	400	0	400	1 530	3 575	35.0	81.8

the fuels must be liquified. Hydrogen turns into liquid at –253 degrees Celsius and Ammonia at –33 degrees Celsius. While compressing Hydrogen requires less energy than the liquification process, the potential building costs of Hydrogen pressure tanks (Kharel and Shabeni, 2018; Rivard et al., 2019) by far exceed the price of a liquid Hydrogen storage system (NCE Maritime CleanTech, 2016). The benefit of lower energy expenditures for compressed Hydrogen is thus offset by the larger capital investment in the storage system. For the remainder of this paper, we hence only consider liquid Hydrogen as the best pure Hydrogen storage option for deep sea shipping. As an alternative to storing pure Hydrogen, the Haber-Bosch process allows processing Hydrogen into Ammonia ($N_2 + 3H_2 +$ renewable electricity -> $2NH_3$). Ammonia can be stored in liquid form by either pressurizing (approximately 8 bars at ambient temperature) or cooling (–33 degrees Celsius at atmospheric pressure). With acceptable gravimetric and higher volumetric energy density compared to liquid Hydrogen, Ammonia represents another carbon–neutral E-fuel option for shipping.

The Hydrocarbon E-fuels are gaseous or liquid fuels produced from Hydrogen and captured carbon from the air using renewable electricity. They are fully compatible with and blend easily with conventional fuels (Concawe, 2019), which means that E-Diesel is fully compatible and blend-able with MGO, and E-LNG is fully compatible and blend-able with LNG. In addition, there is no need for new infrastructure or bunkering facilities in ports, in contrast to fuelling ships on Hydrogen or Ammonia. Neither is there any need for additional crew training.

Fuel and electricity prices are based on market levels in April 2021 with a crude oil price of 60 USD per barrel including typical price ratios between HFO, VLSFO, MGO, Natural Gas, LNG, and LPG. We use 0.06 USD/kWh for the renewable electricity reflecting the average prices which new capacity needs to be profitable. To get a best-case future price scenario for E-fuels and Hydrocarbon E-fuels, we use a very optimistic low price of 0.02 USD/kWh based on LR&UMAS (2020) and IEA (2019b), while we do not vary the fossil fuel prices. To make the assessment generic and not ship-specific, we have chosen to give the input and perform the assessment and analysis with focus on cost and energy usage per kW and MW in main engine power installed on board the vessel. An annual fuel consumption per MW of 600TOE per MW is based on inhouse data and published studies (Faber et al., 2020; IMO GISIS, 2019). Cost of engine and fuel systems are based on LR & UMAS (2020); Lindstad et al., (2020); ABS (2021); and in-house knowledge. For capital and operational expenses, we have used 12% of newbuilt cost as the annual cost, i.e., 8% for the capital and 4% for the operational cost. Table 2 displays the main input cost data for each fuel and engine combination. In addition, for readers interested in the detailed cost calculations of the alternative E-fuel, costs are included in Appendix 1, while Appendix 2 displays the full version of Table 2.

The main comments and observations from Table 2 are: First, the crude oil price is volatile with prices going up and down, still the price ratios between different fossil fuels are reasonably stable (Lindstad et al., 2017); Second, for natural gas, we have used long term European contracts which typically give a price of two thirds (60 – 75%) of the crude oil price at any time; Third, the low-price columns for all E-fuels are based on renewable electricity becoming available in large amounts at prices far below today's production cost. Fourth, for Hydrocarbon E-fuels, the low-price estimates require in addition to low electricity prices, technology development which reduces cost and energy usage for capturing the carbon directly from the air. Our cost estimations for E-fuels and Hydrocarbon E-fuels are in line with IEA (2019b). The appendixes 1 and 2 contain a compilation of the values used for the analysis.

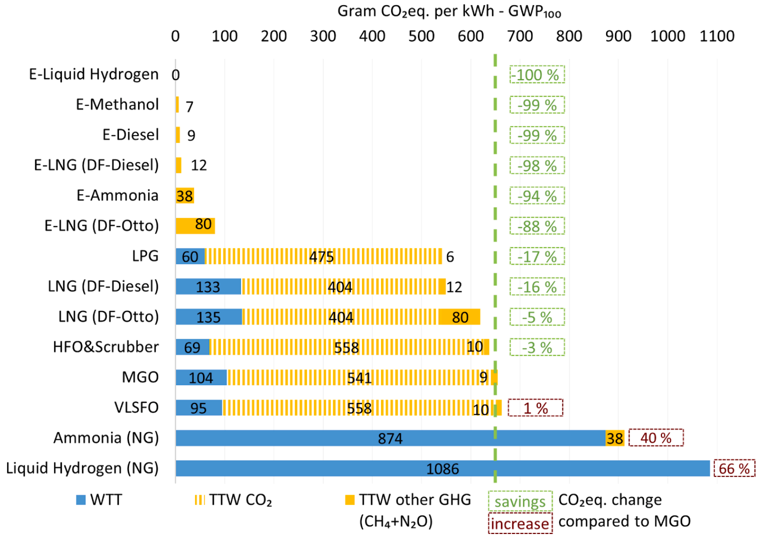

Fig. 2. Well-to-Wake emissions in gram CO_{2eq} per kWh (GWP100).

5. Analysis

In this section we assess the alternative fuels with focus on three criteria: Energy usage, GHG emissions emitted and fuel and engine system cost. Starting with the GHG emissions we get the Well-to-Wake emissions per kWh delivered for propulsion as displayed in Fig. 2. The blue colour is used for the Well-to-Tank GHG emissions, the orange striped colour is used for the pure Tank-to-Wake CO_2 emissions, and the solid orange for the CH_4 and the N_2O emissions. The dashed green vertical line is used to compare all the fuels against MGO on a two-stroke engine and the percentage shows the reduction or increase in Well-to-Wake GHG emissions compared to that reference case.

Main observations from Fig. 2 are: First, that E-fuels give large GHG reduction, i.e., up to 100%. This reflects the critical assumption that the production is based on 100% renewables, a prerequisite that unfortunately is far from reality today. E-fuels are as green or grey as the electricity in the production region; Second, for E-LNG un-combusted methane gives the same challenges as for fossil LNG; Third, with Ammonia we will get more N_2O formed during combustion than for other fuels; Fourth, LPG and LNG combusted in dual-fuel Diesel engines result in 16 – 17% lower GHG emissions than MGO; Fifth, Ammonia and Hydrogen made from natural gas increase GHG emissions with 40 – 66 % compared to MGO, due to transformation losses when first converting natural gas to Hydrogen and afterwards to liquid Hydrogen or Ammonia. In energy terms, today’s total global Hydrogen production is made almost entirely from natural gas and amounts to approximately two thirds of global shipping’s energy consumption (IEA, 2019b). That amount includes Hydrogen being used as a feedstock for Ammonia.

Switching focus from GHG to energy usage, we get the Well-to-Wake energy use as displayed by Fig. 3. Fossil fuels are displayed in grey, and renewable options in green, with the striped bar indicating the difference between current value and a minimum value assuming direct carbon capture from the air. Running a two-stroke Diesel engine on MGO with 50 % thermal energy efficiency implies that on a Tank-to-Wake basis, we need to feed the engine with 2 energy units to get 1 unit delivered at the propeller. In addition, we also use energy to produce the crude at the oil field, transport it to the refinery, refine it and then deliver it to the ships over the whole world. For MGO in total that implies that to deliver 1 energy unit on the propeller we use 2.4 energy units on a Well-to-Wake basis.

The main observations from Fig. 3 are: First, that renewable energy provided through the grid to charge batteries on-board a ship gives the lowest energy consumption per unit of propulsion energy, leading to the conclusion that batteries shall be used wherever batteries can hold sufficient energy for the ship’s intended operation; Second, LPG has the lowest energy consumption of the fossil fuels. A switch from HFO or MGO to LPG will thus reduce conversion losses and GHG emissions; Third, all the fossil fuels are in the range of 2.2 to 2.4 energy units; Fourth producing Hydrogen and Ammonia through electrolysis (from renewable electricity) increases energy consumption by 10 – 15% on a WTW basis compared to producing them from natural gas. In addition, the energy consumption to make Hydrogen and Ammonia is high for both production options; electrolysis and steam methane reforming; Fifth, liquifying E-Hydrogen requires more energy than producing Ammonia; Sixth, Hydrocarbon E-fuels have the highest energy usage, which implies that we need 6.1 to 7.1 energy units of renewable electricity to deliver 1 energy unit at the propeller. In the future, with the foreseen technology development that might be reduced to 5.7 to 6.3 energy units, i.e., a 10 – 15% reduction. To sum up, this implies that if shipping switches to E-fuels such as E-Hydrogen and E-Ammonia, the Well-to-Wake energy consumption doubles compared to today’s fossil fuels. Moreover, with Hydrocarbon E-fuels, the Well-to-Wake energy consumption more than doubles, which means that running the global fleet on E-Diesel with today’s technology would triple shipping’s energy consumption.

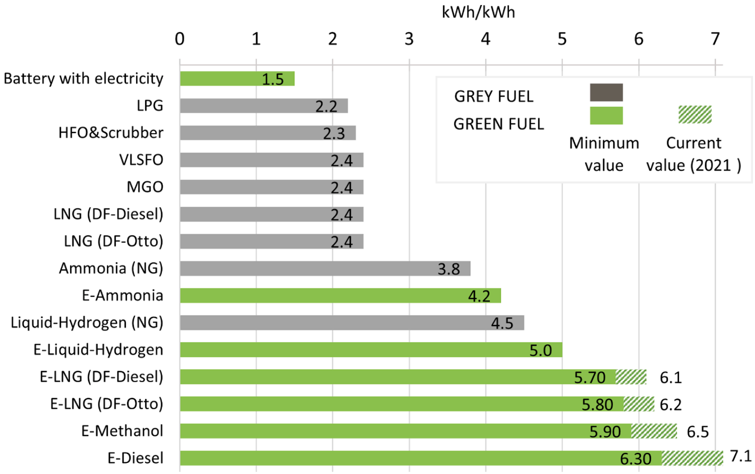

Fig. 3. WTW - energy required as a function of fuel per kWh delivered at the propeller.

We have now assessed the alternative fuels with focus on energy usage and GHG emissions and it is time to turn the focus to fuel and engine system cost. Fig. 4 shows annual costs in USD per kW installed for a low- and high-price electricity scenario respectively. For the reader we recall that the cost of all other fuel is kept constant, and that we use 0.6TOE per kW installed as an annual consumption figure per main engine power Further, we assume that 12% of the newbuilt price is a good proxy for the machinery and fuel related annual CAPEX and OPEX. We have also included an average estimate for the pure vessel cost without engine and fuel system, to give an overview of the total cost structure. In both figures the dashed blue is used for the pure vessel cost, the solid blue for the engine, the vertical purple stripes for the cost for more advanced fuel-tanks and control systems required for LNG, Methanol, Ammonia, and the Scrubber cost when HFO are used as the main fuel. The MGO annual cost is used as benchmark and visualised by the green dot.

The main observations form Fig. 4 are: First, within a high-price scenario for renewable electricity (Fig. 4b), the Hydrocarbon E-fuels E-LNG, E-Methanol and E-Diesel approximately triple the total annual cost of a medium sized tanker or bulker in the 40′ to 80′ deadweight range compared to MGO. For ships the deadweight expresses the maximum cargo carrying capacity in metric tons a vessel can carry. Its real cargo carrying capacity will for ships of this size (40′ to 80′) be up to 95 – 97% of the dead weight after we have deducted for its own fuel, fresh water and supplies; Second, E-Ammonia and E-Hydrogen approximately double the total annual costs

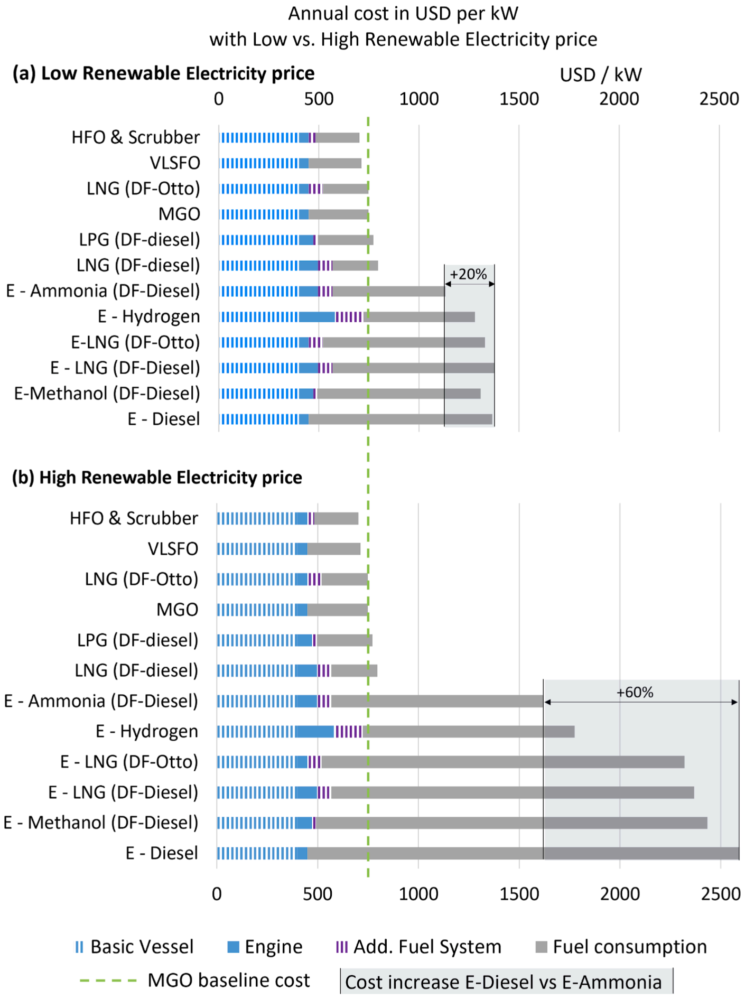

Fig. 4. Annual cost per kW with (a) Low and (b) High Renewable Electricity price.

in a high price scenario. Third, within a low-price scenario for renewable electricity (Fig. 4a), the cost difference between hydrocarbon E-fuels (E-Diesel, E-LNG, E-Methanol) and E-Ammonia and E-Hydrogen is only 20%. Fourth considering that E-LNG and E-Diesel can be used as blend-ins in both existing infrastructure and shipping fleet (Concawe, 2019), the Hydrocarbon E-fuels may become competitive to E-Ammonia and E-Hydrogen in a low-price electricity scenario.

In order to assess the decarbonization options, their cost efficiency should be seen in conjunction with their respective total reduction effectiveness. By combining the GHG emissions and the fuel storage and engine system cost we get the abatement cost per ton of CO_{2eq} as shown by Fig. 5. The figure includes the fuel and engine combinations which reduces GHG and exclude the options which increases GHG compared to the MGO base case. Neither are we showing the HFO & Scrubber option which gives a negative abatement cost (you earn money), because you reduce both cost and emissions compared to MGO, but its reduction potential is anyhow small. The abatement costs are calculated by dividing the additional cost compared to MGO per kW on its GHG reduction potential per kW the WTW. For E-fuels the lowest value reflects the scenario with low E-fuel prices and the highest value reflects the scenario with high E-fuel prices and the solid bar between expresses all prices in between. The percentage in brackets shows the GHG reduction potential for each fuel, which in any case is not influenced by the fuel price.

The main observations from Fig. 5 are: First, that LPG in a low-price scenario comes at a lower abatement cost than LNG; Second, that the E-Ammonia comes at a lower cost than E-Hydrogen; Third, that abatement costs for Hydrocarbon E-fuels (E-LNG and -Diesel) show a larger uncertainty than abatement costs for E-Ammonia and E-Hydrogen but approximately the same emission abatement effect.

Although not being Pareto-optimal solutions, E-LNG and E-Diesel are worth considering in a low-price scenario since they are compatible with the existing infrastructure and fleet. Within a high-price scenario on the contrary, the higher energy consumption for E-LNG and E-Diesel renders their application less competitive. Fig. 6 shows energy usage versus abatement efficiency (Compared to MGO).

The main observations from Fig. 6 are: First that, that LNG in combination with a DF-Diesel engine gives around 16% reduction of GHG and no increase in energy use; Second that LPG gives a slightly higher GHG reduction than LNG and even a decrease in WTW energy use compared to MGO; Third, that E-Ammonia gives a 95% reduction of GHG emission and a 75% increase in WTW energy consumption compared to MGO; Forth that E-Hydrogen gives a 100% GHG reduction and doubling of WTW energy consumption; Fifth, Hydrocarbon-based E-fuels combusted in DF-Diesel engines also gives nearly 100% reduction of GHG, but their WTW energy consumption nearly triples (140% – 200% increase) compared to MGO. Despite this, what makes hydrocarbon-based E-fuels fuels interesting, is that they can be blended into their fossil counterparts and hence be used to gradually decrease shipping's GHG.

6. Discussion

This study seeks to contribute to the discussion on alternative fuels by analysing the emissions Well-to-Wake, energy use and cost. Ultimately aiming at providing support to informed decision making, this study acknowledges that there are numerous alternative fuels and production methods available or under development and that the GHG-reduction potential for each fuel depend on the

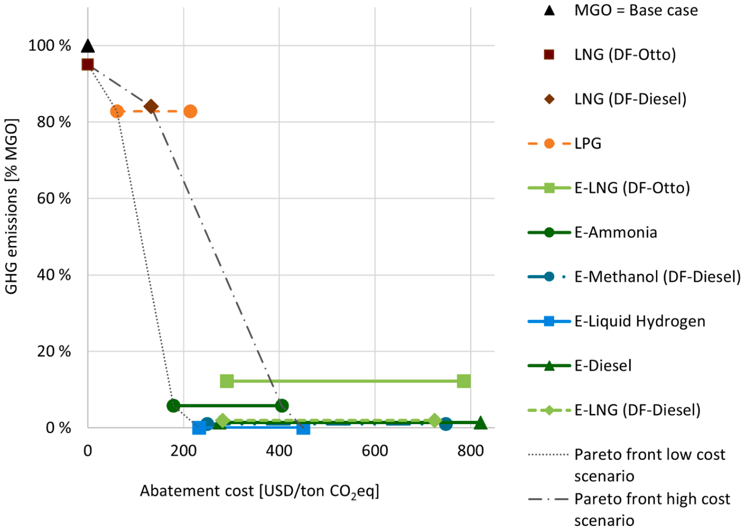

Fig. 5. GHG emissions vs. abatement cost.

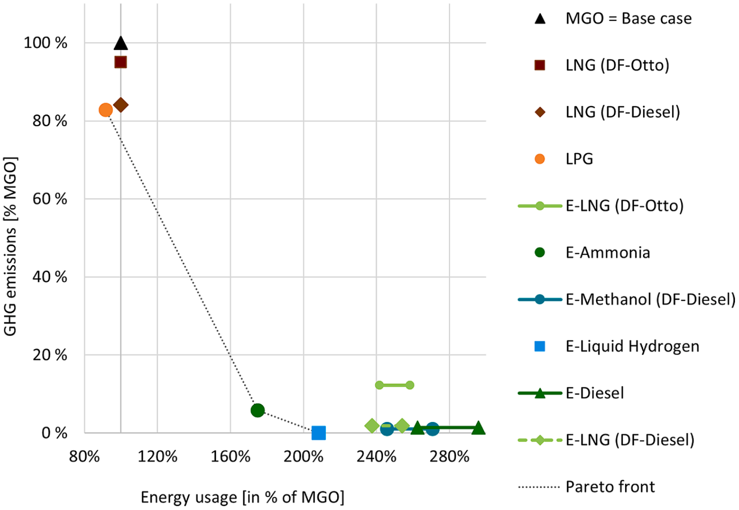

Fig. 6. GHG emissions vs. energy use.

circumstances for the production and use. From a ship owner perspective, flexibility is crucial for minimizing financial risk and disruption of operations. Most gas-fuelled ships are powered by dual-fuel engines, and this testifies of the shipowner's appreciation of flexibility and access to a secondary back up fuel. Therefore, it is relevant to consider fuel maturity, accessibility, compatibility and challenges associated with adoption and utilisation along with the reduction potential and efficiency offered by E-fuels. We discuss the results of the analysis from a strategic decision-making perspective, and describe five main alternative strategic paths, based on alternative technology choice today and their associated future opportunities and limitations.

Pathway No. 1 - Fuel-cell path: With the highest GHG reduction potential, E-Hydrogen represents a real hope for full decarbonization of shipping. Cheaper and more energy efficient than Hydrocarbon-based E-fuels, E-Hydrogen are attracting interest as the next source of power for merchant vessels. Choosing the Hydrogen path means building new vessels, and that ship owners anticipate a global infrastructure to come into place, as well as new operational standards. Betting on E-Hydrogen not only implies betting on sufficient availability of renewable energy, and at a bearable price, but also on possibilities to spread the risk on alternative power sources if renewable electricity becomes a constrained resource as indicated by Table 1.

Pathway No. 2 - Pure Diesel path: as the opposite of the Fuel-cell path, the pure Diesel option requires no technological or operational change, with continued use of combustion engines and increased use of E-Diesel as supply gradually picks up. A clear advantage of this path is the opportunity to gradually increase the blend in percentage of the E-fuel and to avoid investments in new machinery and systems. On the other side, if a full de-carbonization is set as the ultimate target, this strategy will be costly, given the foreseen future shortage in renewable electricity as indicated by Table 1 and the associated discussion which disfavours E-Diesel due to its high energy intensity (highest of all E-fuels). Furthermore, while Biofuels offer an immediate possibility of transition fuel from fossil to E-fuels, they do not make the Diesel path more attractive since Biodiesel comes at a higher cost than Bio-LNG or Bio-Methanol (LR&UMAS 2020).

Dual-fuel engines provides high flexibility in selection of fuel, and therefore enable several fuel combinations and gradual improvement with less risk associated with technology choice and availability of fuels as opposed to Hydrogen. Dual-fuels offer several alternative fuel strategies (MAN 2020; ABS 2021), discussed here below: an LNG path, a Methanol path and a more flexible but also costlier: Methanol- & Ammonia- ready path which also can include LPG as a transition fuel.

Pathway No. 3 - LNG Dual-Fuel path: A dual-fuel path based on LNG offers the possibility to achieve immediate, although limited GHG reduction with fossil LNG and from 88% to 98% GHG reduction with 100% E-LNG, with the largest reduction achieved when combusted in a dual-fuel Diesel engine. Selecting the LNG path implies a large additional capex when building the vessel, as shown in Table 2 and in Fig. 4, compared to the pure Diesel option, so even if LNG comes with a 25% price rebate per energy unit (Primo 2021) compared to MGO and 10 – 15% rebate compared to VLSFO we get abatements cost of up to 132 USD per ton of CO_2 reduction. With high electricity prices E-LNG gives a cost advantage compared to E-Diesel, while with low electricity prices the difference is rather marginal. In a full-decarbonization scenario and in the case of limited renewable electricity supply, E-LNG might be disadvantaged given their higher WTW energy use compared to E-Hydrogen or E-Ammonia.

Pathway No. 4 - Methanol DF path: Preparing for E-Methanol requires lower initial investment than the LNG path or the Ammonia path. While this path offers no possibility for immediate GHG emissions reduction Well-to-Wake, Bio-Methanol might be available when a ship ordered today leaves it berth and serve as a transition fuel towards E-Methanol. If none of them are available when the newbuilt ships leaves the berth, it can run on VLSFO and MGO as fuel efficient as any other vessel with a pure diesel engine.

Pathway No. 5 - Ammonia including Methanol: A dual-fuel path preparing for both E-Ammonia and E- Methanol is worth considering and it could even include starting with LPG as the transition fuel. This implies an engine and tank system able to accommodate both Ammonia and Methanol, plus LPG if selected as transition fuel. Compared to MGO, the volume of the fuel tanks both for Ammonia and Methanol must be tripled due to lower energy density per volume unit and the weight of the fuel will be doubled due to lower energy density per weight unit (DNV, 2021). MAN has announced the introduction (within a few years) of a complete concept including fuel tanks and pipes capable of running both on Methanol and Ammonia in addition to VLSFO and MGO (MAN, 2020). However, it will still require the injection units to be changed and fuel tanks to be emptied. Combining Methanol and Ammonia will come at a comparable CAPEX as the LNG option shown in Fig. 4, while also including LPG as a transition fuel option, will increase the CAPEX compared to the LNG option.

7. Conclusion

Fuels with zero or lower GHG emissions are by many perceived to be the most promising measure to reduce maritime GHG emissions by at least 50% in 2050 compared to 2008. The motivation for this study has therefore been to investigate alternative E-fuels with focus on their feasibility, energy utilization and cost in addition to their GHG reduction potential.

The results indicate: First, that E-fuels will be costly, with additional costs depending to a great extent on renewable electricity prices, confirming similar findings from previous publications. In addition, the present study shows that the prices for the different E-fuels, depends very much on the electricity prices. In the low-price scenario, the disadvantage of high energy use WTW diminishes, and E-Diesel, E-LNG and E-Methanol becomes more competitive with the most energy efficient E-fuels (E-Hydrogen and E-Ammonia).

Second, the present study offers a transparent assessment of alternative fuels with GHG emissions divided into production emissions (WTT) and emissions from converting it to mechanical energy on board the vessel (TTW). The consideration of WTT emission associated with fuel production and supply unveils the huge difference in climate impact for the so-called alternative fuels Ammonia and Hydrogen, all contributing to increase in GHG emissions, as opposed to E-Ammonia and E-Hydrogen. This aspect is important when planning transition to E-fuels.

Third, the energy perspective provides valuable additional insight for the analysis and understanding of the impact of global energy production on decarbonization possibilities for the shipping sector. Fully deployed in shipping, E-Fuels might double or triple the maritime sector’s energy consumption Well-to-Wake. The explanation is that the production of E-fuels for shipping will require large amount of renewable electricity, competing with other sectors, where that renewable electricity might give larger GHG reductions. Therefore, a narrow, solely maritime perspective on both emission ambitions and zero carbon fuels may be counterproductive to a fast, global decarbonization, as it oversees its impact on the global energy supply.

Fourth, the three-dimensional assessment proposed provides valuable insight for exploring logical alternative fuel paths and help ship owners preparing robust decarbonization strategies. The main paths presented in the discussion session are: (i) a E-Hydrogen path, depending on building both new vessels and new infrastructure; (ii) a Pure Diesel path, minimizing financial risks and disruption of operation during transition, and enabling gradual reduction of GHG emission through blend-in of E-Diesel; (iii) a E-LNG path, exploiting existing infrastructure and the decarbonization benefits of existing LNG-based solutions during transition; (iv) a E-Methanol path, which comes at lowest additional CAPEX; (v) a E-Ammonia- and E-Methanol path, requiring higher initial investment but offering highest fuel choice flexibility both in medium and long term.

To conclude, our findings indicate that the most robust path for Zero carbon fuels is through dual-fuel engines and systems to ensure flexibility in fuel selection, to prepare for growing supplies and lower risks. Finally, the GHG reductions of E-fuels depend entirely on abundant renewable electricity, a prerequisite we question since renewable electricity is forecasted to be scarce also in the future.

CRediT authorship contribution statement

Elizabeth Lindstad: Conceptualization, Data curation, Methodology, Formal analysis, Investigation, Validation, Writing – original draft. **Benjamin Lagemann:** Validation, Software, Visualization, Writing – original draft. **Agathe Rialland:** Methodology, Project administration, Visualization, Writing – review & editing. **Gunnar M. Gamlem:** Investigation, Writing – review & editing. **Anders Valland:** Funding acquisition, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

	Present	Future
Annual operating hours with NG	5000	5000 h
Annual operating hours with electricity	5000	5000 h
Cost per MWh of NG	25	25 USD/MWh
Cost per MWh of Electricity	60	20 USD/MWh
Capex and Opex DAC (Carbon capture from air)	200	100 USD per kg of CO_2
Operational energy needed for DAC	2.6	1.5 MWh/ton of CO_2

				Annual Cost USD/kW capacity			
Present Cost		Input	Output	Capex + Opex	Energy	Total	Present cost USD per MWh
	MGO	510	per ton				43
	VLSFO	430	per ton				38
	LNG	445	per ton				32
	NG	345	per ton				25
Hydrogen	NG	100%	76%	134	166	300	60
	Electricity	100%	69%	103	435	538	108
Liquid Hydrogen	NG	76%	53%	45	428	473	95
	Electricity	69%	48%	42	768	810	162
Ammonia	NG	76%	63%	113	361	474	95
	Electricity	69%	57%	102	648	750	150
E-LNG	Electricity	69%	46%	103	803	906	181
	- DAC		7%	242	136	378	76
		69%	40%		939	1284	257
E-Diesel	Electricity	69%	43%	106	862	969	194
	- DAC		9%	327	230	556	111
		69%	34%		1092	1525	305
E-Methanol	Electricity	69%	46%	68	810	878	176
	- DAC		9%	316	191	507	101
		69%	37%		1001	1385	277

				Annual Cost USD/kW capacity			
Future Cost		Input	Output	Capex + Opex	Energy	Total	Future Cost per MWh
Hydrogen	NG	100%	76%	134	166	300	60
	Electricity	100%	69%	103	145	248	50
Liquid Hydrogen	NG	76%	53%	45	428	473	95
	Electricity	69%	48%	42	354	396	79
Ammonia	NG	76%	63%	113	361	474	95
	Electricity	69%	57%	102	299	400	80
E-LNG	Electricity	69%	46%	103	370	473	95
	- DAC		4%	70	34	104	21
		69%	42%	0	404	576	115
E-Diesel	Electricity	69%	43%	106	397	504	101
	- DAC		5%	94	55	149	30
		69%	38%		452	653	131
E-Methanol	Electricity	69%	46%	68	373	442	88
	- DAC		5%	91	46	137	27
		69%	41%	0	420	579	116

Appendix 2

			GHG Emissions					Energy usage	New Built cost			Fuel Cost				Total Annual Cost excluding basic vessel cost		Abate-ment	Abatement cost		LCCF
Fuel types	Engine Type	LCV	WTT	TTW CO_2	TTW CH_4	TTW N_2O	WTW	WTW Input / Power Output	Engine	Tanks and add-ons such as scrubber	Total CAPEX	Low	High	Low per GJ	High per GJ	Low estimate	High estimate	*CO_2eq change* versus *MGO*	Low	High	LCCF -WTW
		Mj/ kg	*g CO_2e/MJ – 100 yrs*					*MJ/MJ*	*USD/ kW*			*USD / ton*		*USD/GJ*		*USD per kWh*		*%*	*USD per ton CO_2eq.*		*CO_2eq factor*
Renewable Electricity								1.5				230	700	5.4	16.3						0
Natural Gas		49.2	18.5									300		7.0							
Crude Oil (60 USD/barrel)		41.9										420		10.0							
HFO&Scrubber	Diesel	40.2	9.6	77.5	0.2	1.1	88.5	2.3	400	300	700	365	365	8.8		303	303	−3%	−778	−778	3.5
VLSFO	Diesel	41.0	13.2	77.6	0.2	1.1	92.1	2.4	400	0	400	440	440	10.6		319	319	1%	***	***	3.7
MGO	Diesel	42.7	14.4	75.1	0.2	1.1	90.8	2.4	400	0	400	500	500	12.0		348	348	0%	***	***	3.8
LNG	DF Diesel	49.2	18.5	56.1	1.0	0.7	76.3	2.4	800	600	1400	380	380	9.0		372	372	−16%	132	132	3.7
LNG	DF Otto	49.2	18.5	56.1	10.4	0.7	85.7	2.4	400	600	1000	380	380	9.0		396	396	−6%	0	0	4.2
LPG	DF Diesel	46.0	8.3	66.0	0.2	0.7	75.2	2.2	600	200	800	460	460	11.0		348	348	−17%	61	61	3.4
Liq.Hydrogen (NG)	Fuel Cell	120.0	150.8	0.0	0.0	0.0	150.8	4.5	1500	1200	2700	1,100	1,100	26.3		978	1,968	66%	***	***	18.1
E-Liq. Hydrogen	Fuel Cell	120.0	0.0	0.0	0.0	0.0	0.0	5.0	1500	1200	2700	925	1,750	22.0	41.6	984	984	−100%	233	450	0
Ammonia (NG)	DF Diesel	18.6	121.4	0.0	0.0	5.3	126.7	3.8	800	600	1400	1,100	1,100	26.3		879	1,374	40%	***	***	2.3
E-Ammonia	DF Diesel	18.6	0.0	0.0	0.0	5.3	5.3	4.2	800	600	1400	940	1,750	22.0	41.0	828	828	−94%	179	405	0
E-LNG	DF Otto	49.2	0.0	0.0	10.4	0.7	11.1	6.2	400	600	1000	1,350	3,000	31.2	69.3	732	1,218	−88%	291	786	0.5
E-LNG	DF Diesel	49.2	0.0	0.0	1.0	0.7	1.7	6.1	800	600	1400	1,350	3,000	31.2	69.3	576	576	−98%	282	724	0.1
E-Methanol	DF Diesel	19.9	0.0	0.0	0.2	0.7	0.9	6.5	600	200	800	1,360	3,235	31.2	74.2	912	2,037	−99%	250	748	0
E-Diesel	Diesel	42.7	0.0	0.0	0.2	1.1	1.3	7.1	400	0	400	1,530	3,575	35.0	81.8	966	2,193	−99%	275	821	0

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Supporting Paper 3

Design methodology state-of-the-art report
Stein Ove Erikstad, Benjamin Lagemann (2022)
14th International Marine Design Conference; Vancouver, Canada; DOI: 10.5957/IMDC-2022-301

DESIGN METHODOLOGY STATE-OF-THE-ART REPORT

Stein Ove Erikstad[1], Benjamin Lagemann[1]

ABSTRACT

Marine systems design methodology is continuously evolving. On a strategic level, we have seen four major evolutionary tracks emerging from the sequential, iterative process captured in the classical design spiral. One is a model-based systems engineering approach that removes iterations by a structured mapping from needs to functions, and further to form elements that are finally synthesized into a complete design. Another is a set-based strategy, where a large number of designs are generated and analysed, from which one or a few solutions are selected for further development. A third direction is a holistic optimization strategy where the major steps in the spiral model are integrated onto a common platform that enables the automatic identification of one or a few balanced, preferable solutions. Finally, as a strategy towards improved competitiveness through standardization in a typical engineered-to-order industry, we have seen the emergence of modular architectures combined with configuration-based design methods.

Across these four evolutionary tracks there have been several more focused developments on different levels of maturity. This includes design-for-sustainability, simulation of operations, design-for-flexibility to handle uncertainty and change, and design of wind-assisted vessels. Finally, we have pointed to some emerging developments that we find promising but have yet to mature into having a significant impact on industry-level applications. This includes artificial intelligence and machine learning, extended system boundaries, and digital twin technologies.

KEY WORDS

Design methodology; system-based design; set-based design,; design optimization

INTRODUCTION

The design methodology state-of-the-art (DM-SoA) report as part of the IMDC has a long history. Yet it has still to settle into a final structure, form and style. An excellent synopsis of the DM-SoA timeline from the start of the IM(S)DC until 2018 was given by Andrews et al (2018) at the Helsinki conference. This timeline shows a large variety of interpretations of what the SoA report at the IMDC should comprise, ranging from reviews of the ship design history, different variants of “Design-for-X" (e.g. X being safety (Vassalos 2012) as well as challenges related to the design of particular ship types, such as cruise vessel designs and LNG Carriers. The last DM-SoA report presented in 2018 contained three somewhat separate parts: First a review of three substantial books considered relevant for the design of complex marine vessels, followed by a review of selected design research activities, and finally a study of structural selection in early-stage design. Also, in the wake of the previous IMDC a comprehensive compilation of a wide array of research contributions within the field appeared as a RINA Special Edition authored by Andrews (2018), pointing towards a unique theoretical platform for marine systems design of complex vessels.

Recognizing the importance of the DM-SoA as a binding thread between the tri-annual IMDC conferences, and the so far lack of a clear consensus on style, form and structure was the background for bringing this issue on the agenda at the IMDC International Committee interim meeting at UBC in February 2020. A formulation of the DM-SoA goal and purpose was proposed, namely to “*analyse and summarize, on behalf of the marine systems design community, the current state and key developments within our field, based on a review of current research and technology achievements, as well as feedback from academia and industry*”. Regarding form, style and structure, a set of characteristics were proposed. It should be *focused* on marine systems design, with a clear emphasis on *design methodology* within the larger framework of engineering design/systems design. It should be *contemporary*, giving priority to what have been key topic areas and achievements since

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the last conference, as well as ongoing research developments towards the next venue. It should be *opinionated*, to the extent that the authors of the report need to make an educated prioritization of what are the most important developments, as well as provide a basis for discussions and comments at the conference. Finally, it should also *balance* the focus between academia and industry and look into how research and technology developments are adopted in industry and actual design practice.

In this year's DM-SoA paper we have aimed at following up on these principles. The focus will be on recent and emerging developments as well as state-of-the-art, more mature methodologies applied by those design companies and shipyards that are at the technology frontier. We will also summarize recent research contributions based on journal articles, conferences, and research projects. Finally, we will point to emergent models, methods and technologies that we find promising, and where we would expect to see some more tangible results and piloting industrial applications towards the next IMDC.

DESIGN STRATEGIES – TRACKS AND DIRECTIONS

A *strategy* is a high-level plan for achieving an overall goal. Related to ship design methodology, it can be translated to the way we organize the design process from the initial capturing of customer needs and expectations until a final design solution is described and documented.

It may be useful to make a distinction between *descriptive* and *prescriptive*, or *normative,* design strategy models. Descriptive models are developed based on observations of how design processes are actually executed in an industrial setting, and subsequently capture and describe the important phenomena and relationships as objectively and accurate as possible. The classical ship design spiral is a good example. Initially it served as a normative model for how the ship design should be executed, by "balancing out" the conflicting requirements of the customer. Today the spiral is rather considered a *descriptive* model. Partly, it captures the sequential, iterative aspects of the design problem space, as such *characterising* this process rather than describing it. Partly the model represents at least some instances of actual ship design processes in many companies, that typically start with a catalogue vessel or a previous project to be sufficiently modified to fit the needs and requirements of a new customer. Thus, to the extent being descriptive, it is not a "one-size-fits-all" model as pointed out by Andrews (2018), p.2, but rather a common reference point for the discussion of alternatives, also in this paper. Today, most books, papers, tools and experts would *prescribe* alternative design strategies, typically pointing to the spiral model´s lack of concurrency and the inefficiency of a large number of iterations, its inclination towards the initial design proposal and limited coverage of the design space, and its "outside-in" direction that gives little support for deriving form from needs and functions. Still, we consider the spiral model a useful, commonly understood reference point for discussing alternative design strategies, regardless of its relevance for modeling real-world design processes.

Our proposition is that over the last decades we have seen four major evolutionary tracks emerging from the sequential, iterative design spiral model. One is a *model-based systems engineering* approach that removes iterations by a structured mapping from needs to functions, and further to form elements that are finally synthesized into a complete design. Another is a *set-based strategy*, where a large number of designs are generated and analysed, from which one or a few are selected for further development. In *configuration-based design* a customized design solution can be derived by combining modules from a product platform. Finally, we have seen an *optimization strategy* where the spikes in the spiral model are integrated into a common framework that supports the identification of preferable solutions by an optimization algorithm. These tracks are illustrated in Figure 1.

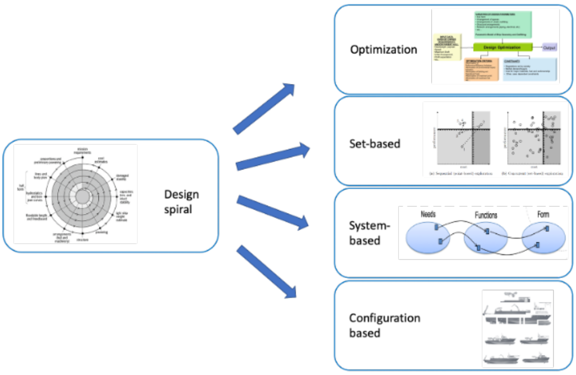

Figure 1: The four main design strategy directions emerging from the design spiral model

Later in this paper we will use this coarse sketch of high-level design strategies as a map for locating different research contributions in the design methodology landscape. We will observe that most of these contributions do not fall neatly into a single category. Rather, they will contain elements of several or all of these. For instance, in the building block approach (Andrews and Dicks 1997) we can have a system-based development of ship modules followed by a configuration-based synthesis into a set of alternative conceptual solutions. Or we can have a set-based approach exploring the design space and based on this derive a surrogate model that can be optimised by gradient search. It is safe to say that most comprehensive design methodology frameworks will contain at least traces of each of these categories. Thus, it is worthwhile expanding somewhat more on each of them.

System-based design methods/strategies

Though system-based ship design might sound like being a domain specific variant of systems engineering, it has more in common with the influence of the “German design school”, most comprehensively described in the book “Engineering Design: A systematic approach” (Pahl et al. 2007). The systematic approach is basically a stepwise process from needs, via functions to physical solution principles and ends up with form elements that can be synthesized into a complete solution. Related to commercial marine systems design, the contributions by Kai Levander have had a major influence, developing this systematically over many years based on his work at the Kvaerner Masa Yards. The key element in this process, as compared to the more traditional approach, was to drive the volumes, areas and key characteristics of the main ship systems based on the combination of functional requirements and experience-based functions and coefficients. This replaced the not very well explained process on arriving to the initial design solution in a spiral-based approach, and instead prescribed a series of abductive logical steps in which all the main components of the solution were mature in terms of areas, volumes and capacities. This process is somewhat similar to a set of Lego bricks that could be combined towards many possible conceptual solutions while still representing a balanced solution. Thus, in the subsequent synthesis steps towards a complete form, the focus is shifted from “balancing out” requirements, to a focus on the overall conceptual solution and arrangement optimization. Further, this approach represents what is often referred to as an “inside-out” methodology, by first developing and arranging all internal systems and volumes of the ship, and finally wrapping a hull around this assembly. The process is illustrated in Figure 2, where we see that though the initial design should be derived systematically from needs via function, there will still be a need for a “spiral-like” sequential, iterative “outbalancing” of the vessel to converge.

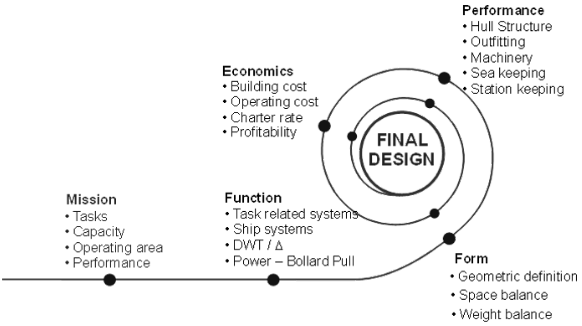

Figure 2: System-based ship design, unwinding the first loops of the spiral to achieve an improved initial solution based on systems thinking, from (Levander, 2006)

Similar to the system-based design model from Levander, the Design Building Block approach proposed by Andrews and Dicks (1997) promotes a shift to the early stages. This method supports the difficult balance of on the one hand making the design problem tractable by developing the necessary form elements as building blocks that each deliver one or a few required functionalities, while on the other hand keeping the problem sufficiently open to explore and analyze alternative conceptual solutions, system architectures and various aspects of “style”. This is closely connected to the concept of “requirements elucidation” presented by Andrews at the IMDC Athens conference (2003b), pointing to the simple fact that in real-world design processes the customer does not come to the table with a set of well-stated, optimal requirements, nor would the customer have a rational basis for determining those without exploring what capabilities that can be achieved within the budget constraints and economic reality of the business case or naval acquisition program. The importance of understanding the needs and expectations of key stakeholders has been further elaborated in the keynote paper by Brett and Ulstein at IMDC in Tokyo (2015), with their paper “What is a better ship? It all depends …".

We also find many of the more recent contributions and development relevant for this DM-SoA paper to have strong links to the system-based design strategy. The “packing approach” first introduced by van Oers et al. (2007) and continued by Duchateau (2016) emphasized the exploration of a design space formed by legal combinations of blocks or modules given a set of configuration rules and arrangement-related performances, thus combing a system-based, set-based and configuration-based approach. More recent contributions from Garcia Agis (2020) emphasizes the uncertainty related to the decision-making context of key stakeholders, while Ebrahimi (2021) points to perceptual and decision-making complexity as important factors.

Set-based design strategies

The use of set-based design (SBD) strategies for the maritime industry, specifically naval ship design, gained increased attention from the late 90s, with the University of Michigan being the focal point. According to Singer (2009) the inspiration was based on Toyota’s design process for automobiles and built of four basic features: a broad set of parameters, keeping these parameters open until late in the design process to allow for trade-off studies, a gradual narrowing of the set towards an optimal solution combined with an increased fidelity level of the model. The SBD model was tested for its applicability in ship design in a series of projects at the University of Michigan around 2000. The conclusion was that this strategy performed better than point-based methods (“spiral”) and optimization-based methods. Set-based design strategies have received considerable attention in naval ship design, with recent contributions from Doerry et al. (2019) on SBD used in acquisition processes, Gray et al. (2018) for upgradability studies and Rapp et al. (2018) for tradespace analysis of naval vessels.

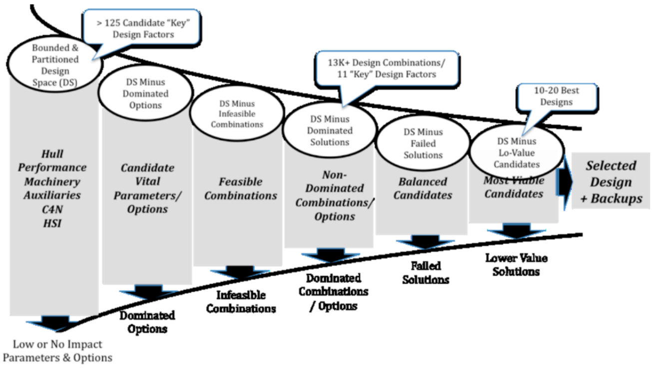

Figure 3: Down-selecting the solution space in set-based design, from McKenney et al. (2012)

Optimization-based design methods/strategies

Inherent in design is to find the *best* possible solution that will meet key stakeholders needs and expectations, which implies that design can be framed as an optimization problem. Still, considering real world design processes, optimization-based design processes are not very common, at least not in a classical mathematical programming framing. The main problem is simply that the typical ship design problem is too complex to be efficiently and accurately captured within the relatively strict boundaries of an optimization model. As said by Coyne (1990, p. 19): *Optimization has failed to influence the field of design greatly, in part because it does not address the question of how to arrive at such well packaged formulations*.

A recent effort to overcome these challenges has been the HOLISHIP project (Papanikolaou 2019). The objective of this project has been to integrate all main ship design disciplines into an integrated software platform that enables parametric, multi-objective optimization of the vessel design. Two of the strengths of the HOLISHIP project is that it is predominantly based on commercially available software, and that maritime industry partners have been actively participating in the project group. HOLISHIP builds on a long series of optimization-oriented projects, with a variety of overall design objectives. Examples are SAFEDOR for risk-based design optimization, GOALDS for RoPax and cruise safety, BEST for tanker environmental performance and SHOPERA for tanker hull form, to name a few.

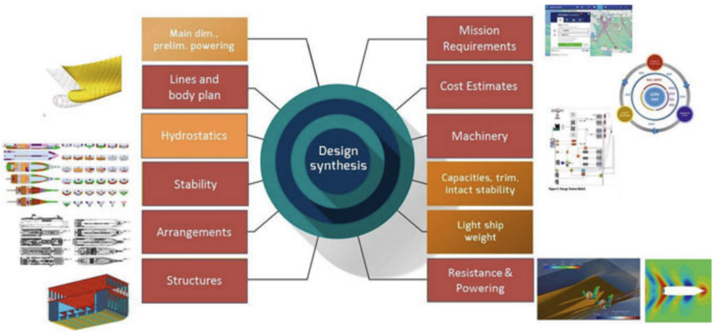

Figure 4: The main structure of the HOLISHIP project, (Papanikolaou, 2019)

Configuration-based design strategies, product platforms, “design for modularity” and system architecture driven design

By using configuration-based design strategies based on product platforms, it is possible to combine the requirements for customized solutions with standardization on a module or component level. Compared to other industries such as automotive and aviation, shipbuilding remains a typical “one-of-a-kind", “engineered-to-order" industry. A modular design strategy concurrently supports standardization and diversification on the product level, and has the potential to reduce cost and shorten development time, Erikstad (2019).

Configuration-based design requires a modular design architecture. From a wider systems perspective, modularity is a strategy for handling complexity by encapsulation, Simon (1996). This strategy is characterized by subdividing the larger system into smaller parts with a high degree of self-sufficiency, and the recombination of these parts into multiple end products. This recombination of parts corresponds to the synthesis process inherent in engineering design, which may be governed either by rules that define allowable re-combinations (Brathaug et al., 2008), by “style” that defines patterns of alternative product solutions (Andrews 2018), by the direct “creative” interaction with a designer, or by a combination of these.

Configuration-based design decouples the design process into two separate stages. First, a platform development stage in which the modules are defined and developed and integrated into a product platform. Second, a “configuration-to-order" stage in which individual designs are derived from the platform, customized to each end-users specific needs, (Erikstad 2019).

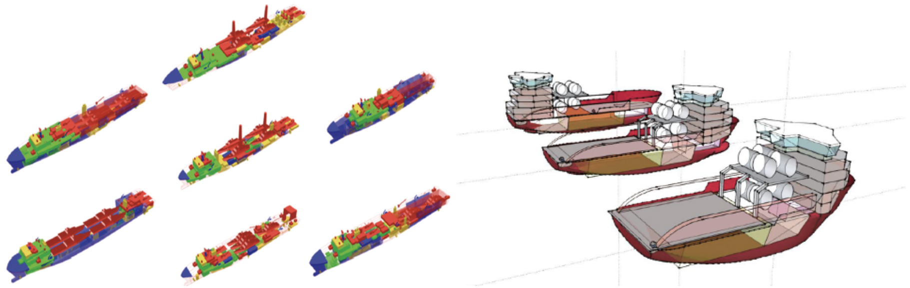

Figure 5: Ship designs based on modular configurations from a product platform-based architecture, left from Andrews 2011, right Vestbøstad 2011)

Recently, we have seen several interesting contributions on configuration-based design. Pfeifer et al. (2020) have developed a product platform for high-speed electrical ferries, in which standardized, reusable modules are identified using model-based system engineering methods. Choi et al. (2018) have developed a product platform combined with an optimization-based approach for designing modular adaptable ships. Here, the modular design configuration also considers the need for flexibility in the operational phase of the ship lifecycle to adapt to changing contextual circumstances that are uncertain in the design phase.

The four “strategic directions” for marine systems design pointed out here provides us with a map that is useful for navigating among the many research contributions in this field. Most of the methods and models proposed cannot easily be placed into a single one of these strategies, but rather contain elements from several or all. For instance, the interactive evolutionary concept exploration method from TU Delft (Duchateau 2016, van Oers 2011) resembles a system-based development of arrangement modules, a set-based exploration of the design space over a 3D GA configuration model, and with the definition of high-level objective functions and constraints similar to optimization. The modular adaptable ship design method by (Choi et al. 2018) is combing a platform architecture with an optimization-based configuration process. And the holistic ship design optimization (HOLISHIP) process by Papanikolaou (2019) also includes design space exploration aspects. Thus, rather than representing mutually exclusive categories, these high-level strategies rather serve as an indication towards what specific aspects a certain design method is emphasizing.

SOA AND KEY DEVELOPMENTS WITHIN SELECTED AREAS

In the previous section the focus was on the state-of-the-art of high-level design strategies. In this section we will go into the details of a few selected topic areas in which we believe we have seen the most interesting development and contributions since the last IMDC conference. Adhering to the general principle that "less is more", there obviously will be deserving topic areas that will be omitted.

The first selected topic, sustainability, is perhaps the one highest on the agenda for most stakeholders in the maritime community, namely, how to respond to the challenge of global warming, and meeting the targets set by IMO towards 2050. This will require new designs comprising new technology. The crucial question in the context of this paper is whether designing for sustainability will also influence *how* we design. Further, and keeping in mind that we are always designing for the future, we have seen a development towards explicitly integrating uncertainty and flexibility into the design process as a consequence of the fact that today´s technology is not capable of providing a "licence-to-operate" for new vessels under expected emission requirements towards the end of their design life. This is followed by design for safety, and the corresponding wider topic of risk-based design.

We have also seen that realizing the next generation of low or zero emission solutions will require that we shift the focus from exclusively on the vessel design itself into a wider system perspective that includes the concurrent design of vessels, concepts of operation and infrastructure and external resources. This is accompanied with system-level simulation of operations as a means for assessing complex performance parameters. As a final topic we have included wind-assisted ship propulsion (WASP). It can be argued that specific technologies or analysis models are not within the scope of a design methodology SoA. However, WASP is a good case for illustrating how technologies still under development could be included in a more mature design process, as well as requiring both the consideration of operational concepts and a simulation-based platform to fully assess the system level performance.

Design for sustainability

As for other DfX categories, such as design-for-production, design-for-safety, etc., design-for-sustainability is primarily about focusing on a particular set of high-level performance aspects related to three "pillars": environmental, economic and social. DfX categories will necessarily put requirements on the *content* of the design process, such as specific analysis methods for quantifying relevant performances (say, emission footprints), as well as the inclusion of new technology solutions, especially related to ship powering and fuel systems.

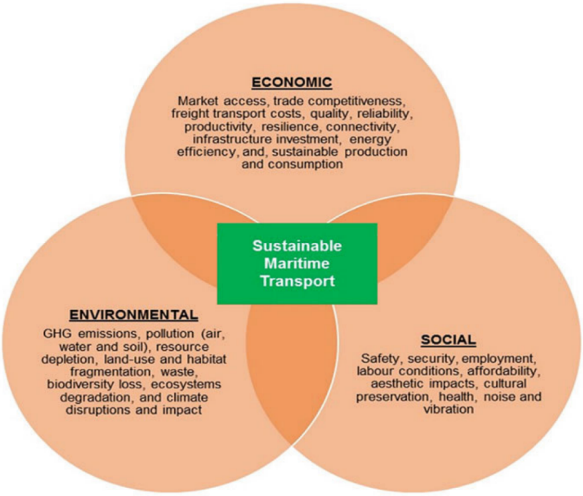

Figure 6: Sustainability pillars (source: Psaraftis 2019, reproducing UNCTAD 2015)

The relevant question from the perspective of this SoA paper is whether the introduction of this DfX category has spurred changes also from a design methodology point-of-view. Even though specific design and decision-support methods for groups of technologies, such as alternative fuels, are developing along with case studies and important pilot applications in industry, we currently perceive a methodological gap when it comes to sustainable marine design. The challenge is not only grasping today's design space to a fuller extend while simultaneously elucidating requirements, but also to design for likely future change(s). Sustainability is driven by both concrete requirements for newbuilds at present, such as the global Sulphur cap or EEXI and EEDI requirements, as well as long-term decarbonization strategies (e.g. IMO 2018). The longer the time horizon, the more uncertainty is brought into the game: Neither are technologies, regulations nor economic incentives fully in place today to meet future decarbonization requirements. We need to design for change in one way or the other, and hence many of the methods presented in the next paragraph are highly relevant from a sustainability perspective. In addition, taking a larger system perspective which includes fleets instead of single ships and infrastructure is gaining importance.

An excellent state-of-the-art paper on sustainable ship energy systems was recently published by Trivyza et al. (2022). Based on a comprehensive list of nearly 170 relatively recent papers, they summarized the needs for further developments into design methods by four points: 1) methods for developing potential solutions, 2) methods to assess the performance of alternative design solutions, quantifying energy efficiency and their mitigation potential, 3) methods to understand the impact of future uncertainty on the lifecycle performance of systems, including the generation of scenarios, and LCA, see Wang and Zhou 2018 and 4) methods for selecting among the different alternatives. The latter includes optimization-based approaches as well as multi-criteria approaches, see Frangopoulos and Keramioti 2010, also Mansouri et al. 2015. Lagemann et al. (2022) present a method for deciding among alternative fuels with given fuel price trajectories over the lifetime. Mestemaker et al. (2020) investigate the overall system integration of such alternatives and energy conversion options in more detail.

In general, we see that sustainability is receiving increasingly attention as a design driver and performance criterion in the design process (Papanikolaou 2010; 2019). It has certainly brought forward specific methods for assessing this criterion and selecting among innovative and emerging technologies, such as alternative fuels and wind assisted propulsion concepts, as well as life cycle perspectives receiving increased attention in the design process.

Design for uncertainty and flexibility

As mentioned previously, we are always designing for the future, and the future is inherently uncertain. The outcome of the ship design process is necessarily affected to a certain extent, whether we choose to explicitly address this uncertainty or not. Garcia Agis (2020) finds that regulatory, stakeholder expectations and economic uncertainties are overall perceived as the most influential uncertainties. Both regulatory and economic uncertainty are strongly linked to time, while stakeholder expectations hints towards lacking requirements elucidation (Andrews 2003; 2011).

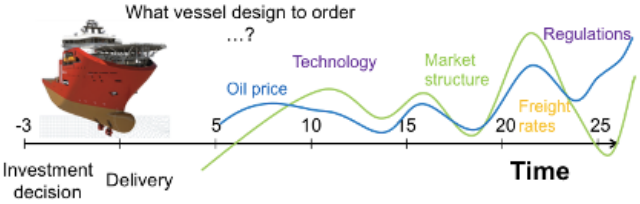

Figure 7: We are always designing for the future, and the future is inherently uncertain

The different methods for explicitly handling uncertainty in the design process typically share the following aspects. First, there is a need to effectively capture and model the relevant future operating context, as a set of scenarios. This may include markets (e.g. fuel prices, freight rates), technologies, regulations and physical environment. Then, within this set of alternative scenarios, we need to model and simulate the operations of the system to be designed in order to derive the technical, economic, environmental and safety performance in a lifecycle perspective. One of the challenging parts is to link those operational scenarios back to design decisions today, both related to "classical" ship characteristics, as well as quantified lifecycle performances such as flexibility, adaptability, versatility and robustness. Finally, all these steps need to be integrated into a holistic system design process.

De Neufville and Scholtes (2019) give a comprehensive overview on flexibility in engineering design and suitable methods. Rehn et al. (2018) find that changeability/flexibility can be a suitable strategy to respond to time-affected uncertainties and is hence worthwhile discussing in the early design phase. Within an extensive report, Schank et al. (2016) provide a naval perspective on flexibility and modularity. Choi et al. (2018) apply the concept of modularity to offshore service vessels. Based on a common platform, a configure-to-order strategy enables to quick response to varying customer mission requirements. Similar to Rehn et al. (2018), they find that reconfigurability through modularity can be of significant value under uncertain lifetime circumstances, such as changing ship missions or requirements. When designing flexible systems, agility, as a parameter denoting the ease of change, needs to be determined.

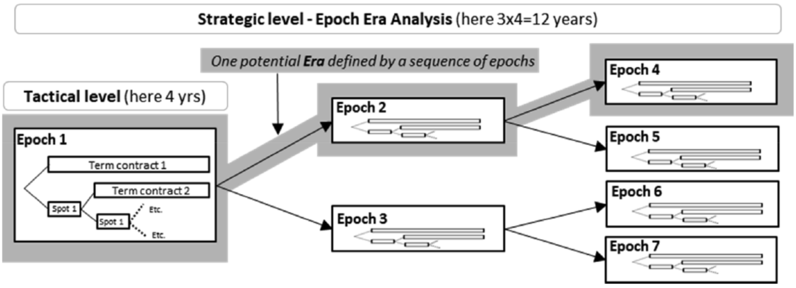

Figure 8: Designing for different future, taken from Rehn et al. (2018)

Design for safety

Safety has been a recurring theme throughout the past IMDC conferences (Papanikolaou et al. 2009). With stability accidents responsible for the largest share of fatalities, the topic is still highly relevant. The introduction of the second-generation intact stability criteria has impacted requirements but also spurred the development of tools (Petacco et al. 2021, Wang et al. 2020). On the damage stability side, dynamic simulations of damaged ships have gained attention (Vassalos 2022). The principal of equivalent safety can lower the required damage stability for autonomous ships (Vos et al. 2020). A similar probabilistic concept has been applied to fire safety of passenger ships by (Koromila et al. 2018). A design method for the safe-return-port regulation is presented by Valcalda et al. (2022).

Simulation of operations

Simulation as a tool for 'unveiling knowledge' (Simon 1996), is becoming increasingly integrated into the design process. To name a few recent developments:

- Based on the work of Sandvik et al. (2018), Dæhlen et al. (2021) the development of a voyage simulation tool that enables time-efficient comparisons of several designs.
- Open simulation platform (OSP): co-simulation of onboard systems (mechanical, electrical, control) (Perabo et al. 2020)
- Coupling of simulation and optimization in a design of a short-sea feeder network (Medbøen et al., 2020).

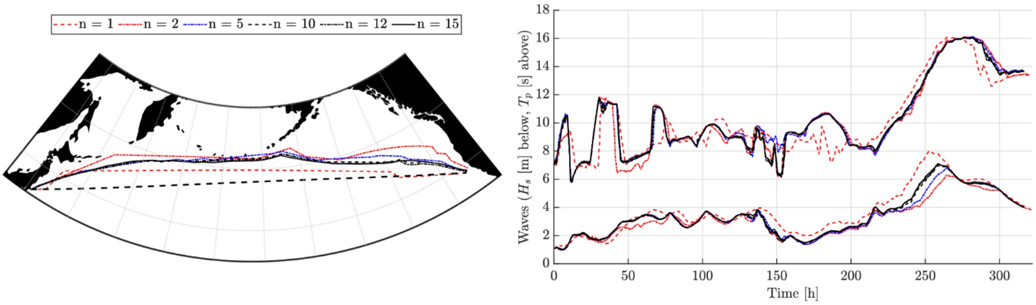

Figure 9: Voyage simulation for different route generation parameters, from Sandvik et al. (2020)

Coupled with virtual prototyping, we see simulation increasingly used as a tool in the design process. Simulation fidelity is application-dependent: Discretization may range from milliseconds (e.g. electric systems dynamics) to hours (e.g. voyage simulation) and needs to fit the purpose (effectiveness) and resources (efficiency). Moreover, the open simulation platform (www.opensimulationplatform.com) indicates that distributed simulations are developing, with individual systems running at separate locations and connected online.

From a design methodology perspective, we see an emerging need for operational system-of-systems simulations, that includes ships, infrastructure, fleets, and supply chains. The following section on WASP is one specific example that will require simulations. Our understanding of such larger systems is still limited. Simulation can be used as tool for 'unveiling' the required knowledge to meet either changing overarching system requirements or simply meet the same requirements in a very different way.

Design for wind-assisted ship propulsion (WASP)

Herbert (1980) describes the fundamental challenges of wind-powered ships as robust and efficient rig design (aerodynamic lift-drag ratio) and efficient hull design (hydrodynamic lift-drag ratio) within economic constraints. Arguably, the economic constraints may be challenged and perhaps changed as part of a result of thorough requirements elucidation (Andrews 2003; 2011). However, technical challenges and system interdependencies (see Figure 10) ultimately remain. Thus, specific methods are developed for the design and analysis of WASP: An integrated simulation model is used to account for and resolve the various interdependencies such as drift, heel or auxiliary power consumption (e.g. van der Kolk et al. 2019; Tillig et al. 2020; Reche-Vilanova (2021). Kramer (2022) presents an open-source CFD simulation for the hydrodynamic part of the equation. A useful collocation of scientific papers on various aspects of WASP can be found on (https://www.wind-ship.org/en/research/).

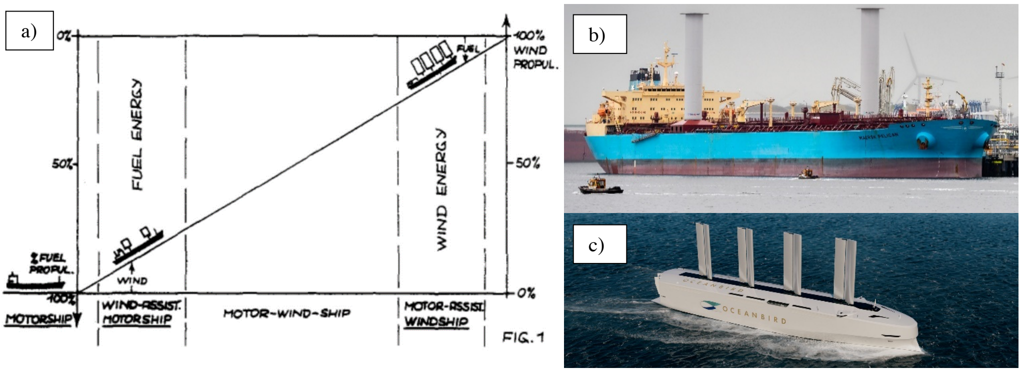

Figure 10: a) range of wind propulsion options, taken from Schenzle (1985); b) wind-assisted motorship; c) motor-assisted windship, courtesy of Oceanbird

Figure 10 illustrates the range of wind assistance, between a few percentage fuel savings up to 100% wind propulsion. While the aforementioned system performance prediction tools are needed for any type of wind-assisted ship, higher fractions of wind assistance will require a rethinking of the transport system design and possibly an extension of the system boundaries (Hagen and Grimstad 2008). For a higher uptake of WASP, the requirements imposed on a fleet or single ship need to be revisited to answer questions like:

- Is it possible to lower the average speed to allow for higher assistance of wind? If so, what is a minimum speed requirement?
- How much variation/flexibility do we allow for in the voyage schedule? What is the effect on the overall transport chain?
- Do shipping contracts need to be changed?

Simulating fleet operations may help answering addressing some of these issues and build confidence in innovative and fundamentally different system solutions. We think that a lot of design work on a system/fleet level, in addition to components, is still do be done for wind to become a viable power option.

SOA RESEARCH IN PRACTICE: A SELECTION OF RECENT PHD SCHOLARSHIPS

Similar to the last SoA report at the IMDC 2018, Table 1 attempts to provide an overview of recent developments by means of published PhD theses we consider having a clear marine design focus. The timeframe covered is basically since the Helsinki conference, but we have included some that were completed slightly before as well. We have categorized these PhD projects according to the four general design strategies, namely optimization (Opt), system-based design (Sys), set-based design (Set) and configuration-based design (Con), acknowledging that this classification might be both inaccurate and imprecise. To provide a quick idea of the topic, we additionally assign key words. The table is organized chronologically.

Table 1: Recent PhD scholarships related to marine systems design

Name	**Title**	**Design strategy**	**Key words**
Etienne Duchateau 2016	Interactive evolutionary concept exploration in preliminary ship design	Set, Con (Opt)	3D arrangement concept exploration
Francesco Baldi, 2016 (Chalmers)	Modelling, analysis and optimisation of ship energy systems	SysB	onboard energy systems
Ian Matthew Purton, 2016 (UCL)	Concept Exploration for a Novel Submarine Concept Using Innovative Computer-Based Research Approaches and Tools	Set, Con	submarine design
Ties van Bruinessen, 2016 (TU Delft)	Towards controlled innovation of complex objects. A sociotechnical approach to describing ship design	Sys	innovation management
Peter de Vos, 2018 (TU Delft)	On early-stage design of vital distribution systems on board ships	Opt, Sys, Con	system topology
Dorian Brefort, 2018 (Michigan)	Managing Epistemic Uncertainty in Design Models through Type-2 Fuzzy Logic Multidisciplinary Optimization	Opt, Set	optimization under uncertainty
Carl Fredrik Rehn, 2018 (NTNU)	Ship design under uncertainty	Set, Sys	design for flexibility
Minjoo Choi, 2018 (NTNU)	Modular Adaptable Ship Design for Handling Uncertainty in the Future Operating Context	Con, Opt	design for flexibility, modularity
Sigurd Solheim Pettersen, 2018 (NTNU)	Resilience by latent capabilities in marine systems	Sys	latent capabilities
Syavash Esbati, 2018 (UCL)	Design for Support in the Initial Design of Naval Combatants	Set, Con	3D arrangement, -ilities
Endre Sandvik, 2019 (NTNU)	Sea passage scenario simulation for ship system performance evaluation	SysB	simulation of operations
Nikoletta Trivyza, 2019 (Strathclyde)	Decision support method for ship energy systems synthesis with environmental and economic sustainability objectives	Opt, Con	decarbonization
Alexandros Priftis, 2019 (Strathclyde)	Multi-objective robust early stage ship design optimization under uncertainty	Opt	optimization under uncertainty
Etienne Gernez, 2019 (Oslo)	Human-centered, collaborative, field-driven ship design: implementing field studies for the design of ships in operation		UX design
Nikolaos Kouriampalis, 2019 (UCL)	Applying Queueing Theory and Architecturally-Oriented Early Stage Ship Design to the Concept of a Vessel Deploying a Fleet of Uninhabited Vehicles	Set, Con	fleet design
Linying Chen, 2019 (TU Delft)	Cooperative Multi-Vessel Systems for Waterborne Transport	Sys	logistics
Michael Sypaniewski, 2019 (Michigan)	A Novel Analysis Framework for Evaluating Predisposition of Design Solutions through the Creation of Hereditary-Amelioration Networks Derived from the Dynamics within an Evolutionary Optimizer	Opt, Set	design methodology
Lauren Claus, 2019 (Michigan)	Design Space Covering for Uncertainty: Exploration of a New Methodology for Decision Making in Early Stage Design	Opt, Set	optimization under uncertainty

Conner Goodrum, 2020 (Michigan)	Conceptually Robust Knowledge Generation in Early Stage Complex Design	Set	Knowledge-based design
Helong Wang, 2020 (Chalmers)	Development of voyage optimization algorithms for sustainable shipping and their impact to ship design	Opt	simulation
Wo Peng, 2020 (UCL)	Decarbonising coastal shipping using fuel cells and batteries	Sys	decarbonization
Jose Jorge Garcia Agis, 2020 (NTNU)	Effectiveness in Decision-Making in Ship Design under Uncertainty		design process management
Fang Li, 2020 (Aalto)	Numerical simulation of ship performance in level ice: evaluation, framework and modelling	Sys	simulation
Agnieta Habben Jansen, 2020 (TU Delft)	A Markov-based vulnerability assessment of distributed ship systems in the early design stage	Set	vulnerability of distributed systems
Fabian Tillig, 2020 (Chalmers)	Simulation model of a ship's energy performance and transportation costs	SysB	simulation of operations, decarbonization
John Marius Hegseth, 2021 (NTNU)	Efficient Modelling and Design Optimization of Large Floating Wind Turbines	Opt, Con	floating wind turbines
Carmen Kooij, 2021 (TU Delft)	Towards unmanned cargo ships: A task based design process to identify economically viable low and unmanned ship concepts	Sys	autonomous ships
Aleksandr Kondratenko, 2022 (Aalto)	Goal-based optimization in Arctic offshore support vessel design and fleet composition	Opt	arctic
Marjo Keiramo, 2021 (Aalto)	Pathways of the creative journey – the significance of a cruise ship concept design		UX design
Samantha Taylordean, 2021 (Michigan)	A Novel Framework Utilizing Bayesian Networks Structured as Logical Syllogisms to Determine Sufficiency of Early Stage Ship Design Knowledge Queries	Set	design methodology
Mark Allen Parsons, 2021 (Virginia)	Network-Based Naval Ship Distributed System Design and Mission Effectiveness using Dynamic Architecture Flow Optimization	Opt	distributed system design
Ali Ebrahimi, 2021 (NTNU)	Handling Ship Design Complexity to Enhance Competitiveness in Ship Design	Sys	design process management
Hao Yuan, 2021 (Michigan)	Early-Stage Ship Design Operational Considerations as a Thin Abstraction Enabled by a Grid-Supported Markov Decision Process Directional Decision Ensemble Framework	Set	simulation of operations
Muhammad Hary Mukti, 2022 (UCL)	A Network-Based Design Synthesis of Distributed Ship Services Systems for a Non Nuclear Powered Submarine in Early Stage Design	Set, Con, Opt	distributed systems design

Many of the listed PhD theses are related to optimization – often with the addition of accounting for uncertainty – and simulation. So far, we see surprisingly few theses on design method tackling sustainability as well as extended system boundaries, that is fleet and infrastructure design.

EMERGENT DEVELOPMENTS IN DESIGN METHODOLOGY

In many situations, the questions are just as interesting as the answers. For a state-of-the-art paper, this means asking what will be next in design methodology. Thus, in this "emergent developments" section we will include recent contributions that we either consider promising, or have received a certain degree of attention, but for which it remains to be seen whether it will have a lasting and substantial influence on the design methodology within our domain. One obvious candidate in this category is digital twin technologies, with relevant opportunities for the design of complex systems, but with tangible results still awaiting. Another is an extended system perspective by many seen as necessary for solving complex problems like sustainability and seaborne transport emission footprint. A third is the potential impact of artificial intelligence (AI) and machine learning (ML) on design methodology.

Digital twins and the influence of digital technologies on design methodology

A digital twin (DT) can be defined as a model capable of rendering the state and behaviour of a unique real asset in (close to) real time, Erikstad (2017). Inherent in the concept of a "twin" lies the concurrent existence of both a physical and a digital realization of the object. Thus, from a design perspective the DT might be deemed irrelevant simply because design is about developing *descriptions* of artifacts that typically pre-dates their physical counterpart by time gaps far from "real time". Still, DTs are likely to have an impact on (marine systems) design along three main paths:

By developing the DT during the design process:
The digital models that are central in most of today's design processes will (hopefully) eventually result in a newbuilding. Thus, by easing the "real time" requirement of the definition, the DT concept may add value to the digital design model beyond its immediate use in the design process itself. Additional defining characteristics of a DT are identity, representation, state and behaviour (Erikstad 2017). These can be entrenched into the digital model throughout the design (and production) process (Fernades and Cosma 2020), to be "born" as the digital twin counterpart to the ship at delivery, and subsequently by digital entanglement serve the vessel throughout the lifecycle.

By "designing" the DT towards digital services as a primary design objective:
It is expected by many that digital services based on DT technology will comprise an increasingly large share of the total value of a newbuilding delivery in the future (Garcia Agis et al. 2022, Drazen et al. 2019). These digital services neither will nor should come into existence as a mere biproduct of the design of the physical vessel. Rather, they should be derived from the needs and expectations of key stakeholders, and they should be designed following, in principle, the same engineering design process as for the vessel itself, as described in "Designing ship digital services" by Erikstad (2019). This includes the following elements:

- The overall goal of the service, i.e. what are the high-level operational decisions the service will support
- The primary users of the service, as well as other involved stakeholders
- The scope of the service, both from a temporal perspective as well as decision-making level
- The quality of the service, which is primarily a cost-value trade-off

The specification of "form" should follow functions and needs as in other engineering design processes. For a DT typical "form" elements are sensors type, position, quality and frequency, ship onboard digital infrastructure, capabilities for data acquisition from the vessel's "operating theatre", to name a few. We believe that it is fair to say that of the 3000-5000 sensors typically installed on a PSV, not many of those are designed into the solution from a holistic "needs perspective".

By exploiting operational experience data from DT "siblings":
During the lifetime of the vessel, the DT will continuously capture and store data from real operations based directly on sensor observations, and indirectly from the processing of these data to capture more complex vessel performance data. Naturally, the DT for a particular vessel will be "born" too late for exploiting this data stream into the vessel's own design process. Still, DT data from other vessels that are sufficiently similar ("siblings") can and will be increasingly used as an intrinsic part of future design processes.

As illustrated in Figure 11, the data from the DT can be used in the design process on different aggregation levels. On the operational level, DT data can be used to feed into vessel performance models, such as resistance and powering, motion, structural loads etc. On the tactical level, DT data can be aggregated over shorter time periods to derive for instance distributions of operational states, routing, and capacity utilization. This may provide a much better understanding of the real operational profiles that can be expected for a new design, thus feeding into the "requirements elucidation" process in terms of a reality check that often comes to the surprise of the ship owner as well. One example of this was a new trawler design by Ulstein in 2020, where they had a major revision of the design requirements based on extensive data analysis of current trawler operations. On the strategic level, DT data can be aggregated for longer time periods, up to the lifetime of the vessel.

In addition to the DT data aggregation levels described above, the temporal aspects of DT data are also important from a design perspective. In operation, the DT is typically implemented as a "digital shadow" that trails the real vessel preferably with a small latency and use sensors for observing behaviour. In design, hindsight data from DT "siblings" is also relevant as experience-based input to the process, though even more so the opportunities from "foresight" by establishing the DT at an early stage to be used for simulating vessel operations to explore and validate design solutions.

Figure 11: Aggregation levels and temporal aspects of DT data used in design (Erikstad, 2019)

DTs are still in many ways immature, and their use as an intrinsic part of the design process still need research. There are many ongoing developments where we can expect to see interesting developments towards the next IMDC. Examples are a common, open, cohesive DT model for a ship (Fonseca and Gaspar 2021), open implementation frameworks (Hatledal et al. 2020), the conversion of DT data streams into useful design input (Bekker et al. 2019) and the integration of DT and SE models for design (Arrichiello and Gualeni 2020).

The wider system perspective: Integrating vessel and fleet design, operations and infrastructure

A general insight that has emerged more clearly in the wake of the current development towards low and zero emission shipping is that the ambitions set by the IMO 2050 targets cannot be achieved only by re-designing the individual themselves. We will need comprehensive, system-wide solutions that will include the design of fleets of heterogenous vessels, the re-design of their operations, as well as the development of new commercial, legal and technical infrastructures, or what was called "the extension of system boundaries" by Hagen and Grimstad (2010). Accordingly, *systems design* is likely to take a more prominent role in the coming years.

A systems perspective may result in core functionalities that is typically integrated into a single vessel, to be distributed across several vessels of a fleet. One example is the "vessel train" concept (Colling and Hekkenberg 2020) where a fully manned lead vessel takes over navigational and situational awareness responsibilities from follower vessels as part of a waterborne platoon. Another example is the proposal for a power replenishment and emergency response vessel from Ulstein (2022), offloading core functional capacities from the cruise vessels it is intended to serve.

Extending system boundaries avoids the sub-optimization of parts of the system, thus finding better and more cost efficient overall solutions. The main challenge to take this approach into real-life design processes is the distribution of part system ownership among a large and heterogenous stakeholder group, as well as established system requirements based on domain traditions that have seldom been challenged. Take optimal speed as one example, which is a decision on the interface of the design of the ship and designing the operations, see Psaraftis and Kontovas (2014). Another example that illustrates this was the design of arctic LNG transport with a large fleet of double-acting tankers (Erikstad and Ehlers 2014). Here, a significant reduction in fleet cost to be obtained by relatively moderate redesign of the "operating context" of the fleet, such as contracts that allowed for seasonal variations in destinations and volumes, storage capacity in export ports, and re-scheduling of revision stops at the LNG production facility.

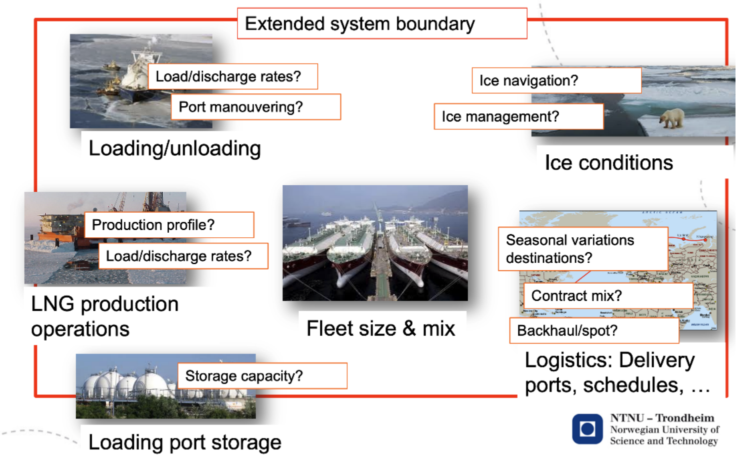

Figure 12: Extending system boundaries for LNG fleet design (Erikstad & Ehlers 2014)

Inhibitors to innovations in the maritime domain have been strong domain traditions and a bias towards standard tonnage for maintaining second-hand value. The rapidly changing context in which ships operates, and the need for new solutions to meet the emission reduction targets towards 2050 is likely to change this. As described in (Rex, 2022): "*The introduction of green corridors presents new dynamics for value creation in the shipping industry. Long-term contracts with not only cargo owners but also fuel producers will allow long-term fleet efficiency optimisation at the expense of access to the asset game. This is a shift that will champion cash flow stability, economies of scale, standardisation and lower cost of capital. It remains to be seen if new business models will begin to redefine the competitive landscape*" (Rex, 2022).

Towards the next IMDC, we expect this systems perspective to take a more central position in the design of tomorrow´s solutions, and with the associated development of new and extended design methods to cater for this.

AI, ML and KBS: Still hyped, or for real this time?

"Hype cycles" are a common phenomenon across industries and technology areas, where an initial wave of inflated expectations is followed by a trough of disillusionment, and, in some cases, a renewed start based on a more mature platform to achieve widespread adoption. Those that have followed developments in design methodology for more than a few decades will remember the high expectations towards artificial intelligence (AI), expert systems and knowledge-based systems (KBS) in the 80s and 90s. For the design community as such, the contribution from Coyne et al (1990) in their book "Knowledge-based design systems" was important. There were also several significant contributions specifically for ship design, such as Hees et al. (1992) with their QUASTOR KBS tool for preliminary design, and MacCallum & Duffy (1987) at the University of Strathclyde developing expert systems for the early design stages.

Still, it is fair to say that the expectations from many at that time for AI-related technologies to become a major factor in real-life design processes by the end of the millennium did not come through, and the research interest in this field diminished. As an illustration, none of the papers presented at the 2009 IMDC in Trondheim were related to this topic area.

During the last decade we have seen an increased focus on AI-related technologies, with efficient, real-life implementations for a wide spectrum of applications. This has ranged from photo recognition and natural language processing on mobile phones, to tackling complex problems on an unprecedented level such as chess with Google's AlphaZero, (Silver et al, 2018). There has also been a shift in the underlying technology focus, from predominantly expert systems based on logically stringent reasoning over rules structures, towards neural network models and data mining/machine learning. This has changed the way knowledge is embedded into the system, from human experts entering facts and rules in expert systems, to self-learning algorithms and reinforcement learning in neural networks. As an example, AlphaZero reached its "superhuman" performance in chess by using a generic AI platform, defining legal moves and then start playing an extremely large number og games between two virtual players. This was combined with reinforcement learning based on the single outcome of winning or not. No domain knowledge, such as human evaluations of different intermediate positions etc. were needed. How this capability will project from this very complex, still well-defined and structured, domain into other, less structured domains, remains to be seen.

One such complex, less structured domain would be engineering design in general and design methodology in particular. In a recent special issue of the Journal of Mechanical Design (Allison et al. 2022), three research interfaces between engineering design and AI were identified: The integration of AI methods directly into engineering design methods, the creation of new AI capabilities that are inspired by engineering design, and the development of engineering design methods for systems in which AI have a dominant role, such as in autonomous vessels. Recent examples are the use of AI for the prediction of ship operational parameters (Alexiou et al. 2021) or power prediction using neural networks (Parkes et al. 2018).

CONCLUDING REMARKS

In this paper we have summarized the state-of-the-art in marine systems design methodology. We first introduced some high-level trends in overall design strategy, notifying that most contributions within this topic area will be a combination of these. Further, we highlighted some more specific developments, such as design-for-sustainability, design for flexibility and uncertainty, design-for-safety, simulation-based design and WASP. Finally, we pointed towards what we believe will be emerging focal topics for the years to come.

As we noted initially, a SoA paper will naturally be a snapshot from the subjective perspective of the authors. There will be many contributions both from industry and academia that we have not included, and it is likely that other authors would have made a different selection.

Still, we hope we have been able to paint an overall picture that is exciting from a design methodology point-of-view. More than before there seems to be a consensus within the maritime industry that radically new, system-level solutions need to be developed to tackle some of the major challenges we see today related to global warming, energy distribution and global logistics chains, to name a few. To meet these challenges, new and improved design methods must be developed and implemented into practical use in industry. The next IMDC will be a checkpoint to see if we have been able to take the required steps in the right directions.

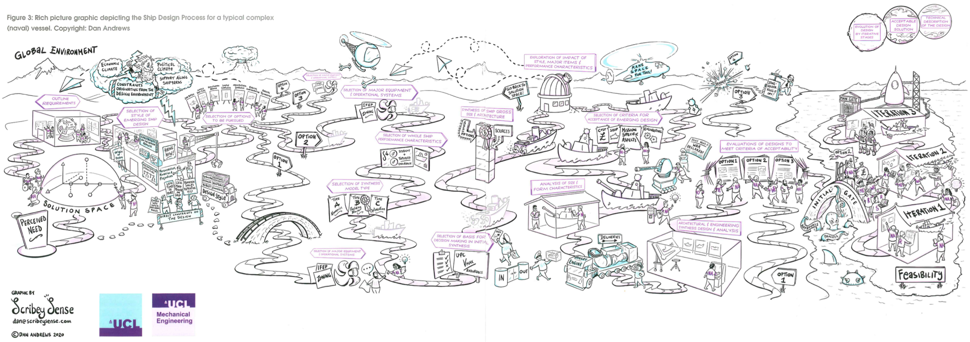

Figure 13: The complexity of the ship design process pictured by Dan Andrews (Andrews 2021)

To conclude this SoA paper we have chosen to include the illustration of the ship design process by Dan Andrews in Figure 13. This captures the "wickedness" of design, and the complexity of the task. At the same time it reminds us of what one of the founding fathers of IMDC, Stian Erichsen, used to say: "One of the most important jobs for an engineer is to make complex things simple".

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Supporting Paper 4

Marginal abatement cost curves (MACCs) for assessing the role of market-based measures (MBMs) in enhancing the adoption of alternative marine fuels

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Marginal abatement cost curves (MACCs) for assessing the role of market-based measures (MBMs) in enhancing the adoption of alternative marine fuels

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Keywords:*Market-Based Measures; Shipping Decarbonization; GHG emissions, IMO, Alternative Marine Fuels, Marginal Abatement Cost*

Abstract

Uncertainties on the global availability and affordability of alternative marine fuels are stalling the shipping sector's decarbonization course. Several candidate measures are proposed at the International Maritime Organization, including market-based measures (MBMs), environmental policies like carbon taxes and emissions trading systems. Their implementation increases the cost of fossil fuel consumption and provides fiscal incentives towards greenhouse gas emissions reductions. MBMs can bridge the price gap between alternative and conventional fuels and generate revenues for funding the up-scaling of alternative fuels' production, storage and distribution facilities and, thus, enhance their availability. By estimating the fuels' implementation and operational costs and carbon abatement potential, this study develops their marginal abatement cost curves and estimates the optimal level of carbon pricing needed to render investments into alternative fuels cost-effective. The results can assist policymakers in establishing the fundamental factors and MBM design principles that can make MBMs a robust and effective decarbonization measure.

1 Introduction

In light of the global attention placed on climate change mitigation, the International Maritime Organization (IMO) adopted the Initial IMO Strategy aiming, among others, to reduce the total annual greenhouse gas (GHG) from shipping by at least 50% by 2050 compared with 2008 while pursuing efforts towards phasing them out entirely (IMO, 2018). However, the results of the 4^{th} IMO GHG Study, show that under a Business As Usual (BAU) scenario, CO_2 emissions from shipping in 2050 are expected to be 90-130% of 2008 levels (Faber et al., 2020). In combination with estimates from UNCTAD (2021) on an expected growth in global trade volumes it becomes clear that without any solid regulatory intervention, emissions from shipping will not peak and decline but might instead continue to rise.

To leverage its decarbonization targets, the IMO strategy proposes several candidate measures classified into short-, medium- and long-term measures that are to be agreed upon and implemented by 2023, between 2023 and 2030, and 2030 and 2050, respectively. Market-based measures (MBMs) belong to the medium-term measures and aim to incentivize GHG emissions reductions. MBMs are environmental policies such as carbon taxes and emissions trading schemes that aim to close the price gap between conventional and zero carbon technologies. By increasing the cost of fossil fuels they provide fiscal incentives to stakeholders to reduce consumption and thus GHG emissions. Their implementation gathers revenues that can accelerate a maritime energy transition by funding research and development projects and by subsidizing first movers or green ships that comply with the carbon elimination regimes (Shi, 2016; Tanaka and Okada, 2019; Wang et al., 2019; Lagouvardou et al., 2020).

There is an increasing number of studies advocating that, to harness the decarbonization potentials, technological measures and especially the uptake of alternative marine fuels is unavoidable (Ashrafi et al., 2022; Lindstad et al., 2021a; Korberg et al., 2021; Lagemann et al., 2022; Wang and Wright, 2021; McKinlay et al., 2021; Xing et al., 2021; Nair and Acciaro, 2018). However, the lack of global availability and sufficient supply of these fuels hamper the energy transition. MBMs can accelerate the upscaling of zero-carbon technologies by closing the price gap between conventional and alternative fuels.

This study aims to assess and quantify the potential of MBMs in enhancing the adoption of alternative marine fuels. We utilize the concept of Marginal Abatement Cost Curves (MACCs) - an environmental policy tool - that associate the cost of any carbon mitigation measure with its abatement potential. The analysis focuses on estimating the net cost of implementing and utilizing alternative marine fuels and their abatement potential for several case studies of newbuilding and existing vessels. The marginal abatement cost of a mitigation measure corresponds to the level of the carbon tax that renders an alternative fuel cost-competitive from a ship owner's point of view. Our study ranks the alternative fuel solutions to reflect the market's preference for their adoption and estimates the carbon price needed to close the price gap with the baseline fuel.

The rest of this study is organized as follows. Section 2 performs a literature survey on the alternative marine fuels pathways and the concept of MACCS for assessing carbon prices and cost-efficient carbon reduction measures. Section 3 contains the methodology we followed to develop and construct the MACCs and Section 4 presents the data set used for this analysis. Section 5 demonstrates the results and, finally, Section 6 highlights the conclusions of this study.

2 Literature review

MACCs have been widely applied in assessing the economics of climate change mitigation policies (Kesicki, 2012). Their development allows policy makers to illustrate the relationship between an abatement measure's emissions reduction potential (measured in tCO_{2e}[1]) and its associated cost for reducing CO_{2e} emissions by one unit (USD/tCO_{2e}). The prospect of MACCs is manifold. They can provide insights on policy-making guiding principles, assist in realizing the impacts of various mitigation options that may not bear the upfront implementation costs but have the capacity to support the GHG abatement efforts, and compare some mitigation technologies relative to their cost-effectiveness along with their abatement spectrum (Ibrahim and Kennedy, 2016). So far, they have been used in environmental theory and energy economics to indicate in a straightforward way the CO_2 tax (= marginal abatement cost) associated with a specific reduction level or the carbon price resulting from an emissions cap in a cap-and-trade system (Newell and Stavins, 2003; Requate, 2005; Kesicki and Ekins, 2012; Huang et al., 2016).

According to Kesicki and Ekins (2012), there are mainly two methods for constructing MACCs. First, the model-based approach generates a linear cost-effectiveness trend-line relative to the abatement potential. In shipping, it has been used to evaluate different carbon mitigation measures (Eide et al., 2009; Franc and Sutto, 2014; Longva et al., 2010; Smith et al., 2016), including operational and technological mitigation measures. IMAREST (2011) developed

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[1] CO_{2e} or carbon dioxide equivalent accounts for other GHGs besides CO_2 and translates their potency in relation to CO_2 on the basis of their global warming potential (GWP). This study considers the 100-year time horizon GWP relative to CO_2 (IPCC, 2001).

their own model-based MACCs to investigate the cost-effectiveness and CO_2 emissions reductions of potential technical and operational measures. Both the 2nd and 4th IMO GHG studies involve MACCs on a model-based approach (Buhaug et al., 2009; Faber et al., 2020), and last but not least, CE Delft has published their analysis on model-based MACCs (Faber et al., 2011, 2009). Model-based MACCs tend to demonstrate macroeconomic responses on international trade more precisely and capture the interdependencies between different mitigation measures. However, they often are criticized for lacking transparency, technical detail, and clarity in their findings (Kesicki, 2012).

The second method for producing MACCs is the expert-based method that uses a step-form visualization of the various mitigation measures and ranks them accordingly by demonstrating the economic and technical merits of reducing GHG emissions. The technique provides a MAC comparison of the assessed mitigation measures, transparency on the calculations of the associated costs, and a simpler representation of the relationship between cost-effectiveness and abatement potential. More specifically, the expert-based model is constructed using several mitigation measures from lowest to highest cost-effectiveness forming multiple steps, representing the MAC over the whole lifetime of the mitigation measure. In shipping, it has been used to study various maritime carbon mitigation measures' interdependencies and propose methods to rank them systematically.

Hu et al. (2019) consider 14 measures and demonstrate the influence of interdependencies between operational and technical standards, highlighting the importance of fuel prices and discount rates on the preference of a mitigation measure. Nepomuceno de Oliveira et al. (2022) gather data on the implementation cost and mitigation potential of 22 measures to assess the applicability of MAC for ships and found that measures with negative MAC are frequently implemented in the sector. The results highlight that MACCs can be an effective tool in forecasting any mitigation measure implementation rate. Lindstad et al. (2021b) calculate the abatement cost of various eFuels and conclude that the most robust path to follow is through dual-fuel engines that ensure flexibility in fuel selection and can set the scene for growing eFuels supplies at lower risks. Kyprianidou et al. (2021) implement the expert-based approach to study several operational and technical measures such as trim and ballast optimization, main engine auto tuning, LNG, and flettner rotors and conclude that the investigated measures with negative abatement cost should only be considered as medium-term solutions as they do not lead to fossil fuel's independence. Huang et al. (2016) assess the different MAC methodologies and suggest that MACCs can be a reliable tool to rank the mitigation options relative to a baseline rather than to focus on the absolute value of the individual measures. Last but not least, (DNV, 2009; Eide et al., 2009) published a study on the development of expert-based MACCs for the shipping sector, estimating the abatement potential of various operational and technological measures towards 2030.

The literature review demonstrated that MACCs are a suitable tool for informed policy-making, and to date, there is a gap in estimating MACCs for alternative marine fuels. This study aims to close this gap by utilizing the principle of MACCs to assess the cost effectiveness of alternative marine fuels and their supporting technology. We use the expert-based approach to rank the alternative fuels from the lowest to the highest MAC and identify the required carbon pricing level that renders these fuels' costs comparable with a baseline fuel. This study assumes that each fuel will be used as the only solution for covering the vessel's energy requirements and that interactions among the fuels do not compromise the utilization of MACCs. The utilization of MACCs allows for the identification of the required level of carbon pricing for closing the price gap between conventional fuels and alternative fuels and for rendering these fuels cost competitive.

3 Methods

To generate the MACC of an alternative marine fuel, it is necessary to determine each project's financial details and the expected GHG abatement volume over the project's lifetime. The analysis follows the five steps below:

1. Conduct a comprehensive survey of the various technologies and their costs required to facilitate the adoption of alternative marine fuels for a case study vessel.
2. Calculate the MAC of these alternatives for various stages of the vessel's lifetime and different scenarios on the evolution of fuel prices.
3. Develop the MACCs and correlate MAC and the fuels' abatement potential
4. Prioritize the alternative fuels based on their MAC
5. Estimate the required level of carbon pricing that renders the alternative fuels' cost-competitive with the baseline fuel.

Table 1 defines the various symbols and variables of this analysis. Both carbon coefficients Cf_A and Cf_B and fuel prices Pf_A and Pf_B are normalized by unit energy (per kWh) to allow for direct comparison of alternative fuels on a common denominator basis. The common denominator is the required energy to propel the ship over its lifetime (equivalently, on an annual basis). For our study, we assume that this energy is known and fixed, equal to F_c, expressed in kWh. Furthermore, we assume that introducing alternative fuel will not change the pattern of trade or service speed of the vessel over its lifetime. Also, we shall only compare fuels that have $Cf_A < Cf_B$, so that they have a (positive) emissions reduction potential and serve the initial goal of reducing the sector's GHG emissions. $\Delta CAPEX(A)$ represents the difference in the capital costs for implementing the alternative fuel A. In the newbuilding scenario, the value represents the difference in newbuilding costs whereas in the retrofit, the cost of retrofitting.

Table 1 – *Symbol Table*

Symbol	**Definition**	**Description/Comment**
A	Alternative Fuel	
B	Baseline Fuel	
R	Project's lifetime	$\begin{cases} 25, \text{ newbuilding scenario} \\ 1<R<25, \text{ retrofit scenario} \end{cases}$
i	Discount rate, investor's cost of capital	assumed 3%
F_c	Annual Fuel consumption	in kWh
Cf_A	Carbon coefficient of fuel A	in gCO_{2e}/kWh. See table 3
Cf_B	Carbon coefficient of fuel B	in gCO_{2e}/kWh. See table 3
Pf_A	Price of fuel A	in USD/kWh. See table 3
Pf_B	Price of fuel B	in USD/kWh. See table 3
$MAC(A)$	Marginal abatement cost of fuel A	USD/MT of CO_{2e} See eq. 1
$\Delta NCOST(A)$	Difference in total net cost over the vessel's lifetime due to A	See eq. 2
$\Delta CAPEX(A)$	Additional capital outlay for implementing fuel A	See table 2
$\Delta OPEX(A)$	Difference in annual operating costs over the vessel's lifetime R due to fuel A	See eq. 3
$OppC(A)$	Opportunity cost calculated based on the vessel's lost cargo capacity to implement A	See table 2
ΔCO_{2e}	The total CO_{2e} averted over the vessel's lifetime R due to A.	See eq. 4
$MAC'(A)$	Marginal abatement cost of fuel A after the imposition of a tax	USD/MT of CO_{2e} See eq 6
$\Delta NCOST'(A)$	Difference in total net cost after the imposition of the carbon price	See eq. 7
$\Delta OPEX'(A)$	Difference in annual operating costs after the imposition of the carbon price	See eq.8
Cp_0	Carbon price for $MAC'(A) = 0$	in USD/MT of CO_{2e} See eq 10

We note that both Pf_A and Pf_B are considered exogenous inputs. These are the costs that the ship operator (ship owner or charterer) needs to bear for purchasing the fuel and usually derive as the sum of the fuel production, transportation, and storage cost. Due to the high level of uncertainty regarding future prices of alternative marine fuels, this study performed a literature survey on the various estimations published so far and presents them in Appendix A. The final purchasing cost is also influenced by market parameters that are hard to predict. For instance, the latest rise in LNG prices does not correlate with an increase in the production cost of LNG but is attributed to a radical decrease in LNG supply.

The definition of the MAC of alternative fuel A is described in the following formula:

$$MAC(A) = \frac{\Delta NCOST(A)}{\Delta CO_{2\mathrm{e}}(A)} \tag{1}$$

$$\Delta NCOST(A) = \Delta CAPEX(A) + \sum_{t=1}^{R} \frac{\Delta OPEX(A) + OppC(A)}{(1+i)^t} \tag{2}$$

$$\Delta OPEX(A) = (Pf_A - Pf_B) \times F_c \tag{3}$$

$$\Delta CO_{2\mathrm{e}}(A) = (Cf_B - Cf_A) \times F_c \times R \tag{4}$$

$$MAC(A) = \frac{\Delta CAPEX(A)}{\Delta CO_{2\mathrm{e}}(A)} + \frac{1}{\Delta CO_{2\mathrm{e}}(A)} \times \sum_{t=1}^{R} \frac{(Pf_A - Pf_B) \times F_c + OppC(A)}{(1+i)^t} \tag{5}$$

The above methodology estimates the MAC of an alternative fuel A vis-à-vis baseline fuel B. Considering that alternative fuel solutions are deemed expensive investments, they are expected to have MAC>0. As mentioned above, in the definition of MAC, investments with MAC<0 are already cost-competitive, and at this point, the carbon abatement option is equally expensive as the baseline scenario from an investor point of view.

To identify the abatement cost turning point that will achieve cost-competitiveness of the alternative fuel, this study identifies the required level of the levy that renders the MAC=0. More specifically, considering the enforcement of carbon pricing at the level of Cp_0, the following considerations are essential:

The imposition of a carbon price is an additional operational cost for the ship that alters the MAC to MAC':

$$MAC'(A) = \frac{\Delta NCOST'(A)}{\Delta CO_{2\mathrm{e}}(A)} \tag{6}$$

where $\Delta CO_{2\mathrm{e}}(A)$ is still given by Eq. 4 and $Cp_0 \geq 0$ the carbon price on $\mathrm{CO_{2e}}$ that makes $MAC'(A) = 0$, expressed in USD/MT $\mathrm{CO_{2e}}$.

The new annual operational costs $\Delta OPEX'(A)$, will be reduced by $(Cf_B - Cf_A) \times F_c \times Cp_0$ due to the emissions reductions achieved by the alternative fuel A, and therefore:

$$\Delta NCOST'(A) = \Delta CAPEX(A) + \sum_{t=1}^{R} \frac{\Delta OPEX'(A) + OppC(A)}{(1+i)^t} \tag{7}$$

$$\Delta OPEX'(A) = (Pf_A - Pf_B) \times F_c + (Cf_B - Cf_A) \times F_c \times Cp_0 \tag{8}$$

From eq. 7 and 8 we identify the carbon price Cp_0 for which $MAC'(A) = 0$ or $\Delta NCOST'(A) = 0$. Since $\Delta CO_{2\mathrm{e}} = (Cf_B - Cf_A) \times F_c \times R$ is constant we get the following:

$$\frac{\Delta CAPEX(A)}{\Delta CO_{2\mathrm{e}}(A)} + \frac{1}{\Delta CO_{2\mathrm{e}}(A)} \times \sum_{t=1}^{R} \frac{(Pf_A - Pf_B) \times F_c + (Cf_B - Cf_A) \times F_c \times Cp_0 + OppC(A)}{(1+i)^t} = 0$$

Or:

$$MAC(A) - \sum_{t=1}^{R} \frac{Cp_0}{R \times (1+i)^t} = 0 \tag{9}$$

$$Cp_0 = \frac{R \times MAC(A)}{\sum\limits_{t=1}^{R} \frac{1}{(1+i)^t}} = 0 \tag{10}$$

Eq. 10 is noteworthy as it proves mathematically that the carbon tax is influenced only by the MAC of a mitigation measure and the mean value of the discount rate over the project's lifetime. It can also be seen that, in this case, a carbon price would preserve the ranking of alternative fuels according to their MAC, since $MAC(A_1) < MAC(A_2)$ would imply that $MAC'(A_1) < MAC'(A_2)$.

4 Data Set

The development of fuel prices depends on various exogenous inputs, such as the price of renewable electricity, the price of carbon capture and storage (CCS), and the global and sufficient availability of these fuels. Given the high level of uncertainty in the evolution of alternative fuel prices, our data set consists of a high and low price expectancy scenario. Fossil fuels, were based on historic trajectories, while the bio-fuel prices depend on the cost of biomass. E-fuel prices rely on the levelized cost of renewable electricity (as well as the cost of CO_2). The two different price scenarios are intended to capture the uncertainty with respect to the named exogenous factors. Data on fuel prices are derived from a comprehensive literature survey of academic research papers and reports from relevant institutions and maritime stakeholders. A larger table, showing various estimates of prices for an expanded set of alternative fuels according to various sources is shown in Appendix A.

Our case study focuses on a 63,000 DWT Supramax bulk carrier of 7500 kW maximum brake power. The analysis assumes that the annual energy output of the vessel will remain constant and thus additional fuel storage space will be required to account for the lower energy density of the alternative fuels. For calculating the opportunity cost associated with the revenues lost due to cargo space being used as fuel storage capacity we keep the total displacement of the ship constant for all power systems and reduce the respective cargo carrying capacity. For the first 58,000 dwt, we assume we assume an average utilization of 90%, and for the next 5,000 dwt, we estimate an average utilization of 25%. According to the aforementioned deadweight ranges' utilizatiom, we assume a charter rate of 25,000 USD per day, which is distributed proportionally among them (Handybulk, 2022).

Firstly, our analysis focuses on a newbuilding scenario, ranks the alternative marine fuels according to their MAC and evaluates the carbon price needed to render these investments cost-effective. In estimating the newbuilding price over the past years, our Very Low Sulphur Fuel Oil (VLSFO) reference configuration costs roughly 30 mUSD (Hellenic Shipping News, 2022). We deduct the cost of a VLSFO power system and instead use the alternative fuel power systems cost per unit of brake power as estimated by Lindstad et al. (2021b) and derive the alternative fuel vessels' newbuilding costs as shown in Table 2. Second, this study estimates the MACCs for a retrofit scenario and uses the same system-based cost factors as for newbuilds plus an additional penalty of 3.6 mUSD to account for shipyard costs and lost income during retrofitting. Table 2 summarizes our inputs.

Our next case study involves a newbuilt vessel equipped with a conventional Diesel internal combustion engine (ICE) that seeks to switch to an alternative fuel at its 5th and 10th year of age. We aim to calculate the carbon price that will incentivize the retrofit. The analysis is conducted for two different price scenarios to account for the uncertainty on the evolution of alternative fuel bunker prices. Retrofitting to alternative marine fuels entails various technical modifications onboard. We assume that additional tanks up to 1600m^3 can be installed on deck in the aft part of the ship to accommodate the new fuel. The case differs from other shipping segments, and decisions on the installment of the alternative fuel storage tanks depend on the type and initial design of the vessel.

In the case of retrofitting to methanol, we assume that the fuel tanks can be integrated into the ship's structure. Retrofitting would require modifications to the fuel supply system regardless of the chosen alternative (MZCCb, 2022). On the other hand, in the case of retrofitting to LNG or ammonia, the advanced requirements for main engine modifications and the installation of additional tank capacity will lead to a relatively higher retrofitting cost compared to methanol. For LPG, we shall assume that retrofitting costs are similar to methanol, and for hydrogen, due to its unique properties and relatively low technological readiness retrofitting costs are considered the most expensive.

Table 2 – *Case study vessel newbuilding, opportunity and retrofitting costs parameters*

Vessel Type		**Supramax Bulk Carrier**					
Main Engine Installation		**HFO**	**LNG**	**LPG**	**Ammonia**	**Methanol**	**Hydrogen**
Fuel Type Supported		**HFO/VLSFO** **Diesel/Bio-Diesel** **E-Diesel**	**Ditto & LNG** **Bio-LNG** **E-LNG**	**LPG**	**Grey-Ammonia** **Blue-Ammonia** **Green- Ammonia**	**Grey-Methanol** **Bio-Methanol** **E-Methanol**	**Grey-Hydrogen** **Blue-Hydrogen** **Green-Hydrogen**
Newbuilding Cost (mUSD)		30	37.5	33	37	33	47.5
	FROM TO	**HFO**	**LNG**	**LPG**	**Ammonia**	**Methanol**	**Hydrogen**
Opportunity Cost (USD/day)	**HFO**	0	-318	-88	-351	-178	-1981
	LNG	318	0	229	-34	140	-1664
	LPG	88	-229	0	-263	-90	-1893
	Ammonia	351	34	263	0	174	-1630
	Methanol	178	-140	90	-174	0	-1804
	Hydrogen	1981	1664	1893	1630	1804	0
Retrofitting cost (mUSD)	**HFO**	0.0	N/A	N/A	N/A	N/A	N/A
	LNG	12.6	0.0	10.4	N/A	N/A	20.5
	LPG	7.4	5.1	0.0	N/A	N/A	22.7
	Ammonia	12.6	5.1	8.9	0.0	10.4	5.9
	Methanol	7.4	10.1	10.7	N/A	0.0	N/A
	Hydrogen	25.0	20.5	22.7	18.2	22.7	0.0

Moreover, we develop the MACCs for an existing vessel equipped with an LNG ICE. Considering the current record on the orderbook for LNG newbuilding vessels (and 25 years life expectancy), it is very likely that LNG ICE ships will seek to comply with the more stringent forthcoming regulations before 2050, and retrofitting will become a viable solution. According to Comer et al. (2018) and Lindstad et al. (2021a), it is only the LNG dual fuel engine operating on a Diesel cycle that can deliver GHG emissions reductions on a WTW and this study will consider this engine technology.

Table 3 – *Fuel prices and WTW emissions*

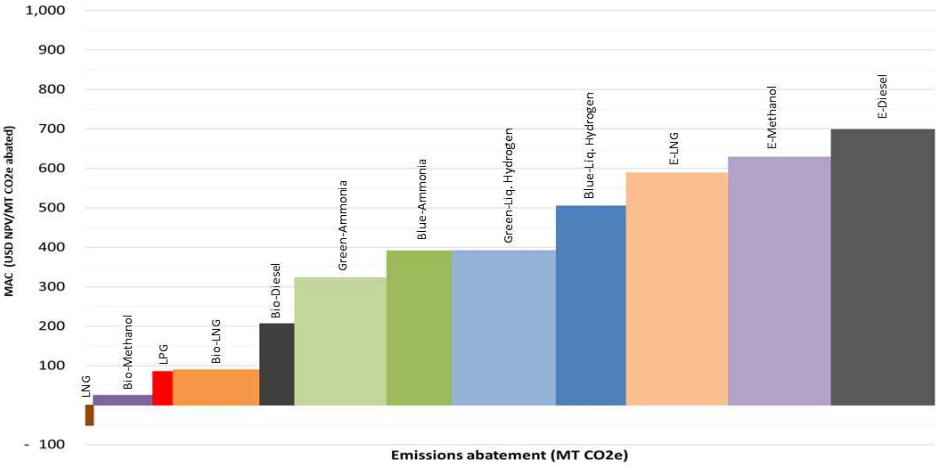
Fuel Type	**Climate Pollutants GWP100 (gCO_{2e}/kWh Fuel)**		**Fuel Prices (USD/kWh)**	
	GWP *WTT*	**GWP *TTW***	**Upper bound**	**Lower bound**
VLSFO	47.5[1]	284.1[1]	0.095[2]	0.038[2]
Bio-Diesel	70.0[5]	150.0[5]	0.128[3]	0.093[3]
E-Diesel	0.0[1]	4.5[1]	0.423[2]	0.131[2]
LNG	66.6[1]	238.8[1]	0.081[2]	0.032[2]
Bio-LNG	49.7[1]	6.0[1]	0.119[3]	0.089[3]
E-LNG	0.0[1]	6.0[1]	0.358[2]	0.115[2]
LPG	30.0[1]	237.5[1]	0.098[2]	0.039[2]
Grey-Methanol	112.7[1]	253.4[1]	0.210[1]	0.090[1]
Bio-Methanol	112.7[1]	3.24[1]	0.097[3]	0.066[3]
E-Methanol	0.0[1]	3.50[1]	0.385[2]	0.116[2]
Grey-Ammonia	360.0[7]	19.0[1]	0.387[7]	0.050[7]
Blue-Ammonia	87.1[1],[4]	19.0[1]	0.220[2],[6]	0.056[2][6]
E-Ammonia	0.0[1]	19.0[1]	0.220[2]	0.080[2]
Grey Liq. Hydrogen	396.0[8]	0.0[1]	0.245[8]	0.120[8]
Blue Liq. Hydrogen	108.7[1],[4]	0.0[1]	0.245[2],[6]	0.055[2],[6]
Green Liq. Hydrogen	0.0[1]	0.0[1]	0.245[2]	0.079[2]

Sources and comments:
[1]Lindstad et al., 2021a
[2]Lindstad et al., 2021b
[3]Korberg et al., 2021
[4]assuming 80% CCS efficiency
[5]The Sustainable Shipping Initiative, 2021
[6]The upper bound is 100% of electricity-based pendants, lower bound is 70% of electricity-based pendants
[7]Al-Aboosi et al., 2021
[8]Atilhan et al., 2021

5 Analysis

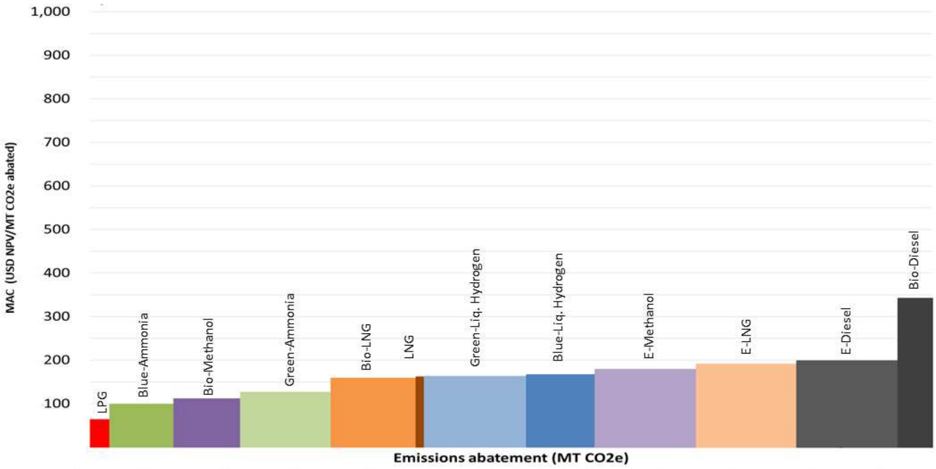
This section presents the results of the analysis in the form of MACCs for our case studies. Figures 1-5 on the y axis illustrate the estimated MAC or the NPV per MT of CO_{2e} abated, and on the x-axis, the width of each column represents the emission abatement potential of each alternative fuel relative to the baseline. Furthermore, the results in the data tables are ranked from the lowest to the highest MAC and contain the total amount of CO_2 averted by implementing the alternative fuel over the vessel's lifetime, the % of GHG emissions reductions achieved relative to using the baseline fuel and the level of carbon pricing that renders the fuels cost viable. A low and high bound of fuel prices is considered to capture the uncertainty of the expected alternative marine fuel production prices and their dependency on exogenous inputs such as the prices of renewable electricity and CCS. As established in the literature review of this study, MACCs are mainly utilized to facilitate a straightforward interpretation of the relationship between cost-effectiveness and abatement potential and to compare some mitigation technologies with respect to their MAC and abatement spectrum.

Figure 1a shows the MACCs for a newbuilding vessel in a high fuel price scenario, assuming a lifespan of 25 years and a discount rate of 3%. The results indicate that investments into an ICE LNG vessel have a negative MAC and thus constitute cost-effective investment choices under high fuel price expectancy. The results are attributed to LNG prices in the future expected being low (lower than VLSFO). When $Pf_A < Pf_B$ then $OPEXf_A - OPEXf_B < 0$, and the investor benefits from a cheaper fuel. However, when the increase in capital expenditure is not high enough to compensate for the difference in the long-term operational cost savings attributed to the low LNG prices, then $MAC(A)$ will be positive. The LNG ship's abatement potential is limited to only 8% of GHG emissions reductions for a WTW scope and GWP100. This insufficient reduction in absolute emissions could be complemented with other operational measures, such as speed reduction, to reach the desired emissions levels. Furthermore, Figure 1a shows that investments into Bio-Methanol can become cost-effective after imposing a tax of around 40 USD/MT CO_{2e}e and CAN achieve 65% GHG reductions. The same rationale is followed for all other fuel choices within the scope.



	LNG	Bio-Methanol	LPG	Bio-LNG	Bio-Diesel	Green-Ammonia	Green-Liq. Hydrogen	Blue-Ammonia	Blue-Liq. Hydrogen	E-LNG	E-Methanol	E- Diesel
MAC (USD NPV/MT CO2e)	-51.08	24.62	85.43	89.82	206.59	323.02	391.66	391.45	504.54	588.45	628.43	698.44
Net Present Value (mUSD NPV)	1.46	-5.78	-5.96	-26.99	-25.11	-103.45	-141.42	-88.28	-122.46	-208.64	-224.52	-248.78
Total Abatement in vessel's lifetime (MT/CO2e)	28,530	234,773	69,800	300,436	121,525	320,254	361,089	225,517	242,722	354,555	357,278	356,189
Carbon Price (USD/ MT CO2e)	0.00	36.70	127.35	133.89	307.95	481.50	583.82	583.51	752.08	877.17	936.76	1,041.13
% GHG reduction	8%	65%	19%	83%	34%	89%	100%	62%	67%	98%	99%	99%

(a)



	LPG	Blue-Ammonia	Bio-Methanol	Green-Ammonia	Bio-LNG	LNG	Green-Liq. Hydrogen	Blue-Liq. Hydrogen	E-Methanol	E-LNG	E-Diesel	Bio-Diesel
MAC (USD NPV/MT CO2e)	63.70	98.84	111.20	126.44	158.99	161.60	162.71	167.05	178.37	190.56	198.03	341.40
Net Present Value (mUSD NPV)	-4.45	-22.29	-26.11	-40.49	-47.77	-4.61	-58.75	-40.55	-63.73	-67.56	-70.54	-41.49
Total Abatement in vessel's lifetime (MT/CO2e)	69,800	225,517	234,773	320,254	300,436	28,530	361,089	242,722	357,278	354,555	356,189	121,525
Carbon Price (USD/ MT CO2e)	94.95	147.34	165.77	188.48	237.00	240.89	242.54	249.02	265.89	284.05	295.20	508.90
% GHG reduction	19%	62%	65%	89%	83%	8%	100%	67%	99%	98%	99%	34%

(b)

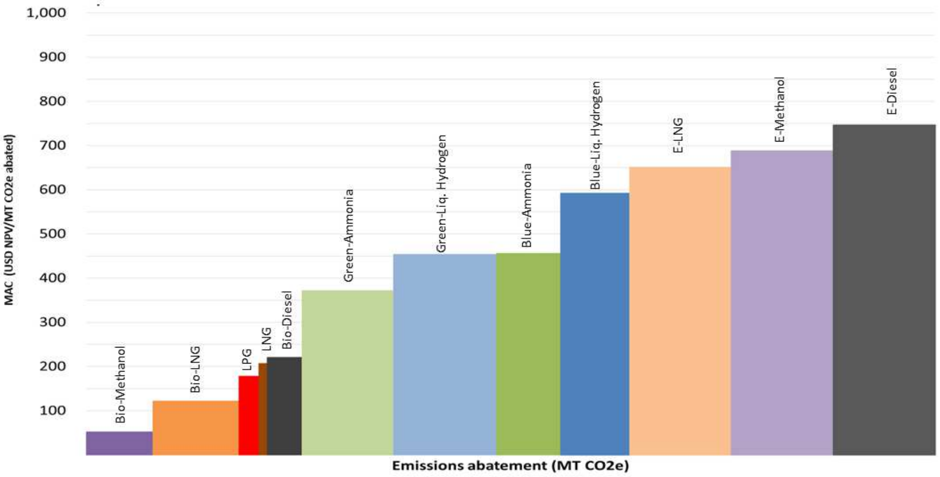
Figure 1 – *(a) MACCs of a newbuilding vessel in a high fuel price scenario based on 100 USD/kg of* CO_2 *cost of CCS and 100 USD/MWh cost of electricity IEA (2019) (b) As for (a) but over low fuel price scenario of 20 USD/MWh cost of electricity.*

Figure 1b shows the MACCs of a newbuilding vessel assuming a lifespan of 25 years and a discount rate of 3% for a low fuel price scenario. In this case, investments into LPG vessels have the lowest MAC and would require a carbon tax of approximately 65 USD/MT of CO_{2e} to become economically viable. The results differ from the high price scenario for various reasons, such as the lower marginal difference in the relevant fuel cost between LPG and Diesel and LNG and Diesel, the higher abatement potential of LPG versus LNG, and the marginal difference in the capital cost of a newbuilding LPG vessel and a conventional Diesel vessel. However, the emissions reduction potential of an LPG vessel is approximately 20% - not enough to reach the 50% target without additional logistic-based practices to complement the fuel choice. Blue-Ammonia, on the other hand, that follows LPG in the MACC figure, can achieve emissions reductions up around 60%, and, from a financial perspective, would require a carbon price of 100 USD/MT CO_{2e} to become financially attractive.

Figures 2-5 contain our results for the retrofitting case. We consider the same Supramax bulk carrier retrofitted after 5 or 10 years, respectively for two fuel price development scenarios. The results show that on the one hand, the ranking of the preferred fuels considered is not influenced significantly by the vessel's age but the derived MAC increases with the vessel's age. This is expected as it shows that retrofitting a relatively younger vessel with alternative fuels has a greater return on investment potential and higher total abatement capabilities. In terms of the MBMs, lower MACCs are translated to lower levels of carbon taxation.

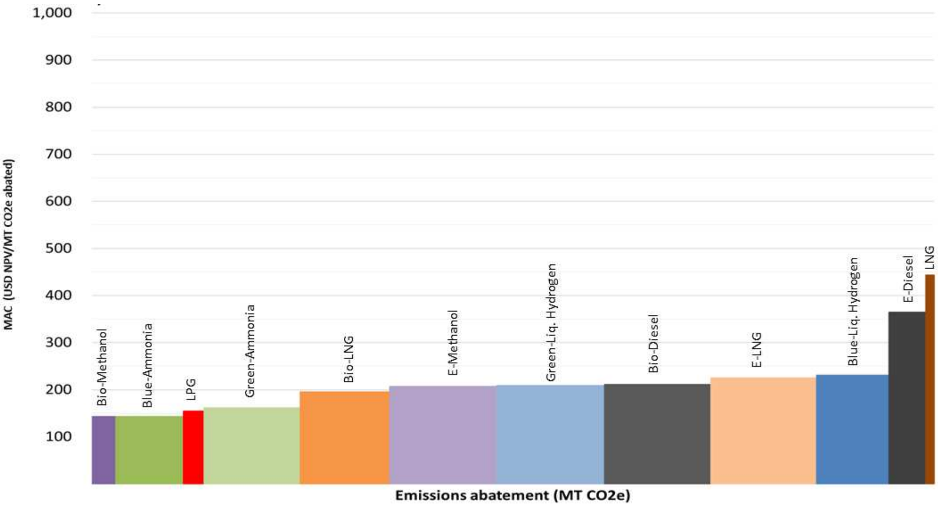
Figures 2 and 3 show the MACCs for our first retrofit case study of a vessel equipped with a Diesel ICE. Bio-Methanol appears to be the most preferred solution due to the low retrofitting costs for upgrading the engine to burn methanol, the expected low-price differential of Bio-Methanol and VLSFO, and the large emissions abatement potential that Bio-Methanol can achieve. However if ammonia production costs come down to approx. 56 USD/kWh, then to incentivize retrofits a carbon price of 200 USD/MT CO_{2e} would be sufficient.ent potential that Bio-Methanol can achieve.

Compared with the newbuilding scenario, the reduced lifespan and the lower price range between LNG and Diesel, do not result in high enough operational cost savings to cover the retrofitting costs. Thus, LNG appears to be further down in the ranking of preference for alternative fuels. A switch to E-Diesel is the most cost-intensive choice, whereas for Green Liq. Hydrogen a levy of 600 USD/MT CO_{2e} is required.



	Bio-Methanol	Bio-LNG	LPG	LNG	Bio-Diesel	Green-Ammonia	Green-Liq. Hydrogen	Blue-Ammonia	Blue-Liq. Hydrogen	E-LNG	E-Methanol	E-Diesel
MAC (USD NPV/MT CO2e)	52.05	121.69	177.86	206.43	220.63	371.48	453.66	455.69	591.46	650.28	688.07	745.92
Net Present Value (mUSD NPV)	-9.78	-29.25	-9.93	-4.95	-21.45	-95.17	-131.05	-82.21	-114.85	-184.45	-196.66	-212.55
Total Abatement in vessel's lifetime (MT/CO2e)	187,819	240,348	55,840	23,965	97,220	256,203	288,871	180,414	194,178	283,644	285,822	284,951
Carbon Price (USD/ MT CO2e)	69.97	163.59	239.11	277.51	296.60	499.40	609.88	612.61	795.14	874.21	925.01	1,002.78
% GHG reduction	65%	83%	19%	8%	34%	89%	100%	62%	67%	98%	99%	99%

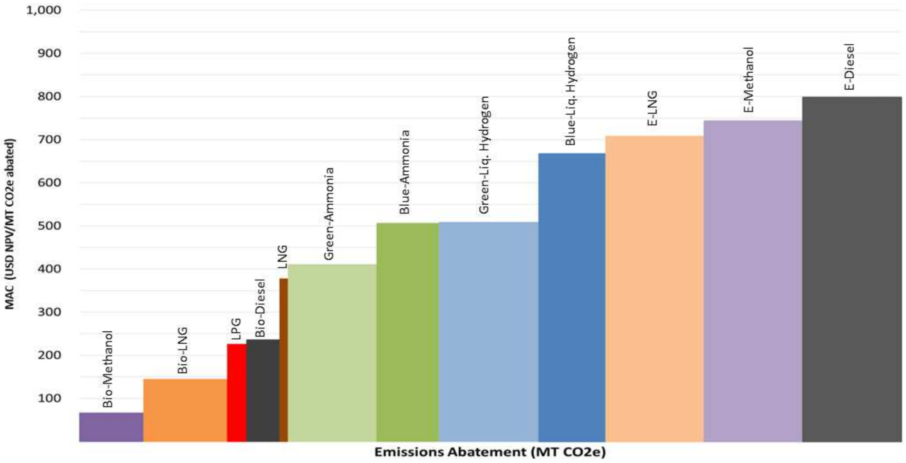
(a)



	Bio-Methanol	Blue-Ammonia	LPG	Green-Ammonia	Bio-LNG	E-Methanol	Green-Liq. Hydrogen	E-Diesel	E-LNG	Blue-Liq. Hydrogen	Bio-Diesel	LNG
MAC (USD NPV/MT CO2e)	143.14	143.20	154.65	161.54	195.56	207.42	209.14	211.50	225.34	231.04	364.60	443.88
Net Present Value (mUSD NPV)	-26.88	-25.84	-8.64	-41.39	-47.00	-59.28	-60.41	-60.27	-63.92	-44.86	-35.45	-10.13
Total Abatement in vessel's lifetime (MT/CO2e)	187,819	180,414	55,840	256,203	240,348	285,822	288,871	284,951	283,644	194,178	97,220	22,824
Carbon Price (USD/ MT CO2e)	192.43	192.51	207.90	217.17	262.91	278.84	281.16	284.33	302.94	310.60	490.16	596.74
% GHG reduction	65%	62%	19%	89%	83%	99%	100%	99%	98%	67%	34%	8%

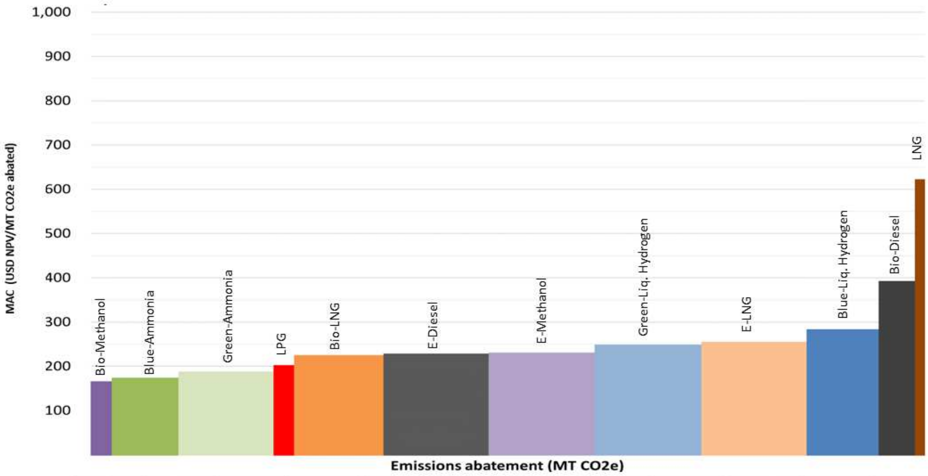
(b)

Figure 2 – *(a) MACCs of a retrofit of a 5-year-old Diesel ICE vessel in a high fuel price scenario. Upper bound based on 200 USD/kg of* CO_2 *cost of CCS and 100 USD/MWh cost of electricity IEA (2019) (b) As for (a) but over low fuel price scenario of 20 USD/MWh cost of electricity.*



	Bio-Methanol	Bio-LNG	LPG	Bio-Diesel	LNG	Green-Ammonia	Blue-Ammonia	Green-Liq. Hydrogen	Blue-Liq. Hydrogen	E-LNG	E-Methanol	E-Diesel
MAC (USD NPV/MT CO2e)	66.07	144.00	225.20	236.05	377.33	410.40	505.94	508.17	666.72	707.43	742.98	798.05
Net Present Value (mUSD NPV)	-9.31	-25.96	-9.43	-17.21	-6.46	-78.86	-68.46	-110.10	-97.10	-150.49	-159.27	-170.55
Total Abatement in vessel's lifetime (MT/CO2e)	140,864	180,261	41,880	72,915	17,118	192,152	135,310	216,653	145,633	212,733	214,367	213,713
Carbon Price (USD/ MT CO2e)	83.01	180.94	282.97	296.60	474.12	515.66	635.71	638.51	837.73	888.89	933.55	1,002.75
% GHG reduction	65%	83%	19%	34%	8%	89%	62%	100%	67%	98%	99%	99%

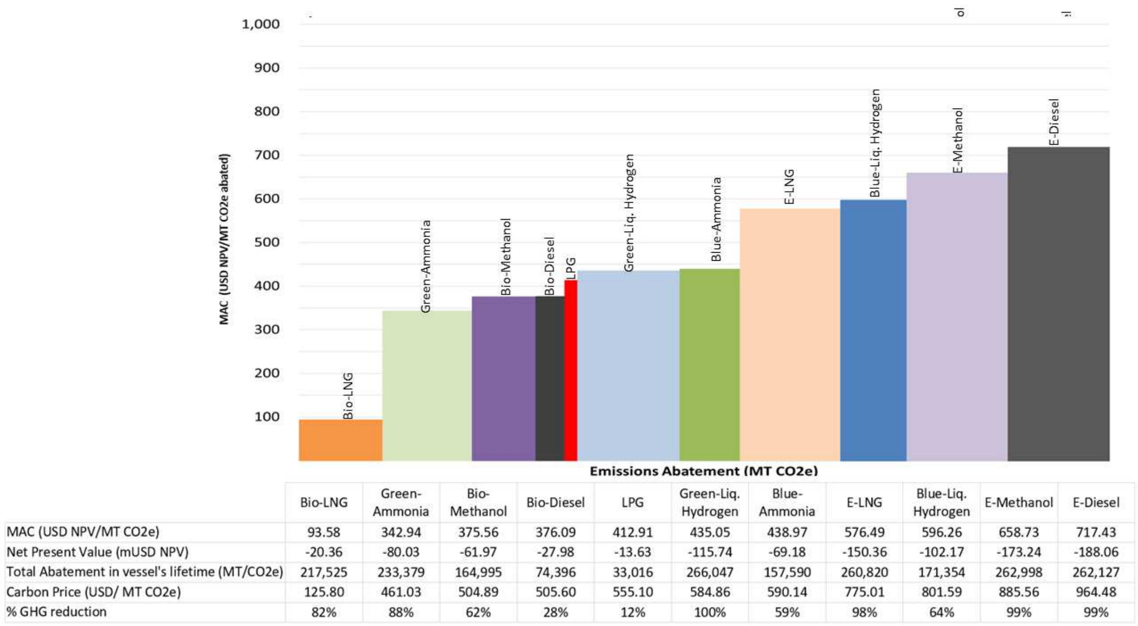
(a)



	Bio-Methanol	Blue-Ammonia	Green-Ammonia	LPG	Bio-LNG	E-Diesel	E-Methanol	Green-Liq. Hydrogen	E-LNG	Blue-Liq. Hydrogen	Bio-Diesel	LNG
MAC (USD NPV/MT CO2e)	163.52	171.61	185.79	200.37	223.04	226.28	228.73	246.56	252.79	281.10	390.09	620.34
Net Present Value (mUSD NPV)	-23.03	-23.22	-35.70	-8.39	-40.21	-48.36	-49.03	-53.42	-53.78	-40.94	-28.44	-10.62
Total Abatement in vessel's lifetime (MT/CO2e)	140,864	135,310	192,152	41,880	180,261	213,713	214,367	216,653	212,733	145,633	72,915	17,118
Carbon Price (USD/ MT CO2e)	205.46	215.63	233.45	251.76	280.25	284.32	287.41	309.80	317.64	353.21	490.14	779.46
% GHG reduction	65%	62%	89%	19%	83%	99%	99%	100%	98%	67%	34%	8%

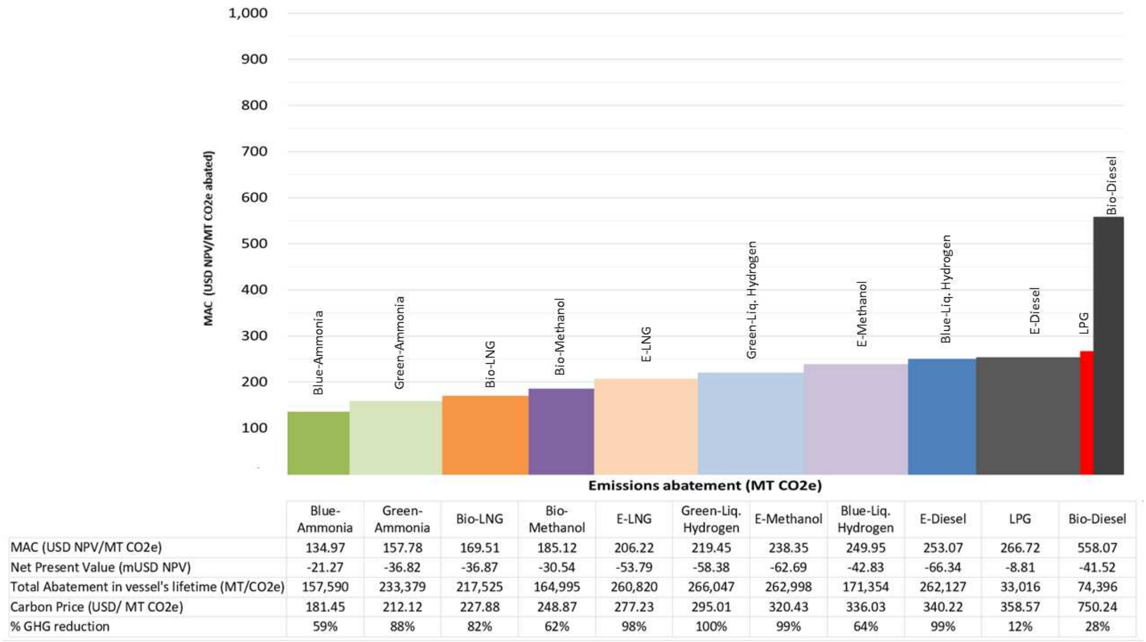
(b)

Figure 3 – *(a) MACCs of a retrofit of a 10-year-old Diesel ICE vessel in a high fuel price scenario. Upper bound based on 200 USD/kg of* CO_2 *cost of CCS and 100 USD/MWh cost of electricity* IEA (2019) *(b) As for (a) but over low fuel price scenario of 20 USD/MWh cost of electricity.*



	Bio-LNG	Green-Ammonia	Bio-Methanol	Bio-Diesel	LPG	Green-Liq. Hydrogen	Blue-Ammonia	E-LNG	Blue-Liq. Hydrogen	E-Methanol	E-Diesel
MAC (USD NPV/MT CO2e)	93.58	342.94	375.56	376.09	412.91	435.05	438.97	576.49	596.26	658.73	717.43
Net Present Value (mUSD NPV)	-20.36	-80.03	-61.97	-27.98	-13.63	-115.74	-69.18	-150.36	-102.17	-173.24	-188.06
Total Abatement in vessel's lifetime (MT/CO2e)	217,525	233,379	164,995	74,396	33,016	266,047	157,590	260,820	171,354	262,998	262,127
Carbon Price (USD/ MT CO2e)	125.80	461.03	504.89	505.60	555.10	584.86	590.14	775.01	801.59	885.56	964.48
% GHG reduction	82%	88%	62%	28%	12%	100%	59%	98%	64%	99%	99%

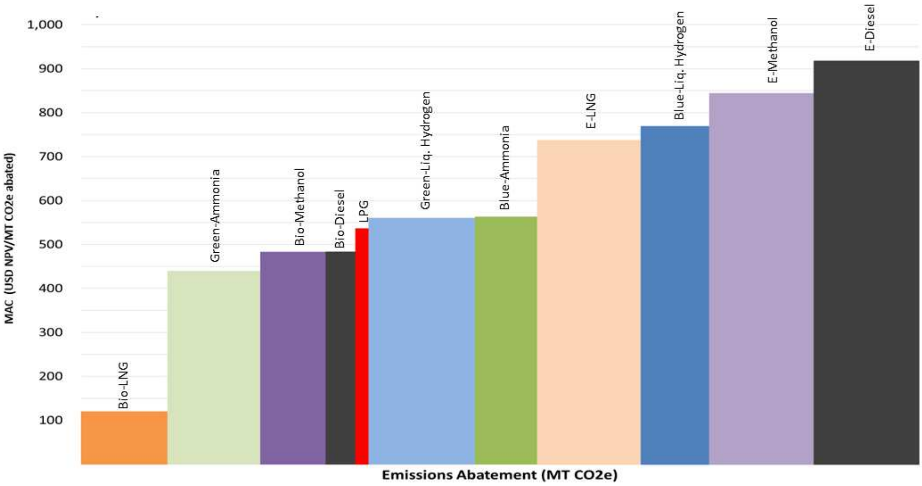
(a)



	Blue-Ammonia	Green-Ammonia	Bio-LNG	Bio-Methanol	E-LNG	Green-Liq. Hydrogen	E-Methanol	Blue-Liq. Hydrogen	E-Diesel	LPG	Bio-Diesel
MAC (USD NPV/MT CO2e)	134.97	157.78	169.51	185.12	206.22	219.45	238.35	249.95	253.07	266.72	558.07
Net Present Value (mUSD NPV)	-21.27	-36.82	-36.87	-30.54	-53.79	-58.38	-62.69	-42.83	-66.34	-8.81	-41.52
Total Abatement in vessel's lifetime (MT/CO2e)	157,590	233,379	217,525	164,995	260,820	266,047	262,998	171,354	262,127	33,016	74,396
Carbon Price (USD/ MT CO2e)	181.45	212.12	227.88	248.87	277.23	295.01	320.43	336.03	340.22	358.57	750.24
% GHG reduction	59%	88%	82%	62%	98%	100%	99%	64%	99%	12%	28%

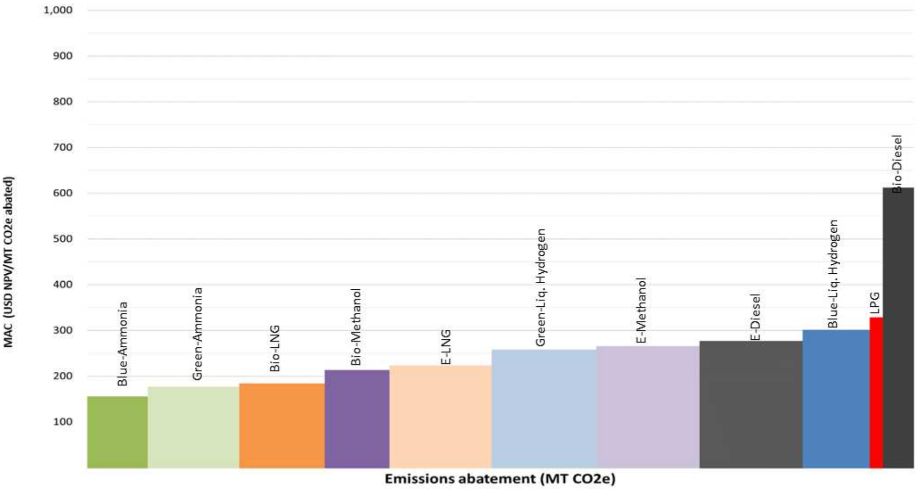
(b)

Figure 4 – *(a) MACCs of a retrofit of a 5-year-old LNG ICE vessel in a high fuel price scenario. Upper bound based on 200 USD/kg of CO_2 cost of CCS and 100 USD/MWh cost of electricity IEA (2019) (b) As for (a) but over low fuel price scenario of 20 USD/MWh cost of electricity.*



	Bio-LNG	Green-Ammonia	Bio-Methanol	Bio-Diesel	LPG	Green-Liq. Hydrogen	Blue-Ammonia	E-LNG	Blue-Liq. Hydrogen	E-Methanol	E-Diesel
MAC (USD NPV/MT CO2e)	119.52	439.24	482.44	483.08	536.05	559.98	562.49	736.32	768.28	843.08	917.10
Net Present Value (mUSD NPV)	-19.50	-76.88	-59.70	-26.95	-13.27	-111.74	-66.48	-144.04	-98.74	-166.30	-180.30
Total Abatement in vessel's lifetime (MT/CO2e)	163,143	175,034	123,746	55,797	24,762	199,535	118,192	195,615	128,515	197,249	196,595
Carbon Price (USD/ MT CO2e)	150.18	551.90	606.19	606.99	673.55	703.62	706.77	925.19	965.35	1,059.33	1,152.33
% GHG reduction	82%	88%	62%	28%	12%	100%	59%	98%	64%	99%	99%

(a)



	Blue-Ammonia	Green-Ammonia	Bio-LNG	Bio-Methanol	E-LNG	Green-Liq. Hydrogen	E-Methanol	E-Diesel	Blue-Liq. Hydrogen	LPG	Bio-Diesel
MAC (USD NPV/MT CO2e)	152.93	174.57	181.36	210.99	220.63	255.08	263.12	274.38	298.94	326.06	609.82
Net Present Value (mUSD NPV)	-18.08	-30.56	-29.59	-26.11	-43.16	-50.90	-51.90	-53.94	-38.42	-8.07	-34.03
Total Abatement in vessel's lifetime (MT/CO2e)	-20,058	118,192	175,034	163,143	123,746	195,615	199,535	197,249	196,595	128,515	24,762
Carbon Price (USD/ MT CO2e)	0.00	192.16	219.34	227.87	265.11	277.22	320.51	330.61	344.76	375.62	409.69
% GHG reduction	59%	88%	82%	62%	98%	100%	99%	99%	64%	12%	28%

(b)

Figure 5 – *(a) MACCs of a retrofit of a 10-year-old LNG ICE vessel in a high fuel price scenario. Upper bound based on 200 USD/kg of CO_2 cost of CCS and 100 USD/MWh cost of electricity IEA (2019) (b) As for (a) but over low fuel price scenario of 20 USD/MWh cost of electricity.*

Figures 4 and 5 contain our results for our Supramax bulk carrier case study that is built with a dual fuel LNG ICE running on a Diesel cycle. We highlight that in this analysis, LNG constitutes the baseline fuel, and due to the engine's dual fuel technology, calculations on retrofitting to Diesel are not examined. The model runs for two distinct vessel age stages and both high and low bounds of alternative fuel price expectancies. Figure 4a shows that in a high-price scenario, a switch to bio-LNG would require a carbon tax of 130 USD/MT CO_{2e} to become cost-effective slightly less than the carbon tax required for incentivizing the same fuel for an older vessel shown in Figure 5a. Green-Ammonia has higher MAC but larger emissions reductions potential. Overall, in high fuel price expectancy, it is mainly the $OPEX$ and the fuel's abatement potential that have the most significant effects on MACCs and only for investments in Hydrogen systems, the high initial capital outlay, has a greater influence on cost viability.

Figures 4b and 5b show that in a low fuel price expectancy scenario where investments in Ammonia ICE seem to become more financially appealing. There are only marginal changes on the fuels' MAC ranking accounting for their age at the time of the retrofit. Green-Liq. Hydrogen that can achieve 100% GHG emissions reduction can become cost-competitive with LNG after a carbon price of 300 USD/MT CO_{2e}.

6 Conclusions

This study focused on the developments of MACCs in order to rank the alternative marine fuels solutions according to their cost effectiveness and calculate the level of carbon pricing needed to close the price gap between alternative and conventional marine fuels. We first considered the capital costs arising from the installation onboard of the relevant power and fuel storage systems for facilitating the alternative fuels both for a newbuilding and a retrofit scenario. Second we estimated the operational costs from the utilization of these fuels during the vessel's lifetime including bunkering and opportunity costs. Our MACCs demonstrated our case study vessel in a newbuilding/design stage and in existing stage were the ship is built with either a Diesel or an LNG Dual Fuel ICE.

Our findings show that biofuels demonstrate high technical potentials for being used as zero-carbon bunker fuels as their future cost projections are relatively lower than their blue or green competitors. For newbuilding vessels, investments into bio-Methanol can achieve 65% of GHG emissions reductions and will become financially attractive after a carbon price of 50 USD/MT

CO_{2e}. However, ensuring their large-scale supply is likely to be constrained by the limited availability of biomass as well as the competing demands from other transportation sectors (The World Bank, 2021). To reach full maritime decarbonization fuels such as green liquid Hydrogen and their supporting technology would require a carbon price of 600 USD/MT CO_{2e} to become cost-competitive. With a projected levelized cost of electricity as low as 20 USD/MWh, investments in ammonia systems will become attractive for a carbon price of 150 USD/MT CO_{2e} and have significant emissions reductions potential.

For existing ships equipped with a Diesel ICE, investments into biofuels can be a promising solution in a high fuel price scenario, whereas in a low fuel price scenario the retrofitting costs to ammonia systems do not influence the resulting MAC significantly more than the operational costs and the abatement potential of the fuel in the denominator. Overall, the fuel choice will depend on its emissions abatement potential and the respective compliance with the regulations, which is the primary goal of retrofitting. For an existing vessel with a Dual Fuel LNG engine, retrofitting to ammonia seems to be a more profound solution regardless of the fuel price expectancy, mainly because ammonia shares some of the technical design specifications of LNG and requires fewer modifications during the retrofit. To incentivize the adoption of ammonia, a carbon price of 250 USD/MT CO_{2e} appears to be able to close the price gap with the baseline LNG power system. The results show that from a policy perspective, any choice on the level of carbon pricing should consider the average age of the global fleet at the time of enforcement and higher carbon levies are required for larger volumes of older vessels.

From a policy perspective, any choice on the level of carbon pricing in the case of a global fixed fuel levy regime should consider the average age of the global fleet at the time of enforcement. Early investments have greater potential for returns in a new building or retrofit case. As we have mentioned above, our results involve assumptions for fuel prices to capture the volatility of the bunker price and the uncertainty of the overall demand for these fuels.

Last but not least, and even though our study used a Supramax bulk carrier as a case study, the methodology can be applied to any ship type. Each ship has its distinct features and special constraints, thus one would expect the numerical values of the MACCs and required levies to differ across ship types. However, we conjecture that the main thrust of our results will remain the same as the one outlined in this study.

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A Appendix

Table 4 – *Alternative marine fuel production costs*

Alternative Fuel	Specifications			COST USD/ton								COST USD/MWh								Source
	kg/M^3	MJ/kg	MJ/M^3	2020		2030		2040		2050		2020		2030		2040		2050		
	Specific gravity	Grav. heat. value	Volum. heat. value	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High	
Grey Amm.	626	18.6	11644	250	250	250	250	250	250	250	250	48	48	48	48	48	48	48	48	Alfa Laval et al., 2020
Grey Amm.	626	18.6	11644	310	388	310	388	310	388	310	388	60	75	60	75	60	75	60	75	Kyprianidou et al., 2021
Grey Amm.	626	18.6	11644	290	1033	290	1033	290	1033	290	1033	56	200	56	200	56	200	56	200	Lindstad et al., 2021b
Grey Amm.	626	18.6	11644	400	400	372	372	351	351	330	330	77	77	72	72	68	68	64	64	Lloyd's Register& UMAS, 2020
Blue-Amm.	626	18.6	11644	350	400	350	400	350	400	350	400	68	77	68	77	68	77	68	77	Alfa Laval et al., 2020
Blue-Amm.	626	18.6	11644	484	502	446	465	465	428	409	428	94	97	86	90	90	83	79	83	MZCCa, 2021; MZCCc, 2021
Blue-Amm.	626	18.6	11644	553	553	467	467	414	414	373	373	107	107	90	90	80	80	72	72	Lloyd's Register& UMAS, 2020
Blue-Amm.	626	18.6	11644	521	856	484	800	446	744	428	707	101	166	94	155	86	144	83	137	Lloyd's Register& UMAS, 2020
Blue-Ammo.	626	18.6	11644	413	1137	413	1137	413	1137	413	1137	80	220	80	220	80	220	80	220	Ryste et al., 2019
Blue-Amm.	626	18.6	11644	1730	670	1730	670	1730	670	1730	670	335	130	335	130	335	130	335	130	Wang et al., 2021
Green-Amm.	626	18.6	11644	650	850	650	850	400	600	400	600	126	165	126	165	77	116	77	116	Alfa Laval et al., 2020
Green-Amm.	626	18.6	11644	911	1004	707	818	818	614	446	521	176	194	137	158	158	119	86	101	MZCCa, 2021; MZCCc, 2021
Green-Amm.	626	18.6	11644	409	1135	409	1135	409	1135	409	1135	79	220	79	220	79	220	79	220	IEA, 2020
Green-Amm.	626	18.6	11644	749	1085	568	930	465	723	310	620	145	210	110	180	90	140	60	120	Kyprianidou et al., 2021
Green-Amm.	626	18.6	11644	414	1135	414	1135	414	1135	414	1135	80	220	80	220	80	220	80	220	Lindstad et al., 2021b
Green-Amm.	626	18.6	11644	468	469	470	471	472	473	474	475	91	91	91	91	91	92	92	92	Lloyd's Register& UMAS, 2020
Green-Amm.	626	18.6	11644	1023	1786	874	1525	725	1265	558	1023	198	346	169	295	140	245	108	198	Lloyd's Register& UMAS, 2020
Green-Amm.	626	18.6	11644	775	1912	775	1912	775	1912	775	1912	150	370	150	370	150	370	150	370	Ryste et al., 2019
Green-Amm.	626	18.6	11644	391	688	391	688	391	688	391	688	76	133	76	133	76	133	76	133	Wang et al., 2021
BioDiesel	900	42.7	38430	769	1366	769	1366	769	1366	769	1366	65	115	65	115	65	115	65	115	IEA, 2020
BioDiesel	900	42.7	38430	1099	1519	1099	1519	1099	1519	1099	1519	93	128	93	128	93	128	93	128	Lindstad et al., 2021b
BioDiesel	900	42.7	38430	939	1068	1025	2092	1153	3160	1238	4185	79	90	86	176	97	266	104	353	Lloyd's Register& UMAS, 2020
BioDiesel	900	42.7	38430	555	1153	555	1153	555	1153	555	1153	47	97	47	97	47	97	47	97	Wang et al., 2021
BioDiesel	900	42.7	38430	830	1542	830	1542	830	1542	830	1542	70	130	70	130	70	130	70	130	Kyprianidou et al., 2021
BioDiesel	900	42.7	38430	1025	1623	598	598	598	598	555	598	86	137	50	50	50	50	47	50	MZCCa, 2021; MZCCc, 2021
BioDiesel	900	42.7	38430	2263	6704	1068	1068	1068	1068	1025	1068	191	565	90	90	90	90	86	90	MZCCa, 2021; MZCCc, 2021
BioDiesel	900	42.7	38430	598	726	470	470	470	470	512	512	50	61	40	40	40	40	43	43	MZCCa, 2021; MZCCc, 2021
BioDiesel	900	42.7	38430	1495	2050	939	939	939	982	982	982	126	173	79	79	79	83	83	83	MZCCa, 2021; MZCCc, 2021
BioFuelOil	991	40.2	39839	811	1025	811	1025	811	1025	811	1025	68	86	68	86	68	86	68	86	IEA, 2020
BioFuelOil	991	40.2	39839	1423	3084	1423	3084	1423	3084	1423	3084	120	260	120	260	120	260	120	260	Ryste et al., 2019
BioFuelOil	991	40.2	39839	939	1537	939	1537	939	1537	939	1537	79	130	79	130	79	130	79	130	IEA, 2020)
BioFuelOil	991	40.2	39839	1068	1661	1068	1661	1068	1661	1068	1661	90	140	90	140	90	140	90	140	Kyprianidou et al., 2021
BioLNG	450	50	22500	1200	1250	1050	1150	1150	1000	850	950	86	90	76	83	83	72	61	68	MZCCa, 2021; MZCCc, 2021
BioLNG	450	50	22500	300	614	112	614	112	614	112	614	22	119	22	119	22	119	22	119	IEA, 2020
BioLNG	450	50	22500	1234	1646	1234	1646	1234	1646	1234	1646	89	118	89	118	89	118	89	118	Lindstad et al., 2021b
BioLNG	450	50	22500	772	773	774	775	776	777	778	779	56	56	56	56	56	56	56	56	Lloyd's Register& UMAS, 2020
BioLNG	450	50	22500	1374	2986	1374	2986	1374	2986	1374	2986	99	215	99	215	99	215	99	215	Nelissen et al., 2020
BioLNG	450	50	22500	405	1600	405	1600	405	1600	405	1600	29	115	29	115	29	115	29	115	Wang et al., 2021
BioMeth.	791	19.5	15425	507	585	488	488	488	468	449	468	94	108	90	90	90	86	83	86	MZCCa, 2021; MZCCc, 2021
BioMeth.	791	19.5	15425	488	867	488	867	488	867	488	867	90	160	90	160	90	160	90	160	Kyprianidou et al., 2021
BioMeth.	791	19.5	15425	360	523	360	523	360	523	360	523	66	97	66	97	66	97	66	97	Lindstad et al., 2021b
BioMeth.	791	19.5	15425	561	561	416	416	324	324	252	252	104	47	35	35	27	27	21	21	Lloyd's Register& UMAS, 2020
BioMeth.	791	19.5	15425	449	449	449	449	449	449	449	449	83	83	83	83	83	83	83	83	Lloyd's Register& UMAS, 2020
BioMeth.	791	19.5	15425	488	650	488	650	488	650	488	650	90	120	90	120	90	120	90	120	Ryste et al., 2019
BioMeth.	791	19.5	15425	410	722	410	722	410	722	410	722	76	133	76	133	76	133	76	133	Wang et al., 2021
E-Diesel	900	42.7	38430	512	598	512	598	512	598	512	598	43	50	43	50	43	50	43	50	IEA, 2020
E-Diesel	900	42.7	38430	1549	5014	1549	5014	1549	5014	1549	5014	131	423	131	423	131	423	131	423	Lindstad et al., 2021b
E-Diesel	900	42.7	38430	5551	8882	4868	7771	4227	6661	3544	5551	468	749	410	655	356	562	299	468	Lloyd's Register& UMAS, 2020
E-Diesel	900	42.7	38430	3886	4782	2647	3203	3203	2220	1495	1836	328	403	223	270	270	187	126	155	MZCCa, 2021; MZCCc, 2021
E-Diesel	900	42.7	38430	3288	4057	2263	2733	2733	1879	1238	1537	277	342	191	230	230	158	104	130	MZCCa, 2021; MZCCc, 2021
E-LNG	450	50	22500	1601	4971	1601	4971	1601	4971	1601	4971	115	358	115	358	115	358	115	358	Lindstad et al., 2021b
E-LNG	450	50	22500	1707	1707	1059	1059	713	713	480	480	144	144	89	89	60	60	40	40	Lloyd's Register& UMAS, 2020
E-LNG	450	50	22500	3450	5650	3000	4900	2550	4200	2100	3450	248	407	216	353	184	302	151	248	Lloyd's Register& UMAS, 2020
E-LNG	450	50	22500	1659	6872	1659	6872	1659	6872	1659	6872	119	495	119	495	119	495	119	495	Nelissen et al., 2020
E-LNG	450	50	22500	3450	3900	2700	3100	3100	2400	1800	2050	248	281	194	223	223	173	130	148	MZCCa, 2021; MZCCc, 2021
E-LNG	450	50	22500	3000	3300	2400	2700	2700	2100	1600	1850	216	238	173	194	194	151	115	133	MZCCa, 2021; MZCCc, 2021
Blue-Liq.H_2	71	120	8520	5040	5160	4800	4920	4920	4800	4680	4680	151	155	144	148	148	144	140	140	MZCCa, 2021; MZCCc, 2021
Blue-Liq.H_2	71	120	8520	1848	7333	1848	7333	1848	7333	1848	7333	55	220	55	220	55	220	55	220	Lindstad et al., 2021b
Blue-Liq.H_2	71	120	8520	2670	2670	2276	2276	2276	2031	1837	1837	80	80	68	68	68	61	55	55	Lloyd's Register& UMAS, 2020
Blue-Liq.H_2	71	120	8520	3000	5280	2760	4800	2520	4440	2280	4080	90	158	83	144	76	133	68	122	Lloyd's Register& UMAS, 2020
Blue-Liq.H_2	71	120	8520	2333	13000	2333	13000	2333	13000	2333	13000	70	390	70	390	70	390	70	390	Ryste et al., 2019
Blue-Liq.H_2	71	120	8520	7560	4200	7560	4200	7560	4200	7560	4200	227	126	227	126	227	126	227	126	Wang et al., 2021
Grey-Liq.H_2	71	120	8520	2000	2000	1861	1861	1753	1753	1651	1651	60	60	56	56	53	53	50	50	Lloyd's Register& UMAS, 2020
Green-Liq.H_2	71	120	8520	7560	8040	6360	6960	6960	5880	4920	5280	227	241	191	209	209	176	148	158	MZCCa, 2021; MZCCc, 2021
Green-Liq.H_2	71	120	8520	2400	6600	2400	6600	2400	6600	2400	6600	72	198	72	198	72	198	72	198	IEA, 2020
Green-Liq.H_2	71	120	8520	2333	5000	1667	3667	1333	3500	1267	3267	70	150	50	110	40	105	38	98	Kyprianidou et al., 2021
Green-Liq.H_2	71	120	8520	2640	8161	2640	8161	2640	8161	2640	8161	79	245	79	245	79	245	79	245	Lindstad et al., 2021b
Green-Liq.H_2	71	120	8520	1831	1831	1196	1196	256	256	628	628	55	55	36	36	8	8	19	19	Lloyd's Register& UMAS, 2020
Green-Liq.H_2	71	120	8520	1622	1622	1067	1067	769	769	570	570	49	49	32	32	23	23	17	17	Lloyd's Register& UMAS, 2020)
Green-Liq.H_2	71	120	8520	6240	11040	5280	9480	4320	7800	3360	6240	187	331	158	284	130	234	101	187	Lloyd's Register& UMAS, 2020
Green-Liq.H_2	71	120	8520	3667	16667	3667	16667	3667	16667	3667	16667	110	500	110	500	110	500	110	500	Ryste et al., 2019
Green-Liq.H_2	71	120	8520	3000	9600	3000	9600	3000	9600	3000	9600	90	288	90	288	90	288	90	288	Wang et al., 2021
Green-Liq.H_2	71	120	8520	2280	5400	2280	5400	2280	5400	2280	5400	68	162	68	162	68	162	68	162	Wang et al., 2021
HFO	944	41.6	39270	600	1440	600	1440	600	1440	600	1440	18	43	18	43	18	43	18	43	IEA, 2020
LPG	537	45.5	24435	497	1243	497	1243	497	1243	497	1243	39	98	39	98	39	98	39	98	Lindstad et al., 2021b
LPG	537	45.5	24435	506	1264	506	1264	506	1264	506	1264	40	100	40	100	40	100	40	100	Ryste et al., 2019
LPG	537	45.5	24435	410	455	364	364	364	364	364	364	32	36	29	29	29	29	29	29	MZCCa, 2021; MZCCc, 2021
LNG	450	50	22500	450	450	450	450	450	450	500	450	32	32	32	32	32	32	36	32	MZCCa, 2021; MZCCc, 2021
LNG	450	50	22500	100	550	100	550	100	550	100	550	7	40	7	40	7	40	7	40	IEA, 2020
LNG	450	50	22500	450	1125	450	1125	450	1125	450	1125	32	81	32	81	32	81	32	81	Lindstad et al., 2021b
LNG	450	50	22500	350	350	350	350	350	350	350	350	25	25	38	38	25	25	25	25	Lloyd's Register& UMAS, 2020
LNG	450	50	22500	663	853	663	853	663	853	663	853	48	61	48	61	48	61	48	61	Nelissen et al., 2020
LNG	450	50	22500	833	2639	833	2639	833	2639	833	2639	60	190	60	190	60	190	60	190	Ryste et al., 2019
LNG	450	50	22500	110	460	460	460	110	460	110	460	8	33	33	33	8	33	8	33	Wang et al., 2021
Grey-Meth.	791	19.5	15425	325	460	325	460	325	460	325	460	60	85	60	85	60	85	60	85	Kyprianidou et al., 2021
Grey-Meth.	791	19.5	15425	488	1136	488	1136	488	1136	488	1136	90	210	90	210	90	210	90	210	Lindstad et al., 2021b
Grey-Meth.	791	19.5	15425	117	429	117	429	117	429	117	429	22	79	22	79	22	79	22	79	Wang et al., 2021
E-Meth.	791	19.5	15425	813	1571	758	1300	650	1029	596	813	150	290	140	240	120	190	110	150	Kyprianidou et al., 2021
E-Meth.	791	19.5	15425	627	2085	627	2085	627	2085	627	2085	116	385	116	385	116	385	116	385	Lindstad et al., 2021b
E-Meth.	791	19.5	15425	742	742	466	466	318	318	219	219	137	137	86	86	59	59	40	40	Lloyd's Register& UMAS, 2020
E-Meth.	791	19.5	15425	1638	2652	1424	2301	1229	1970	1014	1619	302	490	263	425	227	364	187	299	Lloyd's Register& UMAS, 2020
E-Meth.	791	19.5	15425	1385	1560	1073	1229	1229	917	663	780	256	288	198	227	227	169	122	144	MZCCa, 2021; MZCCc, 2021
E-Meth.	791	19.5	15425	2950	3300	2350	2650	2650	2000	1450	1750	212	238	169	191	191	144	104	126	MZCCa, 2021; MZCCc, 2021
VLSFO	944	41.6	39271	500	600	500	600	500	600	500	600	92	111	92	111	92	111	92	111	Alfa Laval et al., 2020
VLSFO	944	41.6	39271	458	541	458	458	458	458	458	458	40	47	40	40	40	40	40	40	MZCCa, 2021; MZCCc, 2021
VLSFO	944	41.6	39271	333	499	333	499	333	499	333	499	29	43	29	43	29	43	29	43	IEA, 2020
VLSFO	944	41.6	39271	438	1093	438	1093	438	1093	438	1093	38	95	38	95	38	95	38	95	Lindstad et al., 2021b
VLSFO	944	41.6	39271	333	333	458	458	458	458	458	458	29	29	40	40	40	40	40	40	Lloyd's Register& UMAS, 2020
VLSFO	944	41.6	39271	749	986	749	986	749	986	749	986	65	85	65	85	65	85	65	85	Nelissen et al., 2020
VLSFO	944	41.6	39271	437.68	1093	438	10938	438	10938	438	1093	38	95	38	95	38	95	38	95	Lindstad et al., 2021b
VLSFO	944	41.6	39270	333	333	458	458	458	458	458	458	29	29	40	40	40	40	40	40	Lloyd's Register& UMAS, 2020
VLSFO	944	41.6	39270	750	986	750	9868	749	986	750	986	65	85	65	85	65	85	65	85	Nelissen et al., 2020

Appendix C: previous PhD theses published at the Department of Marine Technology

Previous PhD theses published at the Department of Marine Technology
(earlier: Faculty of Marine Technology)
NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Report No.	Author	Title
	Kavlie, Dag	Optimization of Plane Elastic Grillages, 1967
	Hansen, Hans R.	Man-Machine Communication and Data-Storage Methods in Ship Structural Design, 1971
	Gisvold, Kaare M.	A Method for non-linear mixed -integer programming and its Application to Design Problems, 1971
	Lund, Sverre	Tanker Frame Optimalization by means of SUMT-Transformation and Behaviour Models, 1971
	Vinje, Tor	On Vibration of Spherical Shells Interacting with Fluid, 1972
	Lorentz, Jan D.	Tank Arrangement for Crude Oil Carriers in Accordance with the new Anti-Pollution Regulations, 1975
	Carlsen, Carl A.	Computer-Aided Design of Tanker Structures, 1975
	Larsen, Carl M.	Static and Dynamic Analysis of Offshore Pipelines during Installation, 1976
UR-79-01	Brigt Hatlestad, MK	The finite element method used in a fatigue evaluation of fixed offshore platforms. (Dr.Ing. Thesis)
UR-79-02	Erik Pettersen, MK	Analysis and design of cellular structures. (Dr.Ing. Thesis)
UR-79-03	Sverre Valsgård, MK	Finite difference and finite element methods applied to nonlinear analysis of plated structures. (Dr.Ing. Thesis)
UR-79-04	Nils T. Nordsve, MK	Finite element collapse analysis of structural members considering imperfections and stresses due to fabrication. (Dr.Ing. Thesis)
UR-79-05	Ivar J. Fylling, MK	Analysis of towline forces in ocean towing systems. (Dr.Ing. Thesis)
UR-79- x	Finn Gunnar Nielsen, MH	Hydrodynamic problems related to oil barriers for offshore application
UR-80-06	Nils Sandsmark, MM	Analysis of Stationary and Transient Heat Conduction by the Use of the Finite Element Method. (Dr.Ing. Thesis)
UR-80-09	Sverre Haver, MK	Analysis of uncertainties related to the stochastic modeling of ocean waves. (Dr.Ing. Thesis)

UR-81-15	Odland, Jonas	On the Strength of welded Ring stiffened cylindrical Shells primarily subjected to axial Compression
UR-82-17	Engesvik, Knut	Analysis of Uncertainties in the fatigue Capacity of Welded Joints
UR-82-18	Rye, Henrik	Ocean wave groups
UR-83-30	Eide, Oddvar Inge	On Cumulative Fatigue Damage in Steel Welded Joints
UR-83-33	Mo, Olav	Stochastic Time Domain Analysis of Slender Offshore Structures
UR-83-34	Amdahl, Jørgen	Energy absorption in Ship-platform impacts
UR-84-37	Mørch, Morten	Motions and mooring forces of semi submersibles as determined by full-scale measurements and theoretical analysis
UR-84-38	Soares, C. Guedes	Probabilistic models for load effects in ship structures
UR-84-39	Aarsnes, Jan V.	Current forces on ships
UR-84-40	Czujko, Jerzy	Collapse Analysis of Plates subjected to Biaxial Compression and Lateral Load
UR-85-46	Alf G. Engseth, MK	Finite element collapse analysis of tubular steel offshore structures. (Dr.Ing. Thesis)
UR-86-47	Dengody Sheshappa, MP	A Computer Design Model for Optimizing Fishing Vessel Designs Based on Techno-Economic Analysis. (Dr.Ing. Thesis)
UR-86-48	Vidar Aanesland, MH	A Theoretical and Numerical Study of Ship Wave Resistance. (Dr.Ing. Thesis)
UR-86-49	Heinz-Joachim Wessel, MK	Fracture Mechanics Analysis of Crack Growth in Plate Girders. (Dr.Ing. Thesis)
UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)
UR-86-51	Walter Lian, MH	A Numerical Study of Two-Dimensional Separated Flow Past Bluff Bodies at Moderate KC-Numbers. (Dr.Ing. Thesis)
UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)
UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)
UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)
UR-86-55	Sigurd Falch, MH	A Numerical Study of Slamming of Two-

		Dimensional Bodies. (Dr.Ing. Thesis)
UR-87-56	Arne Braathen, MH	Application of a Vortex Tracking Method to the Prediction of Roll Damping of a Two-Dimension Floating Body. (Dr.Ing. Thesis)
UR-87-57	Bernt Leira, MK	Gaussian Vector Processes for Reliability Analysis involving Wave-Induced Load Effects. (Dr.Ing. Thesis)
UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
MTA-88-59	Bernt Arild Bremdal, MP	An Investigation of Marine Installation Processes – A Knowledge - Based Planning Approach. (Dr.Ing. Thesis)
MTA-88-60	Xu Jun, MK	Non-linear Dynamic Analysis of Space-framed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
MTA-89-63	Chang Li, MH	Force Coefficients of Spheres and Cubes in Oscillatory Flow with and without Current. (Dr.Ing. Thesis
MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
MTA-89-65	Arild Jæger, MH	Seakeeping, Dynamic Stability and Performance of a Wedge Shaped Planing Hull. (Dr.Ing. Thesis)
MTA-89-66	Chan Siu Hung, MM	The dynamic characteristics of tilting-pad bearings
MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
MTA-89-68	Jiao Guoyang, MK	Reliability Analysis of Crack Growth under Random Loading, considering Model Updating. (Dr.Ing. Thesis)
MTA-89-69	Arnt Olufsen, MK	Uncertainty and Reliability Analysis of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-70	Wu Yu-Lin, MR	System Reliability Analyses of Offshore Structures using improved Truss and Beam Models. (Dr.Ing. Thesis)
MTA-90-71	Jan Roger Hoff, MH	Three-dimensional Green function of a vessel with forward speed in waves. (Dr.Ing. Thesis)
MTA-90-72	Rong Zhao, MH	Slow-Drift Motions of a Moored Two-Dimensional Body in Irregular Waves. (Dr.Ing. Thesis)
MTA-90-73	Atle Minsaas, MP	Economical Risk Analysis. (Dr.Ing. Thesis)

MTA-90-74	Knut-Aril Farnes, MK	Long-term Statistics of Response in Non-linear Marine Structures. (Dr.Ing. Thesis)
MTA-90-75	Torbjørn Sotberg, MK	Application of Reliability Methods for Safety Assessment of Submarine Pipelines. (Dr.Ing. Thesis)
MTA-90-76	Zeuthen, Steffen, MP	SEAMAID. A computational model of the design process in a constraint-based logic programming environment. An example from the offshore domain. (Dr.Ing. Thesis)
MTA-91-77	Haagensen, Sven, MM	Fuel Dependant Cyclic Variability in a Spark Ignition Engine - An Optical Approach. (Dr.Ing. Thesis)
MTA-91-78	Løland, Geir, MH	Current forces on and flow through fish farms. (Dr.Ing. Thesis)
MTA-91-79	Hoen, Christopher, MK	System Identification of Structures Excited by Stochastic Load Processes. (Dr.Ing. Thesis)
MTA-91-80	Haugen, Stein, MK	Probabilistic Evaluation of Frequency of Collision between Ships and Offshore Platforms. (Dr.Ing. Thesis)
MTA-91-81	Sødahl, Nils, MK	Methods for Design and Analysis of Flexible Risers. (Dr.Ing. Thesis)
MTA-91-82	Ormberg, Harald, MK	Non-linear Response Analysis of Floating Fish Farm Systems. (Dr.Ing. Thesis)
MTA-91-83	Marley, Mark J., MK	Time Variant Reliability under Fatigue Degradation. (Dr.Ing. Thesis)
MTA-91-84	Krokstad, Jørgen R., MH	Second-order Loads in Multidirectional Seas. (Dr.Ing. Thesis)
MTA-91-85	Molteberg, Gunnar A., MM	The Application of System Identification Techniques to Performance Monitoring of Four Stroke Turbocharged Diesel Engines. (Dr.Ing. Thesis)
MTA-92-86	Mørch, Hans Jørgen Bjelke, MH	Aspects of Hydrofoil Design: with Emphasis on Hydrofoil Interaction in Calm Water. (Dr.Ing. Thesis)
MTA-92-87	Chan Siu Hung, MM	Nonlinear Analysis of Rotordynamic Instabilities in Highspeed Turbomachinery. (Dr.Ing. Thesis)
MTA-92-88	Bessason, Bjarni, MK	Assessment of Earthquake Loading and Response of Seismically Isolated Bridges. (Dr.Ing. Thesis)
MTA-92-89	Langli, Geir, MP	Improving Operational Safety through exploitation of Design Knowledge - an investigation of offshore platform safety. (Dr.Ing. Thesis)
MTA-92-90	Sævik, Svein, MK	On Stresses and Fatigue in Flexible Pipes. (Dr.Ing. Thesis)
MTA-92-91	Ask, Tor Ø., MM	Ignition and Flame Growth in Lean Gas-Air Mixtures. An Experimental Study with a Schlieren

		System. (Dr.Ing. Thesis)
MTA-86-92	Hessen, Gunnar, MK	Fracture Mechanics Analysis of Stiffened Tubular Members. (Dr.Ing. Thesis)
MTA-93-93	Steinebach, Christian, MM	Knowledge Based Systems for Diagnosis of Rotating Machinery. (Dr.Ing. Thesis)
MTA-93-94	Dalane, Jan Inge, MK	System Reliability in Design and Maintenance of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-93-95	Steen, Sverre, MH	Cobblestone Effect on SES. (Dr.Ing. Thesis)
MTA-93-96	Karunakaran, Daniel, MK	Nonlinear Dynamic Response and Reliability Analysis of Drag-dominated Offshore Platforms. (Dr.Ing. Thesis)
MTA-93-97	Hagen, Arnulf, MP	The Framework of a Design Process Language. (Dr.Ing. Thesis)
MTA-93-98	Nordrik, Rune, MM	Investigation of Spark Ignition and Autoignition in Methane and Air Using Computational Fluid Dynamics and Chemical Reaction Kinetics. A Numerical Study of Ignition Processes in Internal Combustion Engines. (Dr.Ing. Thesis)
MTA-94-99	Passano, Elizabeth, MK	Efficient Analysis of Nonlinear Slender Marine Structures. (Dr.Ing. Thesis)
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		(Dr.Ing. Thesis)
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IMT-15-2015	Anirban Bhattacharyya	Ducted Propellers: Behaviour in Waves and Scale Effects, IMT
IMT-16-2015	Qin Zhang	Image Processing for Ice Parameter Identification in Ice Management, IMT
IMT-1-2016	Vincentius Rumawas	Human Factors in Ship Design and Operation: An Experiential Learning, IMT
IMT-2-2016	Martin Storheim	Structural response in ship-platform and ship-ice collisions, IMT
IMT-3-2016	Mia Abrahamsen Prsic	Numerical Simulations of the Flow around single and Tandem Circular Cylinders Close to a Plane Wall, IMT
IMT-4-2016	Tufan Arslan	Large-eddy simulations of cross-flow around ship sections, IMT

IMT-5-2016	Pierre Yves-Henry	Parametrisation of aquatic vegetation in hydraulic and coastal research,IMT
IMT-6-2016	Lin Li	Dynamic Analysis of the Instalation of Monopiles for Offshore Wind Turbines, CeSOS
IMT-7-2016	Øivind Kåre Kjerstad	Dynamic Positioning of Marine Vessels in Ice, IMT
IMT-8-2016	Xiaopeng Wu	Numerical Analysis of Anchor Handling and Fish Trawling Operations in a Safety Perspective, CeSOS
IMT-9-2016	Zhengshun Cheng	Integrated Dynamic Analysis of Floating Vertical Axis Wind Turbines, CeSOS
IMT-10-2016	Ling Wan	Experimental and Numerical Study of a Combined Offshore Wind and Wave Energy Converter Concept
IMT-11-2016	Wei Chai	Stochastic dynamic analysis and reliability evaluation of the roll motion for ships in random seas, CeSOS
IMT-12-2016	Øyvind Selnes Patricksson	Decision support for conceptual ship design with focus on a changing life cycle and future uncertainty, IMT
IMT-13-2016	Mats Jørgen Thorsen	Time domain analysis of vortex-induced vibrations, IMT
IMT-14-2016	Edgar McGuinness	Safety in the Norwegian Fishing Fleet – Analysis and measures for improvement, IMT
IMT-15-2016	Sepideh Jafarzadeh	Energy effiency and emission abatement in the fishing fleet, IMT
IMT-16-2016	Wilson Ivan Guachamin Acero	Assessment of marine operations for offshore wind turbine installation with emphasis on response-based operational limits, IMT
IMT-17-2016	Mauro Candeloro	Tools and Methods for Autonomous Operations on Seabed and Water Coumn using Underwater Vehicles, IMT
IMT-18-2016	Valentin Chabaud	Real-Time Hybrid Model Testing of Floating Wind Tubines, IMT
IMT-1-2017	Mohammad Saud Afzal	Three-dimensional streaming in a sea bed boundary layer
IMT-2-2017	Peng Li	A Theoretical and Experimental Study of Wave-induced Hydroelastic Response of a Circular Floating Collar
IMT-3-2017	Martin Bergström	A simulation-based design method for arctic maritime transport systems

IMT-4-2017	Bhushan Taskar	The effect of waves on marine propellers and propulsion
IMT-5-2017	Mohsen Bardestani	A two-dimensional numerical and experimental study of a floater with net and sinker tube in waves and current
IMT-6-2017	Fatemeh Hoseini Dadmarzi	Direct Numerical Simualtion of turbulent wakes behind different plate configurations
IMT-7-2017	Michel R. Miyazaki	Modeling and control of hybrid marine power plants
IMT-8-2017	Giri Rajasekhar Gunnu	Safety and effiency enhancement of anchor handling operations with particular emphasis on the stability of anchor handling vessels
IMT-9-2017	Kevin Koosup Yum	Transient Performance and Emissions of a Turbocharged Diesel Engine for Marine Power Plants
IMT-10-2017	Zhaolong Yu	Hydrodynamic and structural aspects of ship collisions
IMT-11-2017	Martin Hassel	Risk Analysis and Modelling of Allisions between Passing Vessels and Offshore Installations
IMT-12-2017	Astrid H. Brodtkorb	Hybrid Control of Marine Vessels – Dynamic Positioning in Varying Conditions
IMT-13-2017	Kjersti Bruserud	Simultaneous stochastic model of waves and current for prediction of structural design loads
IMT-14-2017	Finn-Idar Grøtta Giske	Long-Term Extreme Response Analysis of Marine Structures Using Inverse Reliability Methods
IMT-15-2017	Stian Skjong	Modeling and Simulation of Maritime Systems and Operations for Virtual Prototyping using co-Simulations
IMT-1-2018	Yingguang Chu	Virtual Prototyping for Marine Crane Design and Operations
IMT-2-2018	Sergey Gavrilin	Validation of ship manoeuvring simulation models
IMT-3-2018	Jeevith Hegde	Tools and methods to manage risk in autonomous subsea inspection,maintenance and repair operations
IMT-4-2018	Ida M. Strand	Sea Loads on Closed Flexible Fish Cages
IMT-5-2018	Erlend Kvinge Jørgensen	Navigation and Control of Underwater Robotic Vehicles

IMT-6-2018	Bård Stovner	Aided Intertial Navigation of Underwater Vehicles
IMT-7-2018	Erlend Liavåg Grotle	Thermodynamic Response Enhanced by Sloshing in Marine LNG Fuel Tanks
IMT-8-2018	Børge Rokseth	Safety and Verification of Advanced Maritime Vessels
IMT-9-2018	Jan Vidar Ulveseter	Advances in Semi-Empirical Time Domain Modelling of Vortex-Induced Vibrations
IMT-10-2018	Chenyu Luan	Design and analysis for a steel braceless semi-submersible hull for supporting a 5-MW horizontal axis wind turbine
IMT-11-2018	Carl Fredrik Rehn	Ship Design under Uncertainty
IMT-12-2018	Øyvind Ødegård	Towards Autonomous Operations and Systems in Marine Archaeology
IMT-13-2018	Stein Melvær Nornes	Guidance and Control of Marine Robotics for Ocean Mapping and Monitoring
IMT-14-2018	Petter Norgren	Autonomous Underwater Vehicles in Arctic Marine Operations: Arctic marine research and ice monitoring
IMT-15-2018	Minjoo Choi	Modular Adaptable Ship Design for Handling Uncertainty in the Future Operating Context
MT-16-2018	Ole Alexander Eidsvik	Dynamics of Remotely Operated Underwater Vehicle Systems
IMT-17-2018	Mahdi Ghane	Fault Diagnosis of Floating Wind Turbine Drivetrain- Methodologies and Applications
IMT-18-2018	Christoph Alexander Thieme	Risk Analysis and Modelling of Autonomous Marine Systems
IMT-19-2018	Yugao Shen	Operational limits for floating-collar fish farms in waves and current, without and with well-boat presence
IMT-20-2018	Tianjiao Dai	Investigations of Shear Interaction and Stresses in Flexible Pipes and Umbilicals
IMT-21-2018	Sigurd Solheim Pettersen	Resilience by Latent Capabilities in Marine Systems
IMT-22-2018	Thomas Sauder	Fidelity of Cyber-physical Empirical Methods. Application to the Active Truncation of Slender Marine Structures
IMT-23-2018	Jan-Tore Horn	Statistical and Modelling Uncertainties in the Design of Offshore Wind Turbines

IMT-24-2018	Anna Swider	Data Mining Methods for the Analysis of Power Systems of Vessels
IMT-1-2019	Zhao He	Hydrodynamic study of a moored fish farming cage with fish influence
IMT-2-2019	Isar Ghamari	Numerical and Experimental Study on the Ship Parametric Roll Resonance and the Effect of Anti-Roll Tank
IMT-3-2019	Håkon Strandenes	Turbulent Flow Simulations at Higher Reynolds Numbers
IMT-4-2019	Siri Mariane Holen	Safety in Norwegian Fish Farming – Concepts and Methods for Improvement
IMT-5-2019	Ping Fu	Reliability Analysis of Wake-Induced Riser Collision
IMT-6-2019	Vladimir Krivopolianskii	Experimental Investigation of Injection and Combustion Processes in Marine Gas Engines using Constant Volume Rig
IMT-7-2019	Anna Maria Kozlowska	Hydrodynamic Loads on Marine Propellers Subject to Ventilation and out of Water Condition.
IMT-8-2019	Hans-Martin Heyn	Motion Sensing on Vessels Operating in Sea Ice: A Local Ice Monitoring System for Transit and Stationkeeping Operations under the Influence of Sea Ice
IMT-9-2019|	Stefan Vilsen	Method for Real-Time Hybrid Model Testing of Ocean Structures – Case on Slender Marine Systems
IMT-10-2019	Finn-Christian W. Hanssen	Non-Linear Wave-Body Interaction in Severe Waves
IMT-11-2019	Trygve Olav Fossum	Adaptive Sampling for Marine Robotics
IMT-12-2019	Jørgen Bremnes Nielsen	Modeling and Simulation for Design Evaluation
IMT-13-2019	Yuna Zhao	Numerical modelling and dyncamic analysis of offshore wind turbine blade installation
IMT-14-2019	Daniela Myland	Experimental and Theoretical Investigations on the Ship Resistance in Level Ice
IMT-15-2019	Zhengru Ren	Advanced control algorithms to support automated offshore wind turbine installation
IMT-16-2019	Drazen Polic	Ice-propeller impact analysis using an inverse propulsion machinery simulation approach
IMT-17-2019	Endre Sandvik	Sea passage scenario simulation for ship system performance evaluation

IMT-18-2019	Loup Suja-Thauvin	Response of Monopile Wind Turbines to Higher Order Wave Loads
IMT-19-2019	Emil Smilden	Structural control of offshore wind turbines – Increasing the role of control design in offshore wind farm development
IMT-20-2019	Aleksandar-Sasa Milakovic	On equivalent ice thickness and machine learning in ship ice transit simulations
IMT-1-2020	Amrit Shankar Verma	Modelling, Analysis and Response-based Operability Assessment of Offshore Wind Turbine Blade Installation with Emphasis on Impact Damages
IMT-2-2020	Bent Oddvar Arnesen Haugaløkken	Autonomous Technology for Inspection, Maintenance and Repair Operations in the Norwegian Aquaculture
IMT-3-2020	Seongpil Cho	Model-based fault detection and diagnosis of a blade pitch system in floating wind turbines
IMT-4-2020	Jose Jorge Garcia Agis	Effectiveness in Decision-Making in Ship Design under Uncertainty
IMT-5-2020	Thomas H. Viuff	Uncertainty Assessment of Wave-and Current-induced Global Response of Floating Bridges
IMT-6-2020	Fredrik Mentzoni	Hydrodynamic Loads on Complex Structures in the Wave Zone
IMT-7-2020	Senthuran Ravinthrakumar	Numerical and Experimental Studies of Resonant Flow in Moonpools in Operational Conditions
IMT-8-2020	Stian Skaalvik Sandøy	Acoustic-based Probabilistic Localization and Mapping using Unmanned Underwater Vehicles for Aquaculture Operations
IMT-9-2020	Kun Xu	Design and Analysis of Mooring System for Semi-submersible Floating Wind Turbine in Shallow Water
IMT-10-2020	Jianxun Zhu	Cavity Flows and Wake Behind an Elliptic Cylinder Translating Above the Wall
IMT-11-2020	Sandra Hogenboom	Decision-making within Dynamic Positioning Operations in the Offshore Industry – A Human Factors based Approach
IMT-12-2020	Woongshik Nam	Structural Resistance of Ship and Offshore Structures Exposed to the Risk of Brittle Failure
IMT-13-2020	Svenn Are Tutturen Værnø	Transient Performance in Dynamic Positioning of Ships: Investigation of Residual Load Models and Control Methods for Effective Compensation
IMT-14-2020	Mohd Atif Siddiqui	Experimental and Numerical Hydrodynamic Analysis of a Damaged Ship in Waves
IMT-15-2020	John Marius Hegseth	Efficient Modelling and Design Optimization of Large Floating Wind Turbines

IMT-16-2020	Asle Natskår	Reliability-based Assessment of Marine Operations with Emphasis on Sea Transport on Barges
IMT-17-2020	Shi Deng	Experimental and Numerical Study of Hydrodynamic Responses of a Twin-Tube Submerged Floating Tunnel Considering Vortex-Induced Vibration
IMT-18-2020	Jone Torsvik	Dynamic Analysis in Design and Operation of Large Floating Offshore Wind Turbine Drivetrains
IMT-1-2021	Ali Ebrahimi	Handling Complexity to Improve Ship Design Competitiveness
IMT-2-2021	Davide Proserpio	Isogeometric Phase-Field Methods for Modeling Fracture in Shell Structures
IMT-3-2021	Cai Tian	Numerical Studies of Viscous Flow Around Step Cylinders
IMT-4-2021	Farid Khazaeli Moghadam	Vibration-based Condition Monitoring of Large Offshore Wind Turbines in a Digital Twin Perspective
IMT-5-2021	Shuaishuai Wang	Design and Dynamic Analysis of a 10-MW Medium-Speed Drivetrain in Offshore Wind Turbines
IMT-6-2021	Sadi Tavakoli	Ship Propulsion Dynamics and Emissions
IMT-7-2021	Haoran Li	Nonlinear wave loads, and resulting global response statistics of a semi-submersible wind turbine platform with heave plates
IMT-8-2021	Einar Skiftestad Ueland	Load Control for Real-Time Hybrid Model Testing using Cable-Driven Parallel Robots
IMT-9-2021	Mengning Wu	Uncertainty of machine learning-based methods for wave forecast and its effect on installation of offshore wind turbines
IMT-10-2021	Xu Han	Onboard Tuning and Uncertainty Estimation of Vessel Seakeeping Model Parameters
IMT-01-2022	Ingunn Marie Holmen	Safety in Exposed Aquacultrue Operations
IMT-02-2022	Prateek Gupta	Ship Performance Monitoring using In-service Measurements and Big Data Analysis Methods
IMT-03-2022	Sangwoo Kim	Non-linear time domain analysis of deepwater riser vortex-induced vibrations
IMT-04-2022	Jarle Vinje Kramer	Hydrodynamic Aspects of Sail-Assisted Merchant Vessels
IMT-05-2022	Øyvind Rabliås	Numerical and Expermental Studies of Maneuvering in Regular and Irregular Waves

IMT-06-2022	Pramod Ghimire	Simulation-Based Ship Hybrid Power System Conspet Studies and Performance Analyses
IMT-07-2022	Carlos Eduardo Silva de Souza	Structural modelling, coupled dynamics, and design of large floating wind turbines
IMT-08-2022	Lorenzo Balestra	Design of hybrid fuel cell & battery systems for maritime vessels
IMT-09-2022	Sharmin Sultana	Process safety and risk management using system perspectives – A contribution to the chemical process and petroleum industry
IMT-10-2022	Øystein Sture	Autonomous Exploration for Marine Minerals
IMT-11-2022	Tiantian Zhu	Information and Decision-making for Major Accident Prevention – A concept of information-based strategies for accident prevention
IMT-12-2022	Siamak Karimi	Shore-to-Ship Charging Systems for Battery-Electric Ships
IMT-01-2023	Huili Xu	Fish-inspired Propulsion Study: Numerical Hydrodynamics of Rigid/Flexible/Morphing Foils and Observations on Real Fish
IMT-02-2023	Chana Sinsabvarodom	Probabilistic Modelling of Ice-drift and Ice Loading on Fixed and Floating Offshore Structures
IMT-03-2023	Martin Skaldebø	Intelligent low-cost solutions for underwater intervention using computer vision and machine learning
IMT-04-2023	Hans Tobias Slette	Vessel operations in exposed aquaculture – Achieving safe and efficient operation of vessel fleets in fish farm systems experiencing challenging metocean conditions
IMT-05-2023	Ruochen Yang	Methods and models for analyzing and controlling the safety in operations of autonomous marine systems
IMT-06-2023	Tobias Rye Torben	Formal Approaches to Design and Verification of Safe Control Systems for Autonomous Vessels
IMT-07-2023	YoungRong Kim	Modeling Operational Performance for the Global Fleet & Application of an Energy Saving Measure
IMT-08-2023	Henrik Schmidt-Didlaukies	Modeling and Hybrid Feedback Control of Underwater Vehicles
IMT-09-2023	Ehsan Esmailian	Optimal Ship Design for Operating in Real Sea States
IMT-10-2023	Astrid Vamråk Solheim	Exploring the performance of conceptual offshore production systems for deep-sea mining
IMT-11-2023	Benjamin Lagemann	Conceptual design of low-emission ships