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Carl Fredrik Rehn

Ship Design under Uncertainty

Doctoral Thesis

NTNU
Norwegian University of
Science and Technology
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Department of MarineTechnology

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Abstract

The purpose of this thesis is to develop knowledge to design better ships. More specifically, it concerns the development and application of effective methods and models for handling future contextual uncertainty in the early design stages. Furthermore, it investigates whether changeability in design can improve profitability by reducing risks and enabling upside opportunities. Changeability is the ability of a system to change form, function, or operation, and is a collective term for change-related system properties such as flexibility, adaptability, and agility.

The work is motivated by three general characteristics of the maritime industry: high market uncertainty, capital-intensive projects, and long project time horizons. The thesis uses the design of an offshore construction vessel as a primary case.

The thesis systematically addresses four research objectives (RO):

RO1 Develop models that effectively capture relevant aspects of the future uncertain operating context.
RO2 Define and quantify the level of changeability for a system.
RO3 Develop an understanding of technical tradeoffs for the realization of changeable ship design solutions.
RO4 Develop models to evaluate changeability in design – operationalizing the link between uncertainty, design variables, and operational strategies.

The thesis supplements four main articles attached, and five supporting papers. The three contributions (C) of the research project are:

C1 A framework for describing and quantifying changeable design alternatives, applicable to ship design as well as engineering design in general.
C2 An assessment of the applicability of methods and models for handling uncertainty in ship design, primarily from the real options and systems engineering domains.
C3 An identification of potentially valuable changeable ship design solutions, specifically being “prepared for retrofits” for two cases: fuel flexibility for transport ships and mission flexibility for non-transport vessels.

The research project concludes by highlighting that proactive consideration of changeability in ship design can be of significant value. The primary goal of this research project is fulfilled within the time and resource boundaries provided. This research project contributes to the knowledge on conceptual ship design under uncertainty, and for the design of changeable engineering systems in general.

Prediction is very difficult, especially about the future.

Niels Bohr

Preface

This thesis is prepared in partial fulfillment of the requirements for the degree of Doctor of Philosophy at the Norwegian University of Science and Technology (NTNU).

The work has been conducted from September 2015 to April 2018 and has been carried out primarily at the Department of Marine Technology in Trondheim, Norway. The research has been conducted under the supervision of Professor Stein Ove Erikstad, Professor Bjørn Egil Asbjørnslett, and Professor Stein-Erik Fleten. The fall semester of 2016 was spent as a visiting researcher at the Systems Engineering Advancement research initiative (SEAri) at Massachusetts Institute of Technology (MIT) in Cambridge, USA, under the supervision of Dr. Donna H. Rhodes.

The project funding was provided by NTNU. The Norway-America Association (NORAM) and the Anders Jahre's Grant provided funding in support for the visiting research conducted at MIT. The Norwegian Shipowners' Association Fund provided partial funding in support for attendance at several conferences during the research period.

The target audience for this work include both researchers and practitioners with interest in one or more of the following topics: ship design, systems engineering, strategic decision making, flexibility and other ilities, decision making under uncertainty, real options evaluation for engineering applications, structuring of ill-structured problems, multi-attribute decision making and tradespace exploration.

Carl Fredrik Rehn

Trondheim, 2018

Acknowledgments

This work would have been impossible without significant support from many competent people of which I am very thankful.

First, I would like to thank my main supervisor Professor Stein Ove Erikstad for giving me the opportunity to work on this exciting research project, and for his great support throughout the research period. Furthermore, I would like to thank my co-supervisors Professor Bjørn Egil Asbjørnslett and Professor Stein-Erik Fleten for valuable advice and interesting discussions. At NTNU, I have worked closely with Sigurd Solheim Pettersen and Jose Jorge Garcia Agis (also affiliated with Ulstein). Thank you for a tremendous collaborative period, it would not have been the same without you. A special thank you goes to my office mate Sigurd, who had to put up with me in a room for several years. Most of the research presented in this thesis was conducted under constant discussion and feedback from Sigurd. I hope it was of mutual interest.

I would also like to thank Professor Kjetil Fagerholt, Professor Sverre Steen, Professor Bjørnar Pettersen, Professor Jørgen Amdahl and Professor Bernt Johan Leira for helpful advice whenever asked. During the research period, I have also had the pleasure of co-supervising several MSc degree students. I am especially grateful for taking part in the work by Carsten Christensen, Morten Andreas Strøm, and Jon Hovem Leonhardsen. I would also like to thank Martin Kristiansen, Martin Hjelmeland, Minjoo Choi, Jan Vidar Ulveseter, Jan-Tore Horn, Emil Smilden, Pål Takle Bore, Ole Alexander Eidsvik, Øyvind Øksnes Dalheim, John Martin Kleven Godø and Henrik Schmidt for stimulating discussions, especially around the lunch table.

During the research period, I have also been fortunate to collaborate with Ulstein International AS. I am especially thankful for all help and valuable advice from Dr. Per Olaf Brett. Additional gratitude is extended to Dr. Tore Ulstein, Ali Ebrahimi, and Andre Keane, for exciting discussions providing me with essential perspectives from the industry to support my theoretical work.

At MIT, I would extend my gratitude for support and guidance from Dr. Donna Rhodes and Dr. Adam Ross. I would also like to thank Professor Richard de Neufville for inspiration and engaging lectures, in addition to Professor Olivier de Weck and Dr. Bruce Cameron. Professor Richard de Neufville needs special thanks, as he made me interested in the research topic during an earlier exchange stay at MIT in 2013 – 2014. I am also grateful for getting to know Matt Fitzgerald, Mike Curry, Joel Ong, Parker Vascik and Erling Shane German. Thank you for stimulating discussions in, as well as outside of, the office.

Outside NTNU, MIT and Ulstein, I have had the pleasure of being in contact with researchers at The Norwegian School of Economics (NHH). I thank Professor Roar Ådland for welcoming me multiple times to NHH, and for providing me with new

perspectives. I am also grateful for advice from Professor Stein Wallace and Professor Gunnar Eskeland at NHH. I would also like to thank Dr. H. Elizabeth Lindstad at SINTEF Ocean for exciting discussions and collaboration. Additionally, I have been welcomed several times to DNV GL, where I would like to thank Dr. Ketil Aamnes and Martin Wold for providing industry experience to support my research. I would also generally like to thank the anonymous reviewers for giving valuable feedback to the papers.

Finally, I would like to thank my friends and family for their continuous encouragement, especially my parents Helga and Lars, and Erle for her patience and support.

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List of Abbreviations

AHTS	Anchor Handling Tug Supply
DP	Design Parameter
EEA	Epoch-Era Analysis
ENPV	Expected Net Present Value
FOD	Filtered Outdegree
FR	Functional Requirement
LCM	Lateral Cargo Mobility
LNG	Liquefied Natural Gas
LWI	Light Well-Intervention
MAU	Multi-Attribute Utility
MSV	Multi-Service Vessel
NPV	Net Present Value
OCV	Offshore Construction Vessel
OSV	Offshore Support Vessel
OR	Operations Research
PSV	Platform Supply Vessel
ROA	Real Options Analysis
ROV	Remotely Operated Vehicle
RSC	Responsive System Comparison Method
TEU	Twenty-Foot Equivalent Unit
VaR	Value at Risk

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List of Publications

The papers contributing to this research project are summed up below, are discussed at greater length in Chapter 4, and attached in Appendix B.

Main articles:

Article 1

Ill-Structured Commercial Ship Design Problems: The Responsive System Comparison Method on an Offshore Vessel Case
Pettersen S.S.; Rehn, C.F.; Garcia J.J.; Erikstad, S.O.; Brett, P.O.; Asbjørnslett, B.E.; Ross, A.M.; Rhodes, D.H.
Journal of Ship Production and Design,34(1), 72-83, 2018

Article 2

Investigating tradeoffs between performance, cost and flexibility of reconfigurable offshore ships
Rehn, C.F.; Pettersen, S.S.; Erikstad, S.O.; Asbjørnslett, B.E.
Ocean Engineering, 147, 546-555, 2018

Article 3

Quantification of Changeability Level for Engineering Systems
Rehn, C.F.; Pettersen, S.S.; Garcia, J.J.; Erikstad, S.O.; Brett, P.O.; Asbjørnslett, B.E.; Ross, A.M.; Rhodes, D.H
Under review in an international journal

Article 4

Versatility vs. retrofittability tradeoff in design of non-transport vessels
Rehn, C. F.; Garcia, J. J.; Erikstad, S. O.; de Neufville, R.
Submitted to an international journal

Supporting papers:

Supporting paper a)

Flexible strategies for maritime sulphur emission regulation compliance
Rehn, C.F.; Haugsdal, A.; Erikstad, S.O.
PRADS 2016 - Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures

Supporting paper b)

Investigating feasibility of flexible ship concepts using tradespace network formulations
Rehn, C.F.; Pettersen S.S.; Erikstad, S.O; Asbjørnslett, B.E.
PRADS 2016 - Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures

Supporting paper c)

Sulphur abatement globally in maritime shipping
Lindstad, H.E.; Rehn, C.F.; Eskeland, G.S.
Transportation Research Part D: Transport and Environment, Vol. 57, Dec. 2017, pp. 303-313

Supporting paper d)

Design for Agility: Enabling time-efficient changes for marine systems to enhance operational performance
Christensen, C.; Rehn, C.F.; Erikstad, S.O.; Asbjørnslett, B.E.
13th International Marine Design Conference (IMDC2018)

Supporting paper e)

Combining System Design and Operational Strategy in Offshore Shipping
Strøm, M.A.; Rehn, C.F.; Pettersen, S.S.; Erikstad, S.O.; Asbjørnslett, B.E.; Brett, P.O
13th International Marine Design Conference (IMDC2018)

List of Tables

1. Introduction

1.1. Background

Capital intensive marine engineering projects typically operate in a context characterized by a high degree of uncertainty (Alizadeh and Nomikos 2009; Erikstad and Rehn 2015). Uncertain contextual factors, such as economic, technology, regulatory and physical, are usually highly influential for the viability of a project. These changing factors are difficult to predict and introduce risks for the key stakeholders. Even though it is widely recognized that ships operate in volatile markets, the traditional practice in ship design has been to assume a fixed set of requirements to which the design must comply. To the extent that scenarios have been considered, the most common approach has been to design for the assumed most likely scenario, and subsequently performing sensitivity analyses on contextual parameters to test the robustness of the solution (Erikstad 2014).

To some degree, flexibility is designed for and valued in the shipping industry. There are examples of multi-functional vessels being able to serve several types of cargo, services, or markets (Stopford 2009). For example, oil-bulk-ore (OBO) carriers are designed to take either wet or dry bulk. The ship can thus switch between markets to increase income, in addition to triangulate routes and increase utilization. Other examples include car carriers with hoistable decks and offshore vessels with multi-mission capabilities. The reason for designing multi-functional ships can be to handle the characteristics of the current market efficiently, or it can be to go beyond the immediate market requirements and serve as a strategic hedge towards future market uncertainty. However, adding extra capabilities beyond the immediate need is costly and can reduce operational performance. An alternative strategy to hedge against future uncertainty is to build ships that can be easily retrofitted, while also significantly reducing the up-front cost. This example illustrates the complexity of handling future contextual uncertainty in conceptual ship design. The design needs to strike a balance between optimizing for the most likely short-term scope, while still investing in additional flexibility for an uncertain changing future. These additional capabilities may be made part of the vessel at the design stage, or be provided as design options to be called dependent on information made available in the future.

Stopford (2009) discusses the critical tradeoff between cost and operational performance in design of flexible ships. However, the type of flexibility that he discusses is multi-functionality for transport ships, such as the dual-market capability of OBOs. These multi-functional vessels are more expensive to build and do not usually perform as well as single-purpose ships for their specific tasks. There may be significant upside potential from smarter routing, as the span of possible contracts is higher. Nevertheless, most transport ships in the industry are single-purpose built (Stopford 2009). This may suggest that the economic benefit of specialization outweighs the economic benefit of multi-functional flexibility in general. It is important to notice that Stopford (2009) focuses solely on multi-functional transport ships, and not on flexibility relating to change of form. There are multiple retrofits conducted in the maritime industry as exemplified in Table 1.

Empirical data suggest that equipment retrofits in the offshore industry and capacity expansion for cruise ships are not uncommon (Rehn and Garcia 2018). A recent study pointed out that several conversion projects in the industry are discarded due to too high retrofit costs (Ullereng 2016). These cases could potentially have been profitable if the ship was cheaper to retrofit, i.e., prepared for change. There is a growing interest in being prepared for retrofits in the industry, exemplified with the introduction of the *Gas Ready* classification notation by DNV GL (2015). This motivates research on flexible marine engineering systems, particularly regarding preparation to efficiently change form; reducing up-front costs and increasing the upside potential.

Table 1: Vessel retrofit examples, approx. cost estimates (Rehn and Garcia 2018), mos = months, NB = new build, acc.= accommodation, PSV= platform supply vessel, OCV = offshore construction vessel.

Vessel name	**Type**	**Built**	**NB. cost**	**Retr. year**	**Retr. cost**	**Retr. Dur.**	**Retrofit description**
Belle Carnell	PSV	2004	$25m	2013	$40m	9 mos	Acc., equip.
Aker Wayfarer	OCV	2010	$220m	2016	$90m	8 mos	Equipment
Vestland Cygnus	PSV	2015	$38m	2015	$18m	9 mos	Beam, equip.
Enchantment of Seas	Cruise	1997	$300m	2005	$60m	1 mos	22 m. elong.
MSC Lirica (+3 sis.)	Cruise	2003	$250m	2014	$65m	3 mos	24 m. elong.

Real options theory is often used to address and value managerial flexibility. An option refers to the *right but not the obligation* to perform some action. Options are for example often part of build-contracts, such as setting predetermined prices on changes that may be exercised in the future, or the right to buy additional ships at a given price within a fixed date (Erikstad 2014). Methods and models for quantitative risk management were first developed in the financial sector, for example used to design client portfolios for different risk profiles. The field of financial option pricing (and other derivatives) has received much attention in the literature, exemplified with the widely recognized Black-Scholes option pricing formula (Black and Scholes 1973). Managerial flexibility in the shipping industry was first introduced in the literature by Dixit (1988, 1989), through real options analysis of entry, exit, lay-up and scrapping options. An overview of applications of traditional real options in shipping is given by Alizadeh and Nomikos (2009). The financial markets approach to pricing flexibility using real options analysis was later adapted to design of physical engineering systems. There are however issues with naïve implementation of real options methods outside their natural habitat, for example, because they may rely on the creation of a replicating portfolio that can be traded in an arbitrage-free market (Wang and de Neufville 2005). A general discussion of design of flexible systems is provided by de Neufville and Scholtes (2011), who provide a practical framework for identifying, analyzing, and implementing flexibility in a broad range of engineering systems.

An alternative track that has received attention in the literature on ship and fleet design under uncertainty is stochastic optimization. Stochastic optimization extends deterministic optimization by the potential for considering alternative future scenarios and corresponding probability distributions, potentially taking opportunities to change the design or project at later stages into consideration. Marine applications include design of emission controls for ships (Balland et al. 2013) and fleet design under uncertainty (Pantuso, Fagerholt, and Hvattum 2014). A related method addressed in the literature is Markov decision processes, for example used to assess changeability in ship design (Niese and Singer 2014). A broad systems engineering perspective on handling complexity and uncertainty in design has been provided by the Systems Engineering Advancement research initiative (SEAri) at Massachusetts Institute of Technology (MIT), introducing methods such as multi-attribute tradespace exploration and Epoch-Era Analysis (EEA) (Ross and Rhodes 2008b). These methods have been applied to ship design under uncertainty, by for example Gaspar, Erikstad, and Ross (2012).

Early stage strategic design decisions in the industry are often based upon little or no systematic, data-driven approach explicitly addressing uncertainty. The approach taken today can best be described as predominantly a “gut feeling” approach by key decision makers (Erikstad 2014). Building on the state-of-the-art in the literature and state-of-the-practice in the industry, there is a need to increase the competence-base with regard to methods and models for design of ships under uncertainty. Uncertainty is often related to downside risks, but it is also important to acknowledge that uncertainty can bring significant upside potential (Lorange 2005; McManus and Hastings 2005). From this dual perspective, we are interested in clarifying how we can better conceptualize flexibility in design, and how we gain insight about connections between design decisions, contextual variables, and operational strategies.

1.2. Research Objectives

The underlying goal of this thesis is to develop new knowledge, competence, methods, and models for handling future contextual uncertainty in the early stages of ship design. A further aim is to develop insight into whether and how system-level properties such as flexibility and versatility (generalized as changeability) will be of key importance for the next generation ocean systems. This is considering both satisfying the immediate demands of the market, while at the same time being value-robust towards changes in the future operating context.

To address the research goals, we identify four research objectives (RO) that are addressed in this thesis. These objectives are characterized in the setting of being applicable at the conceptual stage of the ship design process.

RO1	Develop models that effectively capture relevant aspects of the future uncertain operating context for a system.
RO2	Define and quantify the level of changeability for a system.
RO3	Develop an understanding of technical tradeoffs for the realization of changeable ship design solutions.
RO4	Develop models to evaluate changeability in design – operationalizing the link between uncertainty, design variables, and operational strategies.

1.3. Delimitations

The focus of this project is ship design, answering to a certain amount of system complexity, with significant development time and not generally for mass production. This leaves smaller leisure boats out of the scope of this analysis – although the material developed is generalizable. This also leaves product platforms and product families outside of the scope of the case studies.

The research is positioned at the conceptual design stage. Thus, we will not go into detailed considerations of the form, instead focusing on functions, functional requirements, performance and needs. Further, this research mainly focuses on the design of single ships and not fleets. However, the context and needs of a ship (e.g., within a fleet of multiple ships) must be appropriately defined to be able to structure the objectives that drive design decisions. Thus, even though fleet considerations are outside the main scope, it plays a significant role in structuring the design problems.

Aspects of future contextual uncertainty that will be covered are mainly related to the strategic aspects of value delivery, considered of vital importance for the value-delivery of the overall system. This includes, but is not limited to, market structure and rates, fuel types and prices, and environmental regulations. Even though currently essential for the operation of maritime systems, human factors and safety are outside the scope of this project. Operational day-to-day uncertainty, such as the changes in the weather, is also outside of the scope.

We mainly focus on changeability as a system-property to handle uncertainty, whereas changeability is a generic change-related ility defined as the ability of a system to change form, function, or operation. Other "ilities" such as quality, are not considered. Other approaches for handling uncertainty, such as using market mechanisms to hedge market rates, are outside of the topic of this research project.

A limiting factor of this research is the level of data and knowledge regarding design of changeable marine systems, and the limited market data available for offshore shipping. Finally, time was a limiting resource in terms of exploring this research area to the fullest.

1.4. Contributions

The contributions (C) of this research project can be summed up in the three main points below, which are also discussed at greater length in Chapter 5.2 Contributions.

C1 A framework for describing and quantifying changeable design alternatives, applicable to ship design as well as engineering design in general.

C2 An assessment of the applicability of methods and models for handling uncertainty in ship design, primarily from the real options and systems engineering domains.

C3 An identification of potentially valuable changeable ship design solutions, specifically being “prepared for retrofits” for two cases: fuel flexibility for transport ships and mission flexibility for non-transport vessels.

1.5. Thesis Structure

Chapter 2: State of the Art
This chapter presents the state of the art of current research within ship design and design of changeable engineering systems in general.

Chapter 3: Research Approach
A classification of the research methodology and methods is presented, together with a presentation of the research timeline.

Chapter 4: Summary of Publications
This chapter presents the abstract, a discussion of the relevance, and a declaration of the authorship for each of the main articles and the supporting papers.

Chapter 5: Results Overview
The results and the contributions of the research project are presented in this chapter.

Chapter 6: Discussion
This chapter presents a discussion of the results of the research project, addressing methods, research questions and practical implications of the work.

Chapter 7: Conclusions and Further Work

This chapter presents the conclusions of the research project, in addition to suggestions for further work.

Appendix A: Glossary

A collection of definitions of the glossary is attached.

Appendix B: Attached Main Articles

Four articles essential for the research project are attached.

Appendix C: Previous PhD Theses

An overview of previous PhD theses published at the Department of Marine Technology is attached.

2. State of the Art

This chapter presents a state-of-the-art literature review. First, conceptual ship design is discussed in Chapter 2.1. Chapter 2.2 concerns future contextual uncertainty, and Chapter 2.3 discusses how uncertainty can be handled at the design stage through considerations of changeability.

2.1. Design Theory and Ship Design Literature

The chapter presents a discussion of theoretical aspects of design, a definition of conceptual ship design, and a review of ship design literature.

2.1.1. Design theory

There is a difference between *design science* and *design methodology*. According to Pahl and Beitz (1988), in design science, one uses scientific methods to analyze the structures of systems and their relationships with the environment, with the aim of deriving rules for the development of these systems. Design methodology represents particular courses of action for the design of systems - deriving knowledge from design science and cognitive psychology.

Design as a science of the artificial

Simon (1996) introduces a distinction between science in the natural and artificial worlds, where artificial means human-made as opposed to natural. Natural science is knowledge about natural objects and phenomena, and the underlying goal is related to increasing knowledge and to better understand nature. On the other hand, in the sciences of the artificial, it is essential to understand the *purpose* of a system or artifact. The system can be a ship, which is designed for example for efficient transportation of goods. The goal in the sciences of the artificial is then to achieve a better understanding in order to improve the performance of the system.

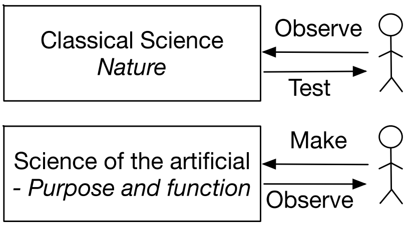


Figure 2-1: Sciences of the artificial and natural science (Simon 1969).

Design as a function-to-form mapping process

On a general basis, design can be considered as a creation of a plan for the construction of an object or system. In a more specific description, design can be considered as a *mapping process from function to form*, or from the performance space to the descriptive space (Coyne et al., 1990, Suh, 1990), as illustrated in Figure 2-2.

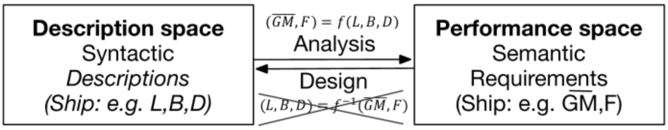


Figure 2-2: Descriptive space (form) and performance space (function), and design as a mapping process from function to form. L, B, D = length, beam, and draught, $\overline{GM}$ = initial metacentric height, F = freeboard.

Suh (1990) formally defines design as "the creation of synthesized solutions in the form of products, processes or systems that satisfy perceived needs through the mapping between the functional requirements (FRs) in the functional domain and the design parameters (DPs) of the physical domain, through the proper selection of DPs that satisfy FRs." One way of explaining the difference between these two spaces is by linguistic terms, where design descriptions belong to the syntactic space and functional performances belong to the semantic space (Coyne et al. 1990). The syntactic space is based on syntax, which describes how words form sentences. This can be interpreted as how, e.g., a ship is formed by its design variables, such as length, beam, and draught (L, B, D). The semantic space is related to meaning and illustrates the purpose of a design. This can, for example, be a ship designed for efficient transportation purposes.

The performance space is typically characterized by requirements, e.g., to the initial metacentric height ($\overline{GM}$) and freeboard (F) for a ship. As illustrated in Figure 2-2, these can be more readily estimated as functions of parameters from the description space (length, beam, depth), a process that can be referred to as *analysis*. As opposed to *synthesis*, *analysis* is related to the separation of a topic or substance into its constituent elements. Although $\overline{GM}$ and F can be calculated based on the design variables (length, beam, depth), this functional relationship does not work the other way directly. This is the core of the traditional design problem. Designing the ship would then be by finding the best set of parameters to satisfy the requirements, generally characterized as *synthesis*.

Axioms of design

How do we make right design decisions and why is a design a good design? To answer these fundamental design questions, and to provide aid in the creative design process, Suh (1990) proposes two design axioms. The axioms govern all design decisions, whether they are for products, processes, systems, software or organizations, and the primary goal is to establish a scientific foundation for the design field.

The Independence Axiom: *Maintain the independence of functional requirements.*

The Information Axiom: *Minimize the information content of the design.*

The Independence Axiom deals with the relationship between functional requirements (FRs) and design parameters (DPs). The axiom states that, during the design process, the mapping from FRs to DPs must be such that a perturbation in a DP must affect only its referent FR. Therefore, an optimal design always maintains the independence of the FRs.

The Information Axiom deals with a minimization of the information content of the design. This can be done for example by minimization of the number of FRs, standardization of parts and the use of symmetry in the general architecture. Both axioms favor a reduction of design complexity. Based on this way of thinking, the best design is a functionally uncoupled design that has the minimum information content.

Knowledge-based design: Design as an abductive reasoning process

Coyne et al. (1990) present a knowledge-based model of the design process. Although the purpose of the model is to enable computers to assist in the design process, it presents exciting points considering design theory. In their framework, the authors start by discussing means of describing designs. *Facts* are statements about relationships between objects. Objects, in turn, are simple units of information. *Knowledge* can be defined as relations between facts and becomes central when it comes to *reasoning processes* (Figure 2-3). That is, for example, how new facts can be described from known facts, such as “A is true if B is true.” Knowledge is relevant in *deductive* reasoning, which is a logical process of drawing specific conclusions from premises (given the rule and case, deduce the result). Additionally, *induction* and *abduction* represent two other reasoning processes. Induction involves the acquisition of knowledge, generally given several examples of premises that produce similar conclusions (given a case and a result, induce the rule). Abduction involves reasoning to premises given the knowledge and conclusions (given a rule and a result, abduce a case). Coyne et al. (1990) argue that abduction most accurately characterizes design reasoning. In such cases, we know what we want, e.g., the design must satisfy specific functional requirements, but we do not have the physical design descriptions that meet the requirements.

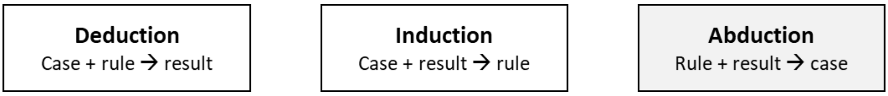
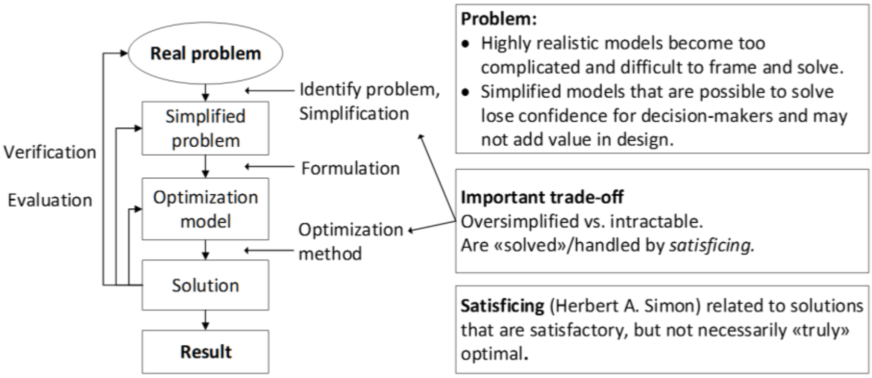


Figure 2-3: Design outlined as an abductive reasoning process (Coyne et al. 1990).

A critical perspective: Fundamental challenges in design

In addition to the fundamental issue of non-uniqueness in mapping from function to form, there are challenges in framing and solving real-life design problems. For general design problems, this process is illustrated in Figure 2-4. In the process of moving from the real problem to a solution, there are mainly three steps that must be addressed:

1. **Characterizing/framing:** The first step involves identifying, simplifying, and characterizing the real problem. What is the problem? Moreover, what are the preferences of the stakeholders and the possible space of solution opportunities?
2. **Formulating/modeling:** The second step involves formulating the problem at a level of complexity that can be handled.
3. **Solving:** The third step involves solving the explicit formulation of the simplified real problem, to reach an "optimal" solution.



Problem:
- Highly realistic models become too complicated and difficult to frame and solve.
- Simplified models that are possible to solve lose confidence for decision-makers and may not add value in design.

Important trade-off
Oversimplified vs. intractable.
Are «solved»/handled by *satisficing.*

Satisficing (Herbert A. Simon) related to solutions that are satisfactory, but not necessarily «truly» optimal.

Figure 2-4: Model formulation as a simplification of reality, satisficing instead of optimizing (figure adapted from Lundgren, Rönnqvist, and Värbrand (2010)).

There are challenges in each of these three steps. In the first step, one must determine the goal of the problem, i.e., what is the ideal end-state? Moreover, what possible means can be made to reach that state? Problems without a defined end-state, and thus with unclear relations between the start-state and end-state, are characterized as *ill-structured* (Simon 1973), or *wicked* (Rittel and Webber 1973) where the *"formulation of a wicked problem is the problem*! … setting *up and constraining the solution space and constructing the measure of performance is the wicked part of the problem*. *Very likely it is more essential than the remaining steps of searching for a solution which is optimal relative to the measure of performance and the constraint system."* (quotes from Rittel and Webber (1973) – also discussed by Andrews (2011, 2012) for maritime applications).

It is usually challenging to define the goal-state of real design problems, and thus these problems can be characterized as ill-structured. Issues with goal specification are particularly apparent for multi-stakeholder problems, of which proper ranking among alternatives may be impossible (Arrow 1950; Hazelrigg 1996; de Neufville 1990). In the second step, the goal is to formulate the characterized problem to a structure that can be meaningfully “optimized,” i.e., searched for the best solution – which is the goal of the third step. This is usually very difficult for design problems, mainly as they are long-term and strategic (de Neufville 2000). Between these two steps, there is a tradeoff between formulating a realistic model, and the tractability of the model.

In an entertaining article, Ackoff (1979) describes a gap between the academic and non-academic practitioners of operations research and management science. He states that, even though operations research and mathematical optimization originated from military planning applications during World War II, trends in 1979 had increasingly pushed it into an imagined reality. It has become synonymous with mathematical models and algorithms, rather than the ability to formulate and solve actual problems. He argues that real problems often are “too complicated” to be easily modeled, and thus presents ideas aligned with fundamental issues of ill-structured design problems.

Hazelrigg (1998) discusses the underlying notions of decision-based engineering design and presents an elegant *in reductio ad absurdum* definition of engineering design as to generate all possible solutions and select the best one. However, this is extremely difficult, if not impossible, for multiple reasons, and he points to four reasons in particular: (1) the range of possible options is limitless, (2) it is not possible to know precisely how a particular design will perform after it is built, (3) identification of a valid measure of value is not trivial and (4) if it was possible to enumerate all options, determine their behavior and evaluate them, it would be computationally infeasible to search all options for the best one.

Even though many design problems are ill-structured, for all practical purposes, they must be “solved.” That is, at least to the degree that a feasible solution is found, although not being truly optimal. In light of psychology of thinking for problem-solving, search strategies and memory, Simon (1996) argues that despite all available tools, finding a *true optimal solution* often is impossible for real-life situations. For example, even the “simple” and well-formulated traveling salesman problem (TSP) quickly becomes a huge, complex problem, as the number of possible paths grows exponentially with the number of nodes. For these problems, we must settle with good solutions, but probably not optimal. Simon labels these methods as *satisficing*. Thus, one can conclude that for all practical purposes, design involves best practices for satisficing.

2.1.2. Conceptual ship design

This thesis focuses on the conceptual design phase, where the main features of the ship are determined. This typically involves the primary dimensions and capabilities documented through an outline specification. To better understand the conceptual design process, we briefly investigate its position within the overall design process. The general design process comprises the activities from design project initiation to the delivery of a detailed design specification. Pahl and Beitz (1988) divide the planning and design process into four main phases: planning and task clarification, conceptual design, embodiment design, and detail design. Each phase is associated with a set of activities and events, as well as an expected result from that phase. This is illustrated in Figure 2-5. However, it is not always possible to draw clear lines between the phases, as some aspects can overlap, and iterations and backtracking can occur.

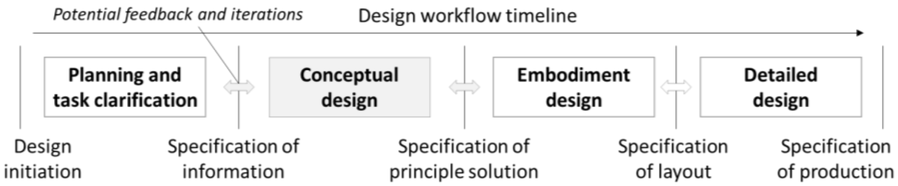


Figure 2-5: Activities in the general design process (Pahl and Beitz 1988).

- **Planning and task clarification**
  The purpose of this initial phase is to clarify the needs, i.e., collect information about the requirements, and identify potential constraints. The result of this phase is the production of an *operable problem description* sufficiently defined such that a search for solutions can start in the next phase.
- **Conceptual design**
  The goal of this phase is to determine the *specifications of a principal solution (concept)*. This involves the identification of solution principles and the establishment of functional structures, which are combined to generate concept variants. These variants must subsequently be evaluated and compared, to decide the best concept.
- **Embodiment design**
  Using the outline concept specification as a starting point, this phase concerns the determination of the construction structure of a technical system in line with economic and technical criteria, resulting in the *specification of the layout*. For traditional shipping applications, this involves the determination of main dimensions, selection of preliminary lines for the hull, and development of main aspects of the general arrangement (Erikstad 1996).

- **Detailed design**
  Based on the layout specification, the goal of this phase is to produce a complete specification of information in the form of *production documentation*. This comprises the complete specification of the arrangement, forms, dimensions, and properties of all the individual parts, materials selection and cost estimations.

Andrews (2011) further divides the conceptual design phase into three stages:

- **Concept exploration** represents an extensive search of all possible options, including modifying existing ships and generating completely novel solution types. This stage thus represents the exploration of the possible design space at an abstract level, i.e., exploring the search boundaries.
- **Concept studies** further examine a subset of possible solutions found in the concept exploration phase. This involves investigating potential solution-related issues.
- **Concept design** involves developing the concept design further, investigating tradeoffs, costs, and benefits of the solution. This is still at a relatively abstract level.

The conceptual phase often appears in the literature under multiple terms, such as preliminary and early-stage. As the result of the conceptual design phase is the choice of design concept, it becomes clear that significant design decisions are made in this process. It is estimated that 60% to 80% of the total lifecycle cost is determined at this stage, even though only a small fraction of the total costs are expended at this stage (Dierolf and Richter 1989; Erikstad 1996). Therefore, it is crucial to make value-robust conceptual design decisions.

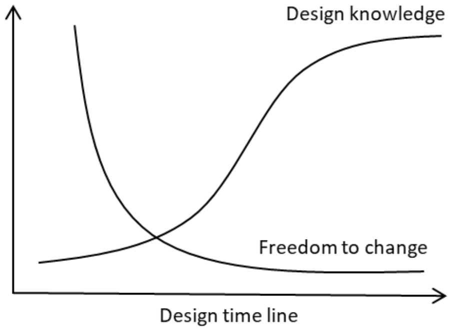


Figure 2-6: During the design process, the knowledge about the design increases while the freedom to change decreases (adapted from Mistree et al. (1990)).

The conceptual design stage is characterized by a high degree of design freedom for the decision maker. Initially, the design problem is open, as no decisions have delimited the design options beyond the bounds given from the motivating problem definition. As the design process proceeds, all subsequent design decisions will constrain the design freedom. Figure 2-6 illustrates the inverse relationship between freedom to make changes and design knowledge during the design process timeline.

Reasons for limited availability of knowledge in conceptual ship design are discussed by Erikstad (1996), where seven characteristics are pointed out: complex mapping between form and function, multi-dimensional performance evaluation, high cost of error, strict time and resource constraints, shallow knowledge structure, strong domain tradition, and predominance of “one-of-a-kind” and “engineered-to-order” solutions. Adding to this, we can improve our understanding of the difficulties of the ship design process by decomposing the complexities into the five aspects proposed by Rhodes and Ross (2010). Aspects of complexity in conceptual ship design are studied by Gaspar et al. (2012), and an illustration of the five aspects of complexity for conceptual ship design applications is given in Figure 2-7. *Structural* and *behavioral* complexity relate to the traditional mapping from function to form, both which are difficult for ships at the conceptual ship design stage. In contrast to many other engineering systems, ships are highly self-contained integrated structures with tight subsystem couplings, operating in the intersection of two fluids in a physically stochastic environment. These factors make the mapping between function and form difficult, for example due to the need for hydrodynamic force- and structural integration calculations.

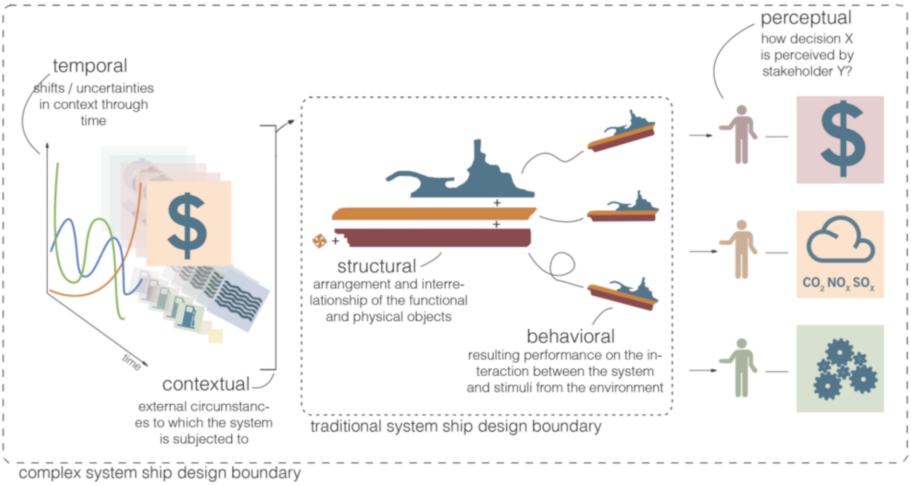


Figure 2-7: Five aspects of complexity in ship design (Gaspar et al. (2012) – adapted from Rhodes and Ross (2010)).

Contextual, *temporal*, and *perceptual* complexities further complicate the conceptual ship design problem. Contextual aspects relate to how the system interacts with the circumstances in which the system exist, at the boundary of behavioral complexity. From a value-focused perspective, we are interested in contextual factors affecting the value proposition of the concept. For offshore ships operating in heterogeneous markets, with tenders with various technical requirements, duration and day rates, the contextual complexities are particularly tricky to handle. Changes in context over time may affect the system, which makes the conceptual design problem extra complicated. Furthermore, to select the *principal design solution*, as a result of the conceptual phase, one needs to evaluate alternative design variants. Perhaps the most ambiguous part of the design process relating to human perception becomes central at this stage. This relates to the process of understanding the preferences of the stakeholders, such that right alternative designs can be selected. This research project extends the "traditional system boundary," focusing mainly on how design features interact with contextual shifts.

2.1.3. Review of ship design literature

This chapter presents a review of the literature on ship design. There are multiple state-of-the-art reports on this material, where a recent report is presented by Andrews and Erikstad (2015). A simplified timeline of the recent academic history of ship design is presented in Figure 2-8.

One of the earliest contributions in the literature on ship design is the well-known design spiral introduced by Evans (1959). This is an iterative spiral, which often is the approach that must be made for complex systems where it is difficult to directly understand the relationship between function and form. The steps in the spiral involve technical details such as machinery, displacement and trim, resistance and propulsion and hull lines. The spiral is related more to the embodiment or detailed phases of the design process (Pahl and Beitz 1988), than the preliminary phases. Furthermore, the spiral as presented by Evans does not involve exploration of potential solution variants, only the point-design iteration to generate an actual feasible solution. Consequently, Evans' spiral is often later criticized for locking the designers to their first assumptions. However, with the limited computing power of 1959, efficiently handling the function to form mapping was a severe problem.

About a decade later than the spiral introduced by Evans (1959), Benford (1967) shifts the focus and presents an interesting discussion on the rational selection of ship size in terms of determining cargo capacity. He proposes an optimization algorithm that can be used to find the most economical design for a given forecast of cargo availability. He thus expands the form-function discussion towards contextual complexity by considering the determination of requirements. Addressing issues in design further, Benford (1970) discusses measures of merit for ship design, primarily focusing on the virtues and shortcomings of economic measures: net present value and internal rate of return, in addition to the required freight rate criterion. His findings are that each valid criterion indicated a design that fell within the reasonable range indicated by the other criterion. Not long after the publication of this paper, Buxton (1972) discusses engineering economics applied to ship design. Buxton outlines a design algorithm inspired by Evans' design spiral, including both technical and commercial aspects.

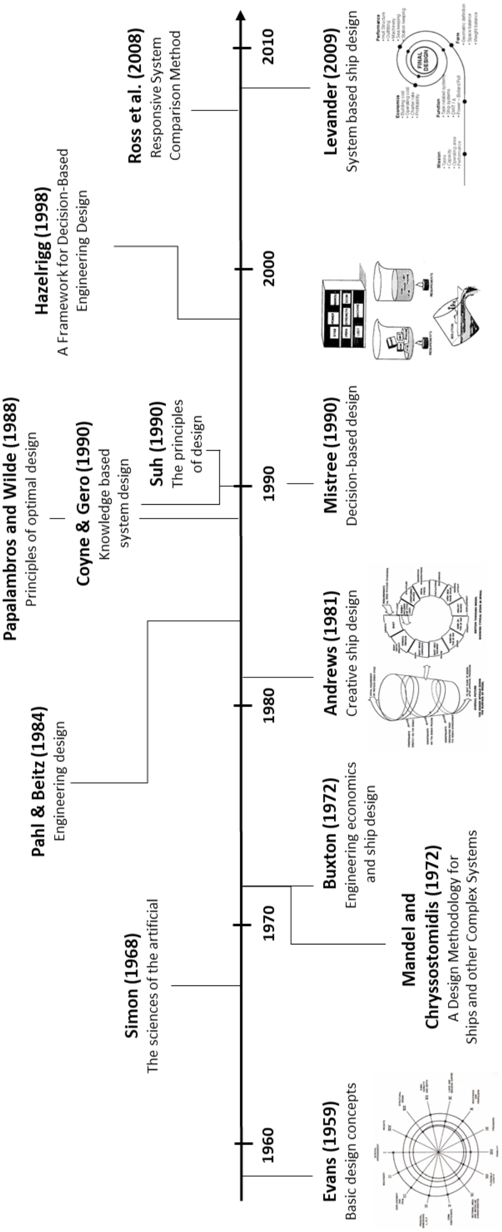


Figure 2-8: Non-exhaustive timeline of ship design literature through the decades from the 1950s to 2010s.

Mandel and Chryssostomidis (1972) make an interesting observation that the effort towards using computers in the design process (in 1972) only aids in the final design stage for the construction of *conventional ships*. For *unconventional ocean systems*, the system configuration that will best fulfill the objective is not known and cannot be predicted from previous experience since no such experience has been gained. They present a methodology to help aid in the early exploratory design process of large multiunit, multipurpose ocean systems.

Andrews (1981) reviews various contemporary design methods and concludes that there is a lack of methods that provide the tools for generating radically new designs. He proposes two steps towards a more creative ship design process. The first is an outline for how Computer Aided Architectural Design (CAAD) can be leveraged to explore the internal ship layout and the complete ship form. The second is regarding how design techniques can be used to produce an open and creative philosophy. Following the lines of Andrews (1981), about a decade later, Wijnolst and Waals (1995) give a comprehensive discussion on innovation in shipping from a design point of view. They also argue that current design methodologies do not stimulate innovation and present a broad overview of different aspects of innovation resulting in a new methodology they call Design Innovation in Shipping (DIS).

Mistree et al. (1990) criticize the traditional ship design spiral as it assumes the process of design to be sequential and that the opportunity to include lifecycle considerations is limited. To increase effectiveness and efficiency, they propose a method called Decision-Based Design which encompasses systems thinking and the concept of concurrent engineering design for the lifecycle. Perhaps the first contribution in the ship design literature explicitly focusing on aspects of flexibility as a lifecycle property in design is by Buxton and Stephenson (2001). They present a compelling case of upgradeability in ship design. Multiple levels of upgradeability built into the design are considered, where higher levels make the upgradeability process easier. Thus, the contribution by Buxton and Stephenson (2001) is highly relevant to the research topic presented in this thesis.

Andrews (1998) presents a comprehensive methodology for the design of ships (and other complex systems) building on the work by Mandel and Chryssostomidis (1972). Andrews points to the significant difference between naval ships (and other complex systems in general) and conventional ships. He attributes these complex ships to two main characteristics: 1) they do not have a single purpose which can easily be optimized, but are multipurpose with sometimes conflicting requirements, and 2) their design process is multi-faceted, not only in technical sense but also in terms of socio-economic, political, and potentially international considerations. As a tool to aid in the design of physically large and complex systems, and especially for spatial synthesis, Andrews (1998) discusses the use of the Design Building Block approach. In this approach, he explains that the required components are defined by building blocks which have all the attributes necessary for placing demands on the vessel, along with the master building block describing the gross ship characteristics. The Design

Building block approach can provide helpful insights into the initial synthesis of preliminary exploration of possible architectures and configurations. A similar approach further developing spatial exploration in early stage design of complex ships is the Packing Approach by van Oers (2011).

As a response to the critics of the lock-in issue on the initial solution in Evans' spiral, Levander (2009) presents the *System Based Ship Design* process. This approach takes the perspective that the starting point for ship design should be to have a well-defined mission so that functional descriptions can be made. Subsequently, all systems that are needed for the design to perform as required can be identified based on the functional descriptions. To handle complexity, and to enhance the creative process, Levander argues that the requirements should be divided into "musts" and "wants." However, as the method in practice often involves regressions for estimating the form from the functional requirements, it typically requires some data from other designs. Two form estimates for an offshore ship can, for example, be the volume of the engine room and the deck space area. The method takes a broader view of the design process so that the design more easily becomes technically feasible and economically preferable. He argues that, in contrast to the traditional ship design spiral method, which locks the designer to initial assumptions, the System Based Ship Design process is more supportive of innovation and creativity.

Following up on an alternative approach for design, Singer, Doerry, and Buckley (2009) discuss *set based design* for maritime applications. Instead of choosing a single-point-design solution upfront, as in the traditional design spiral, set-based design is a practice where alternative design options are kept open as long as possible. Parallel assessments and evaluations are performed, and inferior solutions are eventually rejected until one can synthesize and conclude on the best alternative. One practical approach to set based design is the generation of a set of enumerated design alternatives, ideally spanning the complete space of opportunities, for subsequent evaluation and selection/rejection. This draws similarities to Hazelrigg (1998), who elegantly characterizes the general engineering design process into two steps *in reductio ad absurdum*: (1) determination of all possible design options and (2) choosing the best one. However, for obvious reasons, it is an impossible process to perform correctly. There are for example limitless possible design options to consider, and the development of a valid measure of value is not trivial.

While this thesis focuses on the uncertainty that affects the value delivery of a project, we do not include aspects of human safety. There is little doubt that safety is an essential characteristic of good ship design. For many design considerations, aspects of safety are considered as constraints on the design space. According to Papanikolaou (2009), safety-related risk and reliability analyses have become increasingly frequent in modern design disciplines. His point of view is that, by introducing risk as an objective into the design optimization process, rather than as constraints, new technical solutions can be explored as constraints are relaxed and the design solution space becomes larger.

To evaluate and compare the lifecycle performance of different design alternatives, one needs to understand the operational phase of the lifecycle. In traditional literature, this is often operationalized to functional requirements, and thus the design problem is simplified to a state-of-the-practice mapping process from functional requirements to form. Identification and characterization of requirements are therefore essential for the overall success of the system, and this process is often called *requirements engineering* or *requirements elicitation*. Andrews (2011) argues that for the design of complex marine systems, one should instead use the term *requirements elucidation*. Typical requirements engineering literature, primarily from software engineering, focuses on deriving requirements with no reference to material solutions, according to Andrews (2011). He further cites a book referring to the requirements engineering process as only "defining the solution in abstract" simply "showing what the system will do but not how it will be done." Andrews (2011) argues that this may be ok for software engineering, but not for complex engineering systems such as naval ship design cases. These problems are *wicked* (Rittel and Webber 1973) in nature (or *ill-structured* as defined by Simon (1973)), which explains why the formulation of requirements is complicated and why it is interwoven with the exploration of solutions. Requirements elucidation can thus be defined as the primary task of the concept phase of design. He also discusses the use of the Design Building Block approach to potentially aid in the requirements elucidation process.

Literature from the operations research domain has also attempted to engage in ship design issues, such as the *fleet size and mix* and *fleet renewal* optimization problems. Excellent reviews of this literature are given by Christiansen et al. (2007, 2013) and Christiansen, Fagerholt, and Ronen (2004). An interesting characterization from the operations research literature relating to the planning horizon of a decision problem is the observation that the ship design problem is a *strategic problem* – i.e., characterized by a long-term planning horizon. Fleet renewal problems under uncertainty are studied by Pantuso (2014), focusing on uncertainty applying stochastic optimization. One of his findings is that (for a specific maritime fleet renewal problem case study) the correlations between the random variables had very little influence on the final decision, while the mean value of the variables could have a significant influence on the expected cost if incorrectly estimated. A general observation from the operations research domain is their strong *analytical* focus which is contrasting the fundamental focus on *synthesis* in design. For more design-related aspects of optimization, a good overview is presented by Papalambros and Wilde (1988). In line with Ackoff (1979), a fascinating discussion taking a critical view of the literature on ship routing and scheduling is presented by Psaraftis (2017). He addresses an important difference between focusing on solving real-world maritime planning problems, and "solving" over-simplified problems faster with better optimization algorithms, of which the latter case perhaps has been overrepresented in the literature recently.

Hagen and Grimstad (2010) discuss the extension of system boundaries in ship design, as non-static requirements call for more than the standard mapping from function to form involving structural and behavioral complexities. This extension of the system boundary fits well with the five aspects of complexity in engineering design presented by Rhodes and Ross (2010), which is applied to marine systems by Gaspar (2013). Traditional ship design involves the mapping process between function and form, involving mainly structural and behavioral complexity. Extending the system boundary involves including contextual, temporal, and perceptual challenges. However, system boundary extension is also addressed in the ship design literature long before 2010, for example by Benford (1967, 1970).

Extension of the traditional system boundary, explicitly focusing on lifecycle properties, often called the *ilities* (de Weck, Roos, and Magee 2011), has seen growing attention in the recent ship design literature. Some of this research has been through application of various aspects of the Responsive System Comparison (RSC) method introduced by Ross et al. (2008, 2009) to ship design problems. This includes applications of tradespace exploration in combination with Epoch-Era analyses. Tradespace exploration is a method for exploring the space of design opportunities, often operationalized in terms of costs and utility (Ross & Hastings, 2005), whereas utility is based on multi-attribute utility theory (Keeney and Raiffa 1993). This relates to the fundamental question of *”what is a better ship?”* – which has been addressed in several recent research papers (Ebrahimi et al. 2015; Ulstein and Brett 2015). The RSC method is applied in commercial non-transport ship design cases by Gaspar, Erikstad, and Ross (2012) and Gaspar et al. (2013). An application of the RSC method for a naval ship design case is presented by Schaffner, Ross, and Rhodes (2014). There are alternative research tracks addressing aspects of lifecycle properties without relating to RSC and its methods. For example, Niese and Singer (2014) address changeability in ship design applying Markov decision processes. Knight, Collette, and Singer (2015) evaluate the option to extend service life in preliminary structural design, and Kana and Harrison (2017) analyze the decision of converting a containership to LNG power using a ship-centric Markov decision process.

2.2. The Uncertain Future Operating Context

This chapter presents methods for characterizing and modeling the uncertain future operating context for systems design applications. First, we define what we mean by the uncertain future operating context, breaking it down into aspects of contextual and temporal character, before we present insights from the literature for how to address each of these two aspects.

2.2.1. The uncertain future operating context

Regarding the precision of the *uncertain future operating context,* we mean the main contextual factors that may affect the *value-delivery* of the system during the operational phase of the lifecycle. By uncertainty, we mean “things that are not known, or only known precisely” (McManus and Hastings 2005). Consequences of future contextual uncertainty are often related to harmful downside risks, but it is important to acknowledge that lifecycle uncertainty also can bring significant upside potential (McManus and Hastings 2005). Some examples of uncertain context variables for marine systems are given in Table 2.

Table 2: Example of lifecycle uncertainties in marine systems design (Erikstad and Rehn 2015).

Field	**Example**
Economic	Oil price, freight rates, interest rates, supply/demand.
Technology	Energy efficiency improvements and lifecycle enhancement.
Regulatory	Air emission and ballast water treatment.
Physical	Sea ice, sea states, extreme weather, ports, and canals.

The primal focus in this research project is *temporal* uncertainty, i.e., how changes in contextual variables over time may affect the system and how we can handle that by changeability in design. In order to do so, we need to understand *which* contextual factors that significantly affect the system. Thus, the research project spans both contextual and temporal aspects of complexity in systems design, as two of the five aspects of complexity defined by Rhodes and Ross (2010). Uncertainty and complexity are positively correlated, in that introduced uncertainty increases complexity (and opposite). Figure 2-9 describes the relationship between uncertainty and the five aspects of complexity.

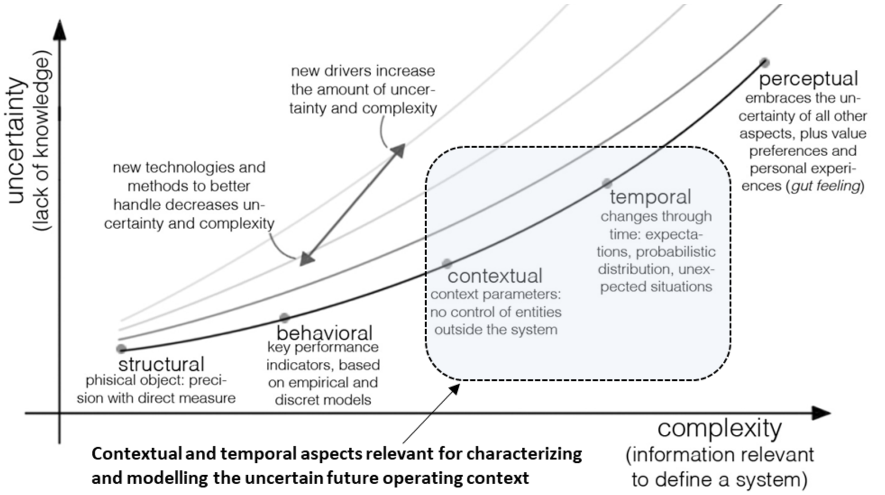


Figure 2-9: Relationship between complexity and uncertainty (Gaspar 2013).

In the literature, a separation is sometimes made between uncertainties of endogenous or exogenous character. According to Lin et al. (2013), endogenous uncertainty can be actively influenced or managed by decision makers, while exogenous uncertainty is independent of any project decisions. For ship design applications, endogenous uncertainty can be related to uncertain physical behavior, for example the actual maximum speed of a ship after it is built. This type of uncertainty can generally be handled by introducing more sophisticated computational models. Exogenous uncertainty can be related to the market rates or the fuel prices. These are contextual *per se*, and outside of the control of decision makers. Contextual factors addressed in this research project can thus generally be characterized as exogenous.

2.2.2. Characterizing contextual factors

The core of contextual complexity is understanding which and how system-external contextual factors affect the value-delivery of the system. Examples of such generic factors for a maritime system is presented in Table 2. There are multiple contributions in the literature attempting to untangle contextual complexity for marine systems, specifically in terms of understanding the drivers of the shipping markets. Two examples of this are given in Figure 2-10. Erichsen (1989) discusses factors influencing demand in the bulk market, and Stopford (2009) presents a general model for the supply and demand system in shipping.

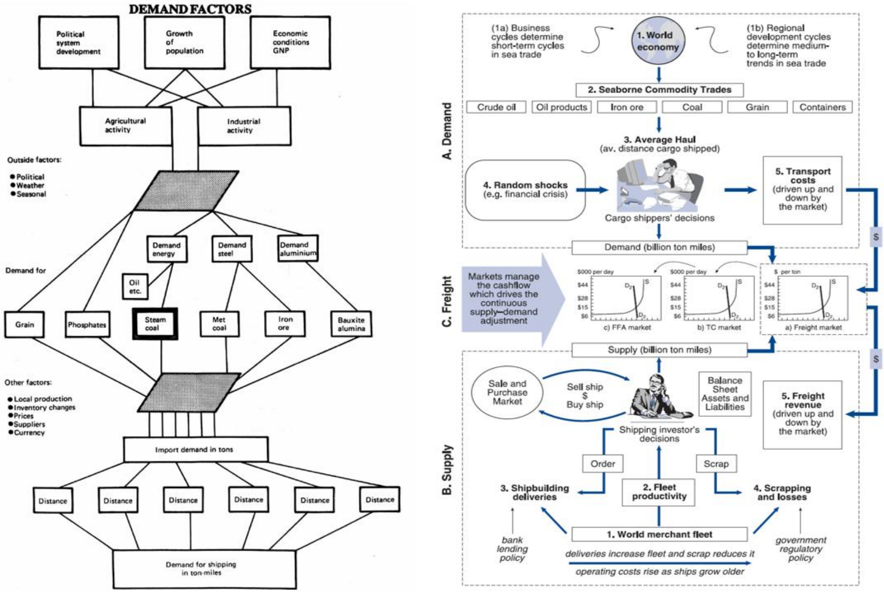


Figure 2-10: Left: an example of the contextual complexity of factors influencing demand in the bulk market (Erichsen 1989). Right: general illustration of the shipping supply and demand model (Stopford 2009).

Despite its high importance for the value-delivery of a ship, the charter rate is often not the only external factor of importance. This obviously depends on the case and the preferences of the stakeholders, but for simplicity let us assume what is considered valuable is profitability. Profitability depends both on revenue and costs. A top-down hierarchy of factors that affect profitability may be a natural approach untangle this complexity on a general basis. An illustration of a profitability value hierarchy for the case of an offshore ship and potential exogenous factors that affect this value hierarchy is presented in Figure 2-11.

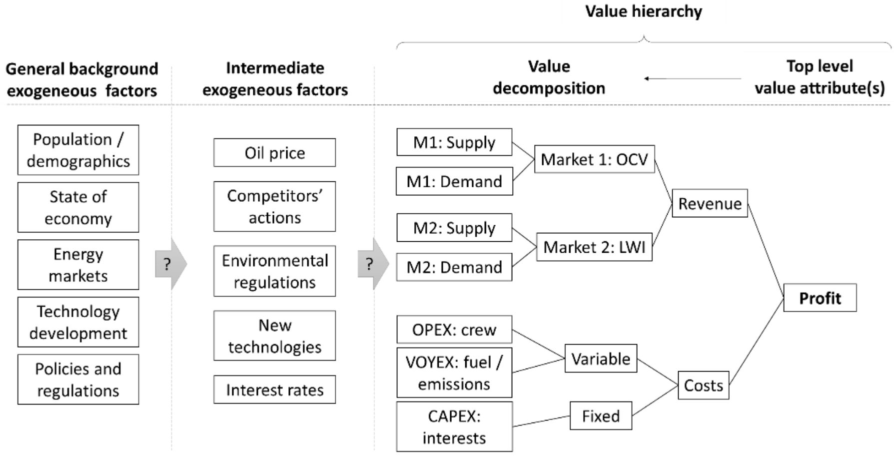


Figure 2-11: Value hierarchy and exogenous factors potentially affecting value, OPEX, VOYEX, and CAPEX are operational-, voyage related-, and capital expenditures respectively, OCV – offshore construction vessel, LWI – light well intervention represent two example markets potentially relevant for a flexible offshore ship.

There are several methods for understanding the relationship between contextual factors at various levels of abstraction. Statistical regression methods, often seen in econometrics, based on historical data may be a good approach to understanding the dynamics of the contextual factors. An empirical model for the bulk shipping market is presented by Lun and Quaddus (2009). For unique maritime systems, with little or no historical data, it becomes less clear what to do. This is often the case for complex non-transport commercial or non-commercial systems, as addressed by Andrews (1998). In the case where no historical data exist; more qualitative methods may be useful – often relying on subject matter experts. The field of scenario planning has developed methods for tackling such problems. For example, Schoemaker (1991) presents a qualitative method for characterizing relationships between key uncertain context variables for scenario planning applications.

From the literature on systems design under uncertainty, Epoch-Era Analysis (EEA), explicitly involves the characterization of contextual variables. EEA was developed by Ross et al. (2008) to handle aspects of contextual and temporal complexity in systems design and is often used as part of the Responsive System Comparison (RSC) method (Ross et al. 2008, 2009). This includes both framing and structuring scenarios by use of epochs as building blocks for eras, and subsequently performing analyses based on these constructs to understand how the performance of a design alternative changes under different contextual situations. An epoch is merely a period with fixed *context and needs*, modeled as epoch variables. An era is a sequence of epochs assembled in time, representing a potential lifecycle of a system. Therefore, eras are scenarios describing potentially changing context and needs over time, enabling different long-term analyses. The “analysis” part of EEA simply means using epoch-era constructs to analyze and extract valuable insight of a system’s behavior under changing contextual conditions. Depending on the level of abstraction, this can be either within an epoch, i.e., with fixed context and needs, or long-term across different epochs to investigate the effects of changing context or needs.

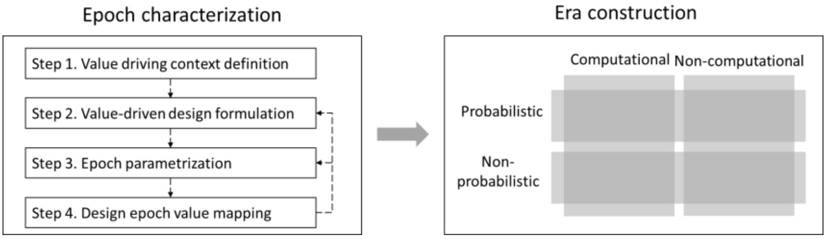


Figure 2-12: Epoch modelling left (a), and era (scenario) construction right (b) (adapted from Ross et al. (2008, 2009)).

As illustrated in Figure 2-12, constructing an Epoch-Era Analysis model involves epoch characterization and era construction. The goal of epoch characterization is to end up with a clear description of the variables describing the context and needs of the system, with its defined system boundary. Four iterative steps are outlined in the epoch characterization process by Ross et al. (2008, 2009):

Step 1: The first step involves defining the *value proposition*, including constraints and a clearly stated problem description. First, one needs to define the problem and problem context. This involves defining the system boundaries, and the relevant system-internal and system-external stakeholders.

Step 2: The goal of the second step is to clarify the expectations of each stakeholder, to operationalize the expectations via meaningful value attributes (objectives), and map between design alternatives and value. To connect design and value, there is a need to define design alternatives and clarify the concepts of operations (CONOPS). Additional information about stakeholders should be identified, such as constraints on resources. Objectives should be *fundamental*, and not *means* (Keeney 1992), that is, they should have the property of being important alone, and not as means to meet some higher-level objective.

Step 3: The goal of step 3 is to identify and parameterize uncertainties in the context and stakeholder needs. Additionally, uncertainty about resource usage and needs should be clarified. We are mainly interested in the uncertain contextual factors that can potentially affect system success. Essential uncertainties commonly originate in domains such as economic and market, technology and infrastructure, policy and regulations, resources and budgetary constraints and end uses. We are also interested in identifying potential uncertainties to stakeholder needs, i.e., uncertainties to what the stakeholders consider as value. This is important, as it drives the whole design and scenario generation problem. Identification of epoch variables may involve methods like brainstorming and consultation with subject matter experts. This step results in a clearly defined epoch vector, perhaps with associated variable constraints. A combination of the epoch variables will thus define an epoch. If there are epochs that are of specific interest, one may name them to facilitate communication and interpretation. One of the challenges is in deciding an appropriate level of abstraction, or fidelity, for the epochs. How information-dense should an epoch be, how long should an epoch be, and how many different epochs should we include in a scenario? There is no general answer on this question, as it is highly case dependent. The point is mainly that this should be addressed based on the goal of the scenario analysis.

Step 4: The goal of the fourth and the last step in the iterative process for epoch characterization is to connect the design-, epoch- and value-space, to gain insight into how different design decision alternatives provide value through epochs. The mapping between design decisions and the value space can be done in multiple ways, depending on the level of ambiguity. If the relationship between design and value is evident, a one-to-one functional relationship can be established. In other cases, one needs to evaluate systematically decision alternatives in different epochs to get insight about the impact of changing epochs. In the other end of the spectrum, this can potentially be entirely subjective. In these cases, communication with subject matter experts may be crucial. For these processes, evaluation, and ranking approaches, such as the decision-matrix method, quality function deployment or multi-attribute utility methods may be useful. It is natural to identify and start with the epoch describing the current situation, and then analyze how contextual changes will affect value.

All four steps are described even though step 3 is the most relevant in terms of determining the context parameters. This is because it is an iterative process, as illustrated by the feedback arrows in Figure 2-12. A proper understanding of how the epoch variables affect the value attributes of the system is not necessarily obtained before step 4. At this step, insights about the relationships are gained, and iterations back to step 2 and 3 may be necessary.

2.2.3. Temporal modeling of uncertain contextual factors

Decomposition based on the duration of the planning horizon is an effective way to handle temporal complexity. It is common to decompose the planning horizon into strategic, tactical, and operational planning (Christiansen et al. 2007; de Neufville 2004). Strategic planning refers to decisions with long-term implications, typically from three to ten years and longer. Tactical planning refers to decisions with medium-term implications, typically from months to three years. Operational planning refers to decisions with short-term implications, typically from day-to-day to months. Examples of maritime planning tasks within this framework are given in Table 3. Due to the long time horizons of marine systems, the ship design problem is classified as a strategic decision problem (Christiansen et al. 2007). A discussion about time scales in design of flexible systems is presented by de Neufville (2004).

Table 3: Strategic, tactical and operational planning horizons, with examples from shipping (adapted from Christiansen et al. 2007).

Planning horizon	**Maritime planning task examples**
Strategic (3-10 years / lifecycle)	- Ship design and fleet renewal problems - Fleet size and mix decisions: type, size, number of vessels
Tactical (months to years)	- Fleet deployment: assignment of specific vessels to missions - Routing and scheduling
Operational (days to months)	- Speed selection - Lifting operations

In this research project, we use scenario and era synonymously, as means to describe possible realizations of the future. A scenario is *"an internally consistent view of what the future might turn out to be – not a forecast, but one possible future outcome"* (Porter 1985). Scenarios are more commonly used in the literature, while era is primarily used in the context of the Epoch-Era Analysis (EEA) framework – representing the operationalization of futures through the combination and sequencing of epochs There are primarily two different aspects of scenario generation that are relevant to consider: (1) how they are generated (computational or non-computational), and (2) whether they are probabilistic or non-probabilistic. This gives four possible quadrants of scenario types, as illustrated in Figure 2-12 (right). We do not argue for which approach that should be used when, other than stating that it depends on: the degree of available data relative to the planning horizon, the stakeholders' expectations about the future, the degree to which the problem is *ill-structured* and *wicked* (Rittel and Webber 1973), and the purpose of the analysis - especially regarding the competence and experience of the intended users and the target audience.

Several authors in the literature even separate between the modeling methods based on the planning horizon for the same decision problem. For example, Gaspar, Erikstad, and Ross (2012) use optimization for tactical planning, and Epoch-Era Analysis for strategic analysis. A similar decomposition is presented by Kaut et al.

(2014) who present a “multi-horizon” approach for stochastic optimization planning applications, separating between the strategic and operational planning horizons. In the scenario planning literature, Schoemaker (1991) presents a decoupled method using scenario planning for strategic issues and Monte Carlo methods at the operational level. Issues with different planning horizons for system design applications are also discussed by de Neufville (2000).

Non-computational scenario generation

Although *scenario planning* can make use of computational methods, the central theme of the field is related to non-computational scenario generation. Scenario planning is a process for exploring alternative futures, where we seek to answer *“What can conceivably happen?*”, and “*What would happen if…?”* (Lingren and Bandhold 2003). Herman Kahn is often credited as the father of scenario planning through his work for the US military and the RAND Corporation with “future now thinking” (Kahn and Wiener 1967). An early proponent of scenario planning was Pierre Wack at Royal Dutch Shell (Paul J.H. Schoemaker and Van der Heijden 1992; Wack 1985). According to Schoemaker (1995), Royal Dutch Shell was often first in seeing overcapacity in several business segments and has been consistently better at forecasting than their competitors. Other companies that have used scenario planning include other oil companies (R. M. Grant 2003) and British Airways (Moyer 1996). There are multiple techniques and approaches for performing scenario planning, where a comprehensive review is given by Bradfield et al. (2005). Randt (2015) presents a case from conceptual aircraft design using scenario planning. The scenarios in scenario planning often do not consider probabilities, but scenarios can, of course, be assigned probabilities manually.

Computational scenario generation

Computational scenario generation methods can either be non-probabilistic or probabilistic, although the latter part seems to be most popular in the literature. Non-probabilistic scenario generation methods generally involve algorithms for sequencing instances of the relevant variables over time. One approach is full enumeration based on a discretized context variable representation, which quickly becomes computationally intractable. Another approach, to explicitly reduce the problem of intractability, is to include rules in the algorithms describing logical path dependencies such as “technological advancement must increase.” Probabilistic methods generally involve generating scenarios by sampling instances of the relevant variables over time, drawing from a probability distribution. A commonly used method for this is by use of Monte Carlo methods. An alternative method is scenario tree generation using moment matching of the properties of a probability distribution (Høyland, Kaut, and Wallace 2003).

2.3. Changeability in Design

This chapter presents the literature on changeability in design. The purpose is to understand how changeability can be utilized to handle lifecycle uncertainty to generate v*alue-robust* solutions, i.e., solutions that are capable of delivering value throughout the lifecycle also when facing unforeseen changes in key context parameters (Ross and Rhodes 2008a). It is of general interest to both reduce exposure to downside risks and increase exposure to upside opportunities. This subchapter starts by first defining changeability in design, before discussing how changeable design alternatives can be characterized and subsequently evaluated. This is in line with Hazelrigg's (1998) elegant simplification of systems design as the two-stage process of generating alternatives and selecting the best one.

2.3.1. What is changeability?

Changeability is a change-related system ility, as defined in Table 4. de Weck, Roos, and Magee (2011) describe the ilities as *"desired properties of systems, such as flexibility or maintainability (usually but not always ending in ility), that often manifest themselves after a system has been put to its initial use. These properties are not the primary functional requirements of a system's performance, but typically concern wider system impacts with respect to time and stakeholders that are embodied in those primary functional requirements. The ilities do not include factors that are always present, such as size and weight (even if these are described using a word that ends in ility)."*

When characterizing ilities for systems, it is important to be specific about the system boundary and the specific aspect of the system that the ility accounts for. For example, value-robustness can be achieved by designing a flexible ship. A demonstration of this example would be that the cash-flow and profitability is insensitive to perturbations in the market for the vessel, as the vessel is flexible and able to change its configuration easily to take a new contract with different technical requirements. At a lower level again, the ship may be robust, for example, that a mission can be carried out despite perturbations in the weather conditions.

In this research project, we may use flexibility and changeability interchangeably, which stems from the different target audience of the various research contributions. Changeability generally corresponds with the ability of a system to change form, function, or operation. Changeability is a collective term for change-related lifecycle properties in the broader set of general ilities, including, but not necessarily limited to, flexibility, adaptability, evolvability, scalability, upgradeability, versatility, and agility. Flexibility and adaptability are two aspects of changeability, corresponding to the location of the change agent, to whether it is respectively external or internal (Ross et al. 2008). Other contributions from the literature reviewing ilities include Chalupnik, Wynn, and Clarkson (2013), Ryan, Jacques, and Colombi (2013), Saleh, Mark, and Jordan 2009 and de Weck, Ross, and Rhodes (2012).

Table 4: Definitions of various ilities (adapted from de Weck, Ross, and Rhodes (2012)).

Ility	**Definition (“Ability of a system…”)**
Adaptability	to be changed by a system-internal change agent with intent.
Agility	to change in a timely fashion.
Changeability	to change its form, function, or operation.
Evolvability	to be inherited and changed across generations (over time).
Extensibility	to accommodate new features after design.
Flexibility	to be changed by a system-external change agent with intent.
Interoperability	to effectively interact with other systems.
Modifiability	to change the current set of specified system parameters.
Reconfigurability	to change its component arrangement and links reversibly.
Retrofittability	to satisfy diverse needs by change of form (contrasting versatility).
Robustness	to maintain its level and/or set of specified parameters in the context of changing system external and internal forces.
Scalability	to change the current level of a specified system parameter.
Survivability	to minimize the impact of a finite duration disturbance on value delivery.
Value robustness	to maintain value delivery despite changes in needs or context.
Versatility	to satisfy diverse needs without having to change form.

We make use of Figure 2-13 to help us understand changeability in the context of systems design. As discussed by N. P. Suh (1990), in the overall process of design, there is a mapping process from the *needs space* to the *functional space* culminating in the functional requirements, in the same manner as there is a mapping *function* to *form* that results in the design solution. To properly make use of the descriptions in Figure 2-13, it is important to be clear on what is meant by needs, functions, and form (with definitions form N. P. Suh (1990) and Crawley, Cameron, and Selva (2016)):

- **Needs** represent the preferences of the stakeholders, encompassing objectives and goals relating to business opportunities in current and future markets.
- **Function** is what the system *does*; it is the activities, operations, and transformations that cause, create, or contribute to performance.
- **Form** is what the system *is*; the physical or informational embodiment representing shape, configuration, arrangement, and layout.

We are generally interested in understanding how a design solution can satisfy changing needs, for example materialized through varying sets of functional requirements. For simplicity, we look at two alternative designs in Figure 2-13 represented by two sets in the form space. As we can see, Design #1 can satisfy a larger set of functional requirements than Design #2. Design #1 is thus more multi-functional, or versatile, by design. However, Design #2 can potentially change its form also, to become Design #1.

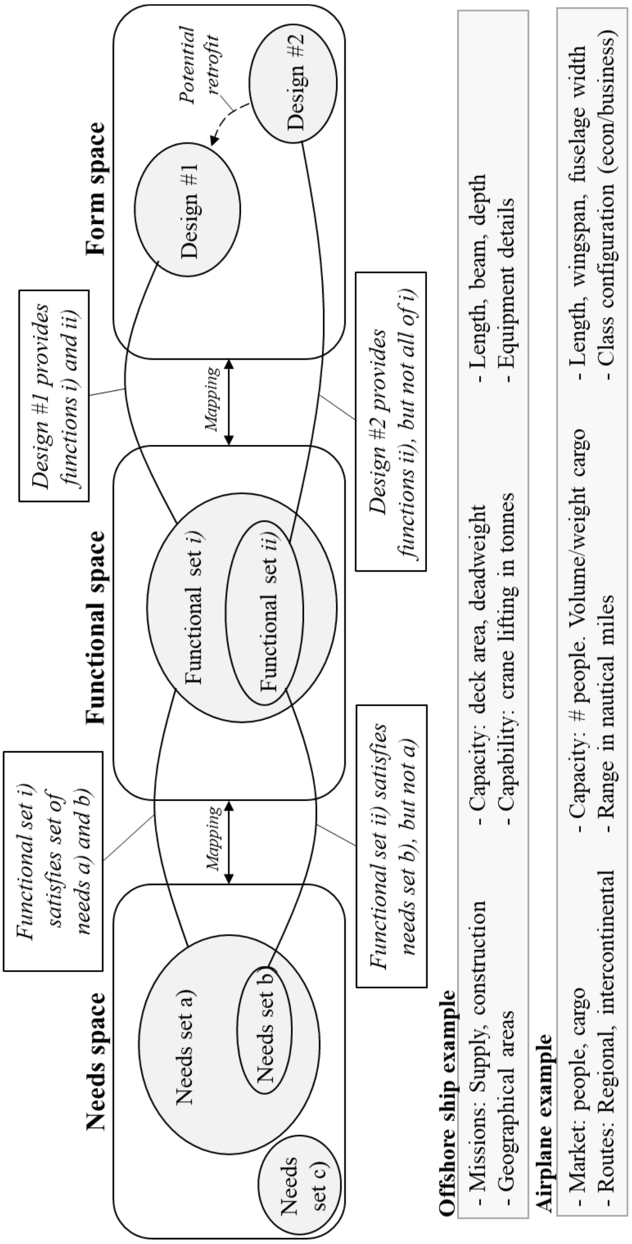


Figure 2-13: Describing changeability in different domains: needs, function, and form.

In terms of changes in form – form does not need to represent a system that is static in space and time – i.e., a description of the form of a ship can include a rotating propeller and a crane that needs to rotate to be used. Therefore, even though the physical geometries of these systems change while they are used, the description of the form is constant.

A motivating example for this research is the issue in conceptual design whether a ship should be designed only for the short-term needs, or to have additional capabilities to handle a broader set of needs that may emerge later in the lifecycle. In the case of design of non-transport ships, this can be regarding the technical requirements of the contracts in the market. However, adding extra equipment increases the investment costs. Alternatively, the ship can be designed for the first needs, but be prepared to be easily retrofitted later. Then, the retrofit decisions can be made after uncertainty has been resolved. This example illustrates two crucial, contrasting aspects of changeability that are central in this research project:

Versatility: the ability of a system to satisfy diverse needs, *without* change of form.

Retrofittability: the ability of a system to satisfy diverse needs, *by* change of form.

Versatility is an established ility in the literature, but there seems to be a lack for an aggregate ility that represents sole change of form. We define retrofittability to relate to any system change concerning change of form, including, but not limited to, reconfigurability, modifiability, scalability, and extensibility as defined in Table 4. Retrofittability thus represents a superset, comprising these four ilities relating to change in form.

The needs space can be challenging to characterize as it, in general, is unbounded: *What do you possibly want the system to do?* Similarly, the space of operational modes is unbounded and not necessarily simple to characterize. A discussion of characterization of operational modes in the context of ilities in systems design is given by Mekdeci et al. (2012). This problem relates directly to operations research, per definition.

A multi-functional ship would be versatile, while a single-functional ship prepared for retrofit would be retrofittable. The entire set of needs potentially relevant would be determined by the context, external to the system boundary. However, the cost and time of the two alternative ships to change between the sets of needs would be significantly different. The versatile ship would be able to provide much faster and cheaper change, compared to the retrofittable (naturally details depending on the case). The cost of this, however, is that the versatile design would be more expensive to build initially. Examples of versatile and retrofittable ships are given in Table 5 and Table 6 respectively. For more examples, the reader is advised to see Rehn and Garcia (2018). Retrofits do occur in the industry, and some examples of ships that have been retrofitted are given in Table 1.

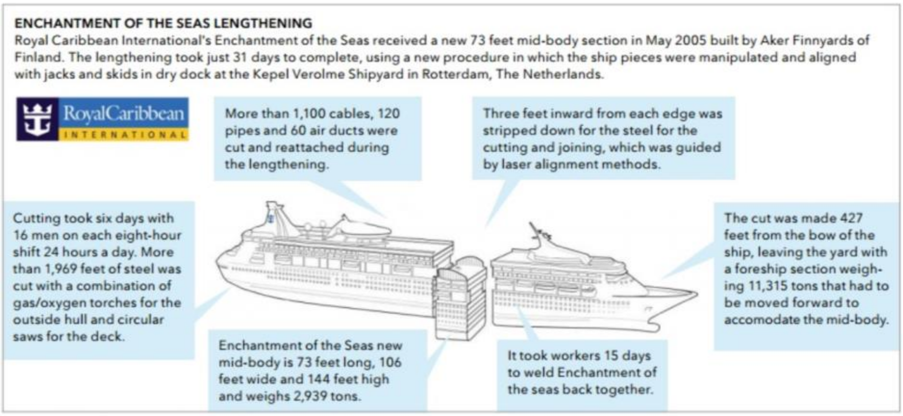
Table 5: Examples of versatile ships (Rehn and Garcia 2018).

Vessel name	Type	Built	Versatility description
Front Striver	Oil bulk ore	1992	Can carry either dry or wet bulk
AKOFS Seafarer	Well Intervention Unit	2010	Multi-purpose offshore ship
Wes Amelie	Container ship	2011	Dual fuel engine: diesel/natural gas

Table 6: Examples of retrofittable ships (Rehn and Garcia 2018), PSV = platform supply vessel, AHTS = anchor handling tug supply, MSV = multiservice vessel.

Vessel name	Type	Built	Retrofittability, prepared for:
Olympic Intervention IV	MSV	2008	Light well intervention tower
Olympic Zeus	AHTS	2009	250 tonnes crane
MV Barzan	Container	2015	Dual fuel capabilities - *LNG ready*
Dina Polaris	MSV	2017	150 tonnes crane, helideck

Trends in the maritime retrofit industry seem to be that equipment retrofit for non-transportation vessels and elongation of cruise vessels are relatively common. This contrasts with retrofits for transport ships, such as tankers and bulk carriers (Rehn 2018). An illustration of the elongation of Enchantment of Seas is given in Figure 2-14. The original ship was positioned in a drydock where it was cut in half, and a pre-produced module was inserted and combined with the two sections to generate the new elongated ship.



ENCHANTMENT OF THE SEAS LENGTHENING

Royal Caribbean International's Enchantment of the Seas received a new 73 feet mid-body section in May 2005 built by Aker Finnyards of Finland. The lengthening took just 31 days to complete, using a new procedure in which the ship pieces were manipulated and aligned with jacks and skids in dry dock at the Kepel Verolme Shipyard in Rotterdam, The Netherlands.

More than 1,100 cables, 120 pipes and 60 air ducts were cut and reattached during the lengthening.

Three feet inward from each edge was stripped down for the steel for the cutting and joining, which was guided by laser alignment methods.

Cutting took six days with 16 men on each eight-hour shift 24 hours a day. More than 1,969 feet of steel was cut with a combination of gas/oxygen torches for the outside hull and circular saws for the deck.

The cut was made 427 feet from the bow of the ship, leaving the yard with a foreship section weighing 11,315 tons that had to be moved forward to accomodate the mid-body.

Enchantment of the Seas new mid-body is 73 feet long, 106 feet wide and 144 feet high and weighs 2,939 tons.

It took workers 15 days to weld Enchantment of the seas back together.

Figure 2-14: Enchantment of the Seas lengthening illustration[1].

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[1] Illustration from DNV GL, source: https://www.green4sea.com/retrofitting-cruise-ships-to-lng-by-elongation/, accessed 12.02.2018.

2.3.2. Characterization of changeable design alternatives

To generate changeable design alternatives, we need to understand how we can measure the degree to which one design alternative is changeable compared to another. The general notion in the literature for determining what is more changeable is that a particular change can be made *quicker and at less effort* (Fricke and Schulz 2005; Ross, Rhodes, and Hastings 2008).

Changeability terminology

In this research project, we adopt the changeability terminology presented by Ross, Rhodes, and Hastings (2008). They propose that change can be described by an alteration between two system states and present a design-neutral framework to define changeability through three aspects: change agents, change effects, and change mechanisms. The change agent instigates a change and can be represented by human or nature. Change mechanisms describe the means by which the system is able to change, i.e., the path taken by the system in a change event. The mechanisms changing the system can be for example replacement of a deteriorated system component, operational changes, or a redesign of the system. The difference in the state before and after the change is quantified by the change effect.

Furthermore, path enablers are characteristics that allow the system to execute some change quicker and with less effort. One or more path enablers for a system can make possible a change mechanism, and the consequent change of end state, at a reduced effort (Beesemyer, Ross, and Rhodes 2012). Standard system design variables and path enabling variables differ in their purpose; while design variables drive value generation, path enablers enhance changeability and can be considered as dynamic change opportunities. An illustrative barge expansion case is given in Figure 2-15. Here we can see the state change, change effects, and change mechanisms. Only three out of several change mechanisms are considered for simplicity. The state change in Figure 2-15 is exemplified by the change of physical design variables (change in form), but changes can also be determined by of the mode of operation without a change in form (versatility).

This agent-mechanism-effect framework can be used for all aspects of changeability: change in form, function, or operation. An example of an operational state-change for a ship without a change in form can be the move an offshore ship between two operational areas, e.g., from the North Sea to the East China Sea. One can take different routes, such as through the Panama Canal, Suez Canal or through the Northwest Passage, each with an associated cost and time. An operational path enabler, in this case, can be to have a ice-reinforced hull to be able to sail in Northwest passage without help from other icebreaking assisting ships. Another path enabler can be to have larger engines to make the transition time quicker. In general, it is important to note that each state change can be enabled by many path enablers, which can be highly case specific.

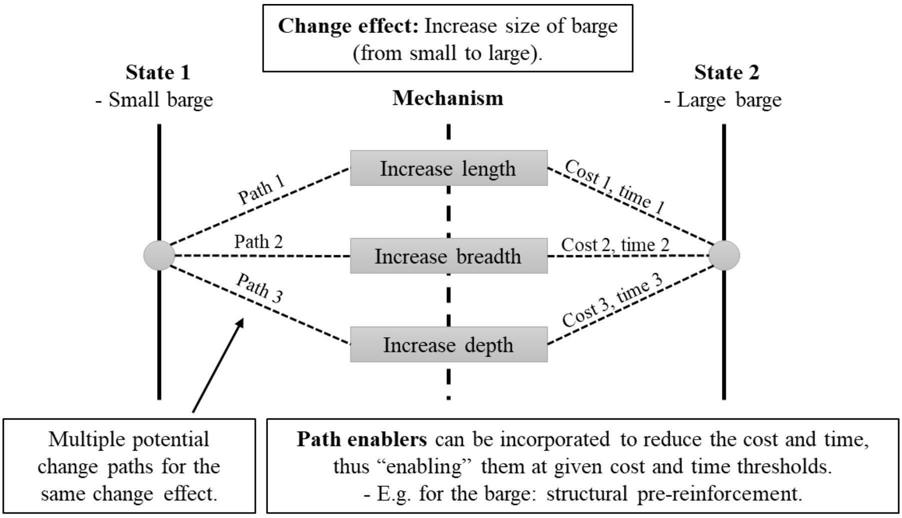

Figure 2-15: Illustration of change mechanisms, paths, path enablers and change effect for the hypothetical state change from a small to a large barge. The size of the barge can, e.g. be measured by the capacity to carry weight in deadweight tonnes.

Table 6 gives some examples of retrofittable ships, i.e., which have been prepared to make the retrofit job easier and quicker. In the agent-mechanism-effect framework, this means that path enablers have been included in the initial design to ease the change process. For crane retrofit, such path enablers can be modular interfaces, hull reinforcement, sufficient stability enabled by the ship as a *platform*, and provision of sufficient space around areas potentially needed for additional systems. For the retrofit of a light well intervention tower, the pre-installation of a moonpool (or prepared for moonpool retrofit) can significantly reduce the change costs and time. Modularity in ship design is discussed by Erikstad (2009) and Doerry (2014).

Identification of candidate flexibilities and characteristics enabling flexibility is generally discussed by de Neufville and Scholtes (2011) and Cardin and de Neufville (2008), including methods such as interviews, information-flow, and screening. Screening models are low fidelity representations of the performance of a system, which easily can be studied under varying contextual conditions, and the most important design variables and candidate flexibilities can be extracted. Screening methods are in detail covered by de Neufville and Scholtes (2011), who characterize it as the recommended approach for identifying the most valuable kinds of flexibility in design. Identification of flexibility in marine systems design is discussed by Rehn (2015).

In the literature on marine systems design, some authors describe characteristics of systems making them prepared for change (what we also call path enablers). An early contribution on upgradeability in ship design (and systems engineering in general) is presented by Buxton and Stephenson (2001). They present a methodology to investigate the economic benefit for design alternatives with varying degrees of upgrade-capabilities, from small and optimized, small and upgradeable, to large and versatile. The general approach in this research project is very similar to the one presented by Buxton and Stephenson (2001). They present a case study from a container ship design case, upgrading from 3500 twenty-foot equivalent units (TEU) to 4500 TEU. They conclude that the ship prepared for elongation has a higher expected net present value, despite the prepared for upgradeability cost of about $10 million. The path enablers Buxton and Stephenson (2001) include for the upgrade case include added space, added services, margins on ancillaries and margins on major equipment. These were combined to generate alternatives with varying degree of upgradeability – all with 3500 TEU capacity to be upgraded to 4500 TEU. These varying degrees of upgradeability means that a potential 1000 TEU upgrade later in the lifecycle can be performed cheaper and quicker. Table 7 presents some of the upgradeable container ship design alternatives from their analysis.

Table 7: Changeable design alternatives characterized by combinations of path enablers, here exemplified for the expansion of a container ship described by Buxton and Stephenson (2001) from 3500 to 4500 twenty-foot equivalent units (TEU).

Design	Built-in path enablers for upgrade from 3500 TEU to 4500 TEU
A	Additional hull strength, space, and weight margins.
B	Additional services “fitted for, but not with”: power dist., piping, ventilation.
C	Additional auxiliary equipment (cranes and el. generators) is provided.
D	Some items of the major equipment are oversized (e.g., propulsion system).

A similar approach as presented by Buxton and Stephenson (2001) to characterize changeable alternative designs is used by Fitzgerald and Ross (2012a, 2012b) and Fitzgerald, Ross, and Rhodes (2012). The latter authors use the “design for changeability (DFC)” notion for characterizing changeable alternatives as introduced by Fricke and Schulz (2005), who in turn discuss principles characterizing changeability in design. In general, the literature seems to converge to elicit flexible design alternatives based on which path enablers are included to make a specific state change easier. However, again, the case for the ship described in Table 7 only accounts for retrofittability for the state-change of upgrading the capacity of a container ship. The structure presented in Table 7 can be generalized to account for state-changes of all sorts: change of form, function, or operation.

A related field of research to flexibility in design is the utilization of platform-based product development. Research on the development of product platforms is related to the development of *product families*, which represent a set of products derived from a common platform. Meyer and Lehnerd (1997) define a product platform as *“a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced.”* The concept of product platforms in the literature is usually discussed in the context of manufacturing, related to mass customization of product families. Thus, platform thinking can be particularly useful for shipyards. Modularization, product platforming and modular production in shipbuilding is discussed by Erikstad (2009). Conceptual ship design research often discusses modularization to incorporate all necessary ship subsystems within the hull, with examples such as Design Building Blocks (Andrews 2012), and the Packing Approach (van Oers 2011). An alternative view of the platform concept is related to the design of large, complex, and unique systems subject to temporal uncertainty of future use and demand. Thus, this can be particularly interesting from a shipowner's perspective, as they need to handle uncertainty throughout the lifecycle of an asset. In this research project, we focus on the latter approach and use *platform* instead *product platform* notation to be specific. However, in the literature, there seems to be overlapping definitions.

The tradeoff between investment cost and changeability level

There is usually is an investment cost of adding path enablers to a design alternative. The consequence is the expected reduction in the cost (and/or time) of the state-change. There is, therefore, a tradeoff between the up-front investment cost and the cost of change, as is illustrated in Figure 2-16 for a single-dimension expansion case. As for practical problems, there are multiple changes that can be made to the system; the tradeoff becomes multi-dimensional and more complex.

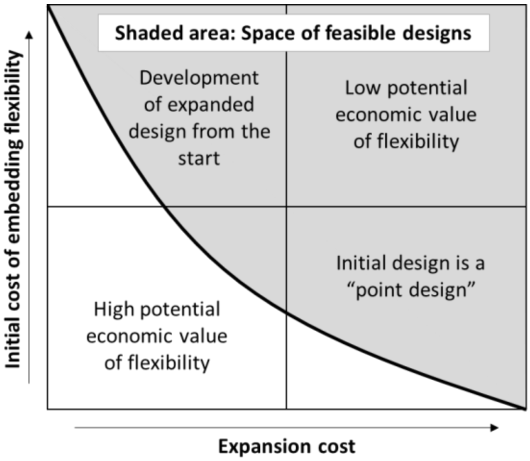

Figure 2-16: Illustration of the tradeoff between initial cost of flexibility (path enablers included) and expansion cost reduction (flexibility "level") (excluding aspects of change time) (adapted from Nembhard and Aktan (2009) – Chapter 10 by K. Kalligeros).

Quantifying the level of changeability for a design alternative

To differentiate between changeable design alternatives more explicitly, it is beneficial to quantify the reduced state-change effort that different sets of path enablers give. For example, what is the reduced expansion cost if we include a particular path enabler?

a) Filtered outdegree

Probably the most significant contribution in the literature on quantification of changeability level in design is the filtered outdegree (FOD) metric, introduced by Ross (2006). The FOD metric quantifies changeability level within a networked tradespace, where nodes are design alternatives and arcs represent change paths. Several paths may exist between two nodes, as different change mechanisms exist resulting in the same change effect (see Figure 2-15). There are a cost and time associated with each change-path. FOD is a measure quantifying the level of changeability by counting the outgoing paths or arcs from a design alternative, counting either change mechanisms or end-states reachable at a given cost and time threshold, respectively. A networked tradespace is illustrated in Figure 2-17, where cost and time filters are applied, resulting in a reduced set of feasible arcs. An arc thus is defined if there exists a change path between the nodes within the acceptable cost and time threshold applied.

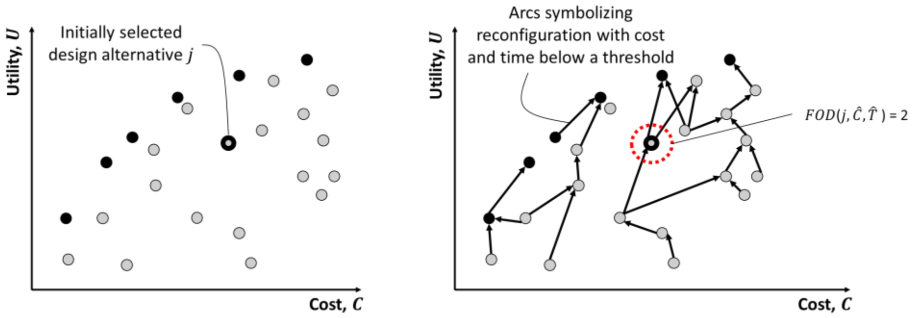

Figure 2-17: Tradespace representation left (a), and filtering for cost right (b) (Rehn et al. 2018).

The outdegree of a design alternative represents the number of outgoing arcs from a node, and by applying a cost and time threshold for a transition between two nodes, the Filtered Outdegree (FOD) is defined. The $FOD\left(j,\hat{C},\hat{T}\right)$ metric quantifies the number of feasible outgoing arcs from node j to all nodes in the set J, under given cost $\hat{C}$ and time $\hat{T}$ thresholds, as given by Equation (3) (adapted from Fitzgerald, Ross, and Rhodes (2012)).

$$FOD(j, \hat{C}, \hat{T}) = \sum_{d \in J} H(C_{j,d}, T_{j,d}), \ \forall\, C_{j,d} < \hat{C}, \ \forall\, T_{j,d} < \hat{T} \qquad (1)$$

$C_{j,d}$ and $T_{j,d}$ are cost and time for transitioning from node j to d, and H is the Heaviside function defined as 1 if there exist a path where both change cost and time for the node transition are below the thresholds, and 0 else. Hence, this consideration only counts end-state changeability. However, the metric can easily be changed to be defined as counting the number of change paths between two states, if that is relevant for the analysis. In general, the FOD metric can be used for changes in form, function, or operation. Equation (3) is given without explicit DFC specification, as this information is assumed integrated in node j. However, DFC can also be explicitly described in the formula.

In the shipping literature, Stopford (2009) introduces an interesting metric for quantifying the flexibility of a design alternative called *lateral cargo mobility* (LCM). LCM measures the number of different types of cargo a vessel can carry and is thus a somewhat similar measure to FOD. However, LCM only concerns versatility – i.e., the ability of a design to satisfy a diverse set of needs without a change in form. The LCM for alternative ship types is illustrated in Figure 2-18.

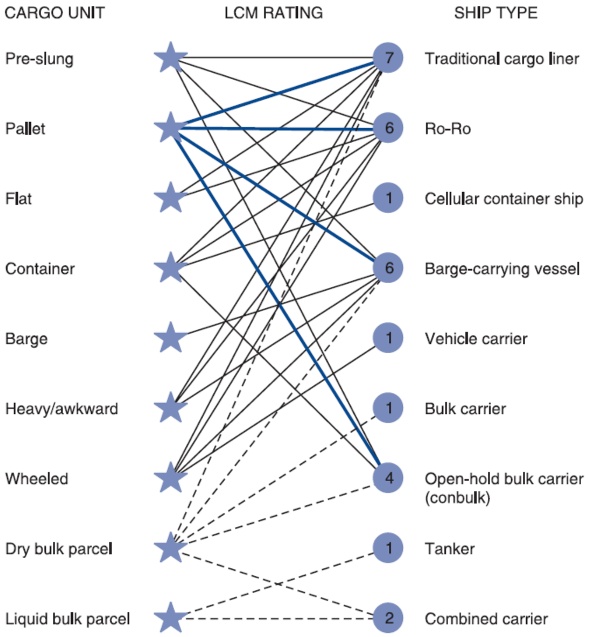

Figure 2-18: Flexibility analysis by Stopford (2009), where LCM refers to lateral cargo mobility measuring the number of different types of cargo a vessel can carry as a measure of flexibility.

b) Other methods

Increased changeability for a design alternative enables it to change between states more easily, i.e., faster and cheaper. Some authors in the literature measure the changeability of a system based on the expected reduction of change cost. Gu, Hashemian, and Nee (2004) and Spackova, Dittes, and Straub (2015) present normalized measures based on the relative cost savings of performing a change. However, change time and range have received less attention in the literature on changeability level quantification.

Issues with quantifying states and state-change costs

There can be issues with discretely quantifying states of form, function, and operation for a system. This may be especially difficult for the modes of operation, as this is system-external and to a higher degree unbounded by the control variables of the designers (Mekdeci et al. 2012). However, even the space of functional representations of a design alternative can be difficult to characterize. E.g., in emergency situations, there are several examples where functions that were not planned for nor recognized in the design phase (*latent*, as opposed to *manifest*) can be identified and utilized to provide emergency support. A classic example of this is the Apollo 13 mission where the lunar module was used as a lifeboat for the crew to safely return to earth after a critical failure to the command and service module. This was an exercised changeability mode that was not intentionally designed for but turned out to be extremely valuable. Pettersen, Erikstad, and Asbjørnslett (2017) discuss latent and manifest functional capabilities, with the perspective of resilience in system design. In this research project, we mainly focus on manifest capabilities explicitly designed for and recognized at the design stage.

Since change many propagate and have unforeseen effects (especially regarding change in form), it can be difficult to estimate the consequences of making changes to systems. Thus, changeability is also related to the field of change propagation and prediction, often referred to as research on *engineering change*, for which an extensive literature review is found in Jarratt et al. (2011). An important contribution to this field is by Clarkson, Simons, and Eckert (2004), who present the Change Prediction Method to predict the risk of change propagation in terms of both change likelihood, and impact. This model is based on the Design Structure Matrix (DSM) system representation method (for DSM see Eppinger and Browning (2012)). In their paper on change and customization in complex engineering domains, Eckert, Clarkson, and Zanker (2004) describe and analyze how change is handled. They discuss strategies for coping with change, such as including adequate margins in a design which can absorb changes. An example is presented to illustrate margins to absorb changes: An engine might be powerful enough to support a certain increase in weight of an aircraft, but if the weight increase is too large, the engine must be modified. This is directly related to research on design for changeability, as it involves means to reduce change effort. In their paper on design of flexible product platforms, Suh, de Weck, and Chang (2007) measure the degree to which a system component amplifies or reduces change propagation using the change propagation index (CPI). This is one approach to identify suitable components that can be made changeable, for example through margins. An alternative approach is presented by Kalligeros, de Weck, and de Neufville (2006), who utilize Sensitivity Design Structure Matrices (SDSM) introduced by Yassine and Falkenburg (1999).

2.3.3. Evaluation of changeable design alternatives

The purpose of evaluation in design decision making is to rank order alternatives (Hazelrigg 1998), so we can select the best alternative. This section briefly presents methods and insights from literature for evaluation of flexible design alternatives. Since the exercise of flexibility is a property of the system that manifests over the lifecycle, explicit understanding of the operational phase is important. To demystify the difference between the quantification of changeability level and the evaluation of changeability, we present Table 8. In contrast to changeability level quantification (which is used to measure the reduced effort of change for a design alternative), evaluation is used to select the best design alternative.

Table 8: Illustrative example of changeability description, level, and value, for a hypothetical container ship expansion case from3500 TEU to 4500 TEU (NB: numbers are for illustrational purposes) ENPV = expected net present value.

“Generate alternative changeable designs”			**“Select the best one”**
Des. alt.	Changeability description	Changeability level	Evaluation (ENPV)
A	Path enabler set 1	5% red. upgrade cost	$5 million
B	Path enabler set 2	10% red. upgrade cost	$7 million
C	Path enabler set 3	15% red. upgrade cost	$10 million
D	Path enabler set 4	25% red. upgrade cost	$5 million

What is value?

The notion of v*alue* is essential for the selection among alternatives, as it dictates what is a better design. Without a definition of value, design as a process of generating alternatives and selecting the best one (Hazelrigg 1998) becomes meaningless. An overview covering multiple aspects of- and methods for evaluation in systems design is presented by de Neufville (1990). This research project does not specifically focus on perceptual complexity (Rhodes and Ross 2010), so we will not discuss aspects of valuation in detail, although it is an interesting field of research. In the following, we briefly cover utility theory and economic measures of merit, as they are observed in the literature for evaluating flexible design alternatives.

Utility theory

Utility is a measure of preferences used to rank alternatives and was first introduced in the 18th century by Bernoulli. In the early 20th century, it was popularly used by economists to explain customer preferences and market behavior (Hazelrigg 1996) and was extended by von Neumann and Morgenstern (1944) to include risk. They present four axioms of expected utility theory defining a rational decision maker: 1) *completeness* – preferences are well defined, 2) *transitivity* – preferences are consistent across options, 3) *independence* – preferences hold independently of irrelevant alternatives, 4) *continuity* – no discontinuous jumps in preferences.

Multi-attribute utility theory is a method to capturing preferences in a hierarchy of objectives. An example of a multi-attribute utility hierarchy for the evaluation of an offshore ship is presented in Figure 2-19. For practical purposes, there should not be more than about seven attributes on each level in the hierarchy (Miller 1956). To represent a meaningful value representation, multi-attribute utility must be structured according to the following five principles (Keeney and Raiffa 1993):

1. **Complete**, representing all important properties.
2. **Operational**, possible to measure and represent in an analysis.
3. **Decomposable**, meaning that it can be broken down into parts that can be analyzed more easily.
4. **Non-redundant**, suggesting that the aspects of importance should not be double-counted.
5. **Minimal**, meaning that the number of attributes should be kept small as possible.

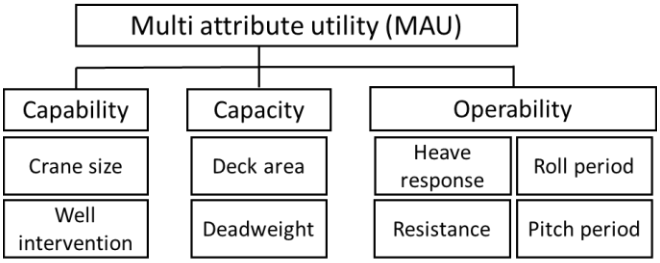

Figure 2-19: Example of a multi-attribute utility function capturing the performance attributes for an offshore ship for a hypothetical ship owner (Rehn et al. 2018).

Economic measures of merit

Economic evaluation in design generally involves the investigation of whether a project is worthwhile to undertake. As discussed by Benford (1970), there are multiple economic measures of merit in ship design. Economic measures comprise some sort of transformation of cash flows in time into a single metric, usually discounted to present value. These can be net present value (NPV) or internal rate of return (IRR), which also can be probabilistically estimated with considerations of their expected value and/or higher moments of the outcome distribution such as variance or tail descriptions such as value at risk (VAR). Thus, these measures can more easily be presented to decision-makers who can attribute preferences of e.g. risk attitude in order to make decisions. Economic measures are obviously relevant for commercial systems but may be difficult to apply to non-commercial design problems such as for the Navy or Coast Guard, as they naturally do not have commercial revenues.

As discussed by Hazelrigg (1998) “it is not a trivial task to identify a valid value measure, particularly one that is valid under conditions of uncertainty and risk.” Two general aspects that complicate evaluation are: (1) what is the attitude towards risk for the stakeholders, and (2) what is the preferences for trading off value in time for the stakeholders? Properly capturing these aspects is difficult. Other interesting critics of the use of utility functions is the regard to which people are rational. For example, Tversky (1969) present evidence that people are not rational as they often do not satisfy the transitivity condition. One can also see how the transitivity axiom is violated in group decision problems without empirical studies, only anchored in Arrow’s impossibility theorem (Arrow 1950). This is discussed by de Neufville (1990) and (Hazelrigg 1996).

What are real options?

The most common approach for valuation of managerial flexibility in the literature is by real options analysis, focusing on economic evaluation. Real options extend the field of financial options to concern physical systems, and was coined by Stewart Myers in 1977.

Options and real options

Options are one category in the larger group of *derivatives*, meaning that their value is derived from an underlying asset. Other derivative categories include future contracts, swaps, and forward contracts. An option has the key feature that it represents the *right but not the obligation* to undertake some action under some predefined arrangements. In the stock world, this is typically the right but not the obligation to buy or sell stocks at a predefined price within a given time. As there are multiple boundary conditions for options, there is a myriad of option types and classes. For example, whether an option gives you the right to buy, or sell, is called *call* and *put* respectively, and whether it can be exercised only on, or also before, the time limit is called *European* and *American* respectively. *Compound* options are options on options. These are just a few of a large class of options that can be constructed. There are multiple good references on options and real options, including McDonald (2003), Trigeorgis (1996) and Dixit and Pindyck (1994).

Table 9: Stock vs. real options analogy (Wijst 2013).

Determinant	Stock option	Real option
Underlying	Stock	Project revenue
Strike	Exercise price	Investment
Time to maturity	Maturity	License validity
Volatility	Stock std.	Price volatility
Interest rate	Risk-free	Risk-free

Real options extend the traditional financial options to concern investments in real assets as underlying values, instead of stocks or bonds. Some fundamental differences between stock options and real options are given in Table 9, and examples of common real options are presented in Table 10.

Table 10: Common real options from the managerial literature (not design) (Wijst 2013).

Call options	Put options	Compound options
Defer	Default	Phase investments
Expand	Contract	Switch inputs
Extend	Abandon	Switch outputs
Re-open	Shut down	Switch technology

As a motivating example for the relevance of real options for ship design, we can consider a ship as an *investment* – which it obviously is for the shipowner. An investment generally means incurring a cost with the expectation of future rewards. Dixit and Pindyck (1994) discuss three important characteristics that most investment decisions share, which interact to determine the optimal decisions for investors:

1. **Irreversibility**: Investments are usually partially or completely irreversible. The initial investment is at least partially sunk, and you cannot recover it all if you should change your mind.
2. **Uncertainty**: There is uncertainty related to the future rewards of the investment, and the best one can do is to assess probabilities of various outcomes.
3. **Timing**: You must have some insight into the timing of the investment. An investment can often be postponed to get more information (but never complete certainty) about the future.

Not only is the ship acquisition itself an investment, but managerial decisions throughout the lifecycle of an asset can also share the characteristics of investments. For example, shutting down a loss-making plant is an "investment" where the *initial expenditure* is the payment made to extract from contractual commitments including labor severance payments, and the *reward* is the reduction in future losses (Dixit and Pindyck 1994). This decision is not fully reversible, anchored in uncertainty about the future losses, and involves the choice of timing. Alternatively, locking a ship on a long-term contract will give some reward, but there is a risk that the shipowner will lose out on a much higher income if the market surges meanwhile the shipowner is locked to the long-term contract. From this perspective, investment decisions are everywhere. Dixit and Pindyck (1994) use this reasoning to motivate the importance of proper assessment of investments, using a real options approach, instead of the "orthodox" deterministic approach often used (like static NPV). "Real options are everywhere." This notion is usually considered by all real options practitioners, for example, addressed by de Neufville and Scholtes (2011) for practical engineering design applications. Another reason to be careful with deterministic NPV analysis is the *flaw of averages* (Savage 2009). Disregarding uncertainties and basing estimates on averages will result in mathematically wrong estimates, given that the underlying system dynamics are nonlinear.

Real options "in" and "on" projects

An interesting differentiation between two types of system flexibility is whether it can be characterized as a real option "in" or "on" projects. "*Real options "on" projects refer to the standard real options treating the physical systems as a "black box," in contrast with real options "in" systems that concern design features built into the project or system"* (Wang and de Neufville 2005). Some types of managerial flexibility are "always present" for assets in operation, such as entry, lay-up, reactivation, and abandoning. For example, if the contribution margin of a ship is negative due to low market rates, then the manager would obviously consider temporary layup. This type of flexibility is characterized as **real options "on" projects.** However, other aspects of flexibility are not equally present for all assets, such as capacity expansions or market switching. These are dependent on the details of the system by design – is it designed so it can be easily expanded, or is the ship a combination carrier? This type of flexibility is characterized as **real options "in" projects**. Real options "in" projects are thus characterized by either of two aspects: (1) versatility explicitly designed for (e.g., a combination carrier), or (2) that the change considers any type of retrofit – i.e., change of *form*. Differences between real options "in" and "on" projects are presented in Table 11.

Table 11: Real options "in" and "on" projects (Wang and de Neufville 2005)

Real "on" options	Real "in" options
Value opportunities	Design flexibility
Valuation important	Decision important (go or no go)
Relatively easy to define	Difficult to define
Path-dependency less an issue	Path-dependency an important issue

Further, the general exercise of a real option by going to the *market* to change a system would qualify as an "on" option, even though the intentions are of "in" options nature such as adding technical capabilities. For example, instead of physically expanding a cruise ship, you can sell the small ship you have, and buy a larger one in the second-hand market. However, for multiple reasons this can be expensive or even not possible – perhaps there is no market, or at least not an efficient market.

Another contemporary example is with radio technology: What if the FM radio network suddenly is shut down in your country and the government decides that DAB radio is the new system to use? What do you do if you still want to have an (integrated) radio in your car? You can retrofit your car with a new radio, or you can sell the car in the market and buy a similar one - except that the new one has the DAB radio. If there exists a market that is efficient with no transaction costs, it would probably not matter whatever you choose. However, this may likely not be the case – even for such a liquid market as cars. Retrofitting the ratio would qualify as an “in” option, while the market option would qualify as an “on” option. This example also illustrates the case of *changeability level*, because some cars have modular radios that make them easily exchangeable (cheap and fast to retrofit), while others have expensive integrated systems which only can be changed by slower and expensive experts. For a thorough discussion on “in” and “on” options, the reader is advised to see Wang and de Neufville (2005).

Applications of real options “on” projects in shipping are generally addressed by Alizadeh and Nomikos (2009). Other contributions include Dixit (1988, 1989), who evaluate entry, exit, lay-up and scrapping options, Bjerksund and Ekern (1995), who present an evaluation of mean reverting cash flows in shipping, Bendall and Stent (2007), who investigate maritime investment strategies as portfolios of real options, Sødal, Koekebakker, & Aadland (2008), who present a real option analysis of market switching in shipping, and Acciaro (2014), who present a real options analysis for the application to invest in liquefied natural gas (LNG). Knight and Singer (2012) present a case involving the evaluation of the elongation option of a container ship, which is an “in” option.

Real option evaluation

The following discussion is largely based on the excellent material provided by de Neufville (2009) and Wang and de Neufville (2005). These authors provide a nuanced discussion on real options evaluation, specifically addressing potential issues with regards to applications to design of flexible systems. If the reader is interested in this topic, we recommend the online learning material provided by de Neufville (2009). That being said, classical options evaluation theory and applications are otherwise covered by for example McDonald (2003), Trigeorgis (1996) and Dixit and Pindyck (1994).

Basic concepts of financial options evaluation

An option will give you *the right but not the obligation* to undertake an action, which gives the option holder a fundamental positive payoff (disregarding the cost of the option). Hence, options have an *asymmetric* value-property: one side is limited, the other side is unlimited. Three fundamental concepts of financial options valuation are shortly discussed: a) replicating portfolio, b) arbitrage enforced pricing and c) risk-neutral “probabilities.”

A central assumption that financial option pricing methods rely on is that you can create a *risk-neutral replicating portfolio* which can be evaluated. Since this portfolio replicates the option’s payoff, their values must be the same according to the *law of one price*. This is done because the evaluation of the replicating portfolio may be easier. However, replicating an option is not necessarily easy. We illustrate how a replicating portfolio works with an example for a simple two-stage binomial call option adapted from de Neufville (2009). A call option can be considered as buying an asset with borrowed money. This is because, if exercised, it results in ownership, and the payment is delayed until the exercise. Illustration of the development of the asset price, the option value and the value of the riskless loan for the example is given in Figure 2-20.

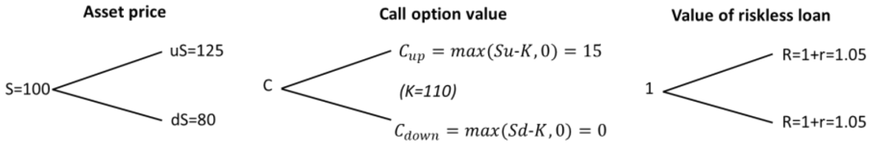

Figure 2-20: Illustration of the asset price, the option value, and the value of the riskless loan over the single-period binomial example, numbers in dollars.

Table 12 presents the portfolio cost and payoffs for a simple two-period binomial tree, starting at an asset price of $100 with two end-states: up to $125 or down to $80. The strike price (*K*) is $110. If the asset price goes up, the option payoff is $15, if it goes down, it is not exercised, and the payoff is 0. The risk-free interest rate for borrowing the money is r, here assumed 5%.

Table 12: Call option replicating portfolio, cost, and payoffs.

Period	**Start**	**End down**	**End up**
Asset price (S)	100	80	125
Buy asset	-100	80	125
Borrow money	80/(1+r)	-80	-80
Net portfolio value	-100+80/(1+r)	0	45

The payoff from the replicating portfolio in Table 12 has the same structure as the call option with a strike price at $110, but the single option payoff is a third of the portfolio payoff. The value of the option is C, interpreted as the maximum one should be willing to pay for the option. Table 13 presents the comparison of the payoffs from the replicating portfolio, and three of the call options, which we can see are identical.

Table 13:Comparison of the payoffs of the replicating portfolio and three of the call option.

Period	**Start**	**End down**	**End up**
Asset price (S)	100	80	125
Buy 3 call options	-3C	0	45
Replicating portfolio	-100+80/(1+r)	0	45

Since the option and the replicating portfolio have identical payoffs, their prices must be the same if the *no-arbitrage* condition holds. The value of this call option is therefore $C = \frac{1}{3}\left(100 - \frac{80}{1+r}\right)$. Since a seller of this option can hedge the sale with a portfolio of equal value, the seller can arrange so that he or she cannot lose. In this case, there would be no risk for the seller. Therefore, the appropriate discount rate r is the *risk-free* interest rate. If we assume the risk-free interest rate to be 5%, the value of this call option would be $C = \$7.94$.

An interesting observation from the call option example is that the calculated value did not involve any probabilities for the two scenarios considered, which is a bit counter-intuitive. We only dealt with ranges of outcomes, with consequent payoffs. Apparently, this example does not deal with the "expected value" of the option price but relies on the *arbitrage-enforced pricing* assumption. That is, the replicating portfolio *defines* the value of the option, as it permits the market to define the value of the option indirectly. Any mispricing of the option itself will be canceled out by risk-free arbitrage in the market.

When applying arbitrage-enforced pricing to the binomial lattice option pricing model (Cox, Ross, and Rubinstein 1979), we make a transformation from the real probability scenarios to risk-neutral "probability" measures. The risk-neutral "probabilities" are determined only by the growth rate and volatility of the underlying asset, and are not actually probabilities.

An illustrative example follows. We look at a two-stage binomial tree again, as illustrated in Figure 2-20. We need to find the weights to generate the replicating portfolio and assume that Δ and B are the fractions of asset and loan respectively. This gives us two equations to solve. The first represents the condition if the underlying price goes up, while the second represents the condition if the underlying price goes down.

$$\Delta uS + B(1 + r) = \max(Su - K, 0) = C_{up} \tag{2}$$

$$\Delta dS + B(1 + r) = \max(Sd - K, 0) = C_{down} \tag{3}$$

We know that the portfolio value equals the option price. Solving the equations then gives us the following option price:

$$C = \frac{1}{(1+r)}\left[qC_{up} + (1-q)C_{down}\right] \tag{4}$$

$$q = \frac{(1+r) - d}{u - d} \tag{5}$$

If we fill in for the values, we get $q = 0.55$, and $C = \frac{1}{1.05}[0.55 * \$15 + 0.44 * \$0] =$ \$7.94. This is the same number that we calculated in the earlier example. We have thus demonstrated how the risk neutral "probabilities" represent arbitrage-enforced valuation.

Probably the most famous contribution of evaluation of options is the Black Scholes formula (Black and Scholes 1973), which is an analytical solution for a European put or call option. This formula relies on the arbitrage-enforced pricing assumption. By solving a partial differential equation that describes the price of the option over time, the following analytical solution can be derived for the value of a call option at time zero of a non-dividend paying stock (McDonald 2003):

$$C = N(d_1)S_0 - N(d_2)Ke^{-rT} \tag{6}$$

$$d_1 = \frac{1}{\sigma\sqrt{T}}\left[\ln\frac{S_0}{K} + \left(r + \frac{\sigma^2}{2}\right)T\right] \tag{7}$$

$$d_2 = d_1 - \sigma\sqrt{T} \tag{8}$$

As in the earlier example, *S* is the price of the underlying asset, *T* is the time to maturity, *N* is the cumulative distribution function of the standard normal distribution, *K* is the strike price, *r* is the risk-free interest rate, and σ is the volatility of returns of the underlying asset. To better understand the value of a European call option under the Black Scholes assumptions, we can investigate some underlying relationships. The Greeks are quantities that represent the sensitivity of the option price to changes in the underlying parameters in the model, mathematically represented as derivatives. From the Greeks, we can see that prime drivers of the value of an option are uncertainty (volatility) and time: the greater the uncertainty, and the longer the option is available, the greater the option value. This is important in general for the value of flexibility in systems design.

The Black Scholes formula works well to illustrate the underlying dynamics of options pricing but is not necessarily used for pricing actual financial options in real life (Taleb and Haug 2011). One of the reasons for this is the assumption that the underlying asset price follows a lognormal distribution which has significantly "thinner tails" than what is the case in reality (Taleb 2009). This discussion is for financial markets, and not even for the case with "in" options which this research project concerns (Wang and de Neufville 2005). A critical perspective on use of financial option pricing methods are also presented by Borison (2005). In addition to the analytical (Black Scholes) and lattice methods (e.g., binomial lattice by Cox, Ross, and Rubinstein (1979)), evaluation by Monte Carlo simulation is popular, for example by using the least-squares approach developed by Longstaff and Schwartz (2001).

Evaluation of real options "in" projects

Arbitrage enforced pricing works when one can create a replicating portfolio, and when the option and the replicating portfolio can be traded. It is critical for the method that these assumptions are met. For financially traded options it may be possible, but it may not be possible for technical systems such as the call option to expand a facility. *"If arbitrage-enforced pricing does not work for a real options project, there is no sense to talk about Black-Scholes formula or risk-neutral valuation"* (Wang and de Neufville 2005). Wang and de Neufville argue that especially the no-arbitrage assumption is often hardly valid for real options "in" projects. In these situations, instead of using risk-neutral "probabilities" and risk-neutral discounting, one has to perform "actual valuation" using actual probabilities and risk-adjusted discount rates.

A generalized flexibility evaluation framework is to estimate the value of the system with and without flexibility, and their difference is the value of flexibility. A multitude of measures of merits and evaluation methods can be used under this framework. A generic approach is to develop a simulation model with an agent that makes the managerial decisions regarding the exercise of flexibility, either "optimally" or exploratory in line with managerial strategies preferred by the stakeholders. Hassan, de Neufville, and McKinnon (2005) present the following formula for estimating the expected discounted value of flexibility in design:

$$flexibility\ value = E(NPV)_{flexible} - E(NPV)_{inflexible} \tag{9}$$

There is additionally a multitude of approaches developed for evaluation of flexibility in design. For example, for non-commercial systems where the lack of cash flows makes financial approaches difficult, alternative representations of value need to be considered. Fitzgerald (2012) presents a valuation approach for strategic changeability, using multi-attribute utility theory and different metrics developed to evaluate design alternatives in concert with Epoch-Era Analysis (EEA). Knight, Collette, and Singer (2015) present a real options evaluation approach using utility theory, loss aversion and game theory for applications to navy ship design. Cardin and de Neufville (2008) present a case using decision analysis to evaluate flexibility. An interesting critical discussion on the use and misuse of real options analysis, in general, is discussed by Hubbard (2009), who points out that perhaps it is better to just call it "what it is": decision theory, dealing with decisions under uncertainty – as options have been around since the beginning of the field of decision analysis (Howard 1968).

Another issue with evaluation of flexibility in design is how to cope with unbounded problems such as the use of a generic modular slot. For example, how do you evaluate the use of a USB connection on your computer, when you do not know what it can be used for in the future? As stated earlier in this thesis, we focus on manifest functions that are recognized and intentionally designed for. A discussion of latent and manifest system functions is presented by Pettersen, Erikstad, and Asbjørnslett (2017). Some interesting comments on modularity are presented by Baldwin and Clark (2000), who characterize it as a portfolio of options.

An important aspect with design of flexible systems is regarding the assumptions about the actual management of the system after it is built. Will the flexibility be exercised as planned? Or even, is it possible to exercise the flexibility as intended? Flexibility that cannot be exercised is worthless, and we must therefore be cautious about how flexibility can, and potentially will, be exercised. This is addressed by de Neufville (2009), who present five potential obstacles to implementation:

1. **Ignorance**: Future managers or system operators forget or otherwise ignore that flexibility exists. For example, the person that knows about the flexibilities that are built into the system quits, and do not transfer the knowledge.
2. **Inattention**: System managers and operators must exercise flexibility at a suitable time to make use of it. For example, inattention and/or poor communication between observants and decision makers can result in situations where flexibility that should be exercised is not exercised.
3. **Failure to plan ahead**: Failure to think ahead can make the future exercise of flexibility difficult. For example, not allocating physical space for an expansion in the planning phase will act as a block, or significantly increase the change costs.
4. **Stakeholder block**: Stakeholders may block the use of flexibility because it can harm them. For example, the business unit of an organization wants a flexible supply of raw materials to have the possibility to ramp up production but can be blocked by other stakeholders in a company that do not recognize the concept or value of flexibility.
5. **External developments**: Outside forces prevent the use of flexibility. This can, for example, be new governmental rules such as emission regulations.

de Neufville (2009) also discusses initial and ongoing preventive actions for obstacles to implementation. Initial preventive actions include the development of a *game plan* where designers lay out the steps managers should take to implement the types of flexibility designed into the system. Ongoing operational actions involve the active management to continue to keep the option available, as the organization may lose track of flexibility over time if the option is not kept available. This can involve keeping political permissions for the right to expand a facility, or renewal of patents. Additionally, the development of simple but effective *trigger values* (decision rules) that can help the management to understand when it should exercise flexibility can be highly beneficial. For example, “with two executive periods of growth over 10% the expansion should be executed." This can, however, be difficult and would also require the continuous tracking of contextual data.

Financial real options evaluation often involves the determination of the "optimal" exercise of options. Instead of this *normative* approach typical in operations research dictating the optimal operation of the system (often unfortunately in a "black box" fashion), a simpler exploratory managerial approach can often be useful. What is the value of a flexible ship if the simulated optimal exercises of real options are not actually followed by the shipowner after the ship is built? To better untangle and understand the actual managerial operation of assets, one can study applied managerial *strategies*. An overview of literature on shipping strategy is presented by Lorange (2009). A highly interesting approach to design of flexible systems is to pair the design alternatives with particular strategies of operation. Fitzgerald and Ross (2012a) study changeable systems under strategies such as "do nothing," "survive," "max utility" and "max efficiency." This *design-strategy pair* approach to design is also discussed by Schaffner (2014), which can be very useful for more comprehensive tradespace exploration studies.

3. Research Approach

This section first covers literature on research methods. The research questions and objectives are then briefly revisited. Thereafter, we present a classification of the research approach conducted in this project, including research methods and design decision making methods. In the end, we present the timeline of the research project.

3.1. Types of Research

Research can generally be considered as a search for knowledge. The Oxford Advanced Learner's Dictionary defines research as a *“careful study of a subject, especially in order to discover new facts or information about it”.* Research is conducted to find answers to questions through the application of scientific procedures (Kothari 2004).

Even though every research project may have its own purpose, there are also similarities to their general objectives. Kothari (2004) characterizes four general research objectives:

1. To gain familiarity with a phenomenon or to achieve new insights into it (*exploratory* or *formulative* research studies).
2. To portray accurately the characteristics of a particular individual, situation or a group (*descriptive* research studies).
3. To determine the frequency with which something occurs or with which it is associated with something else (*diagnostic* research studies).
4. To test a hypothesis of a causal relationship between variables (*hypothesis-testing* research studies).

Research, in general, is applicable for a multitude of application areas. It can therefore be useful to classify different research types, where a comprehensive classification is given by Kothari (2004) – structuring research types into the following four main opposing research pairs:

(i) Descriptive vs. Analytical
  - *Descriptive research* includes various types of surveys and fact-finding inquiries, with the major purpose to come up with a description of the current situation at present.
  - *Analytical research* involves analyzing existing data, facts, or information already available with the purpose to make a critical evaluation of the material.

(ii) Applied vs. Fundamental
  - *Applied research* aims at finding practical solutions for immediate real-life problems facing society or an industrial/business organization.
  - *Fundamental research* is concerned with formulating theories to describe phenomena and is often characterized as *basic* or *pure* research – contributing to the general body of knowledge.

(iii) Quantitative vs. Qualitative
  - *Quantitative research* involves the measurement and analysis of quantities and amounts and is applicable to phenomena that can be expressed in terms of quantity.
  - *Qualitative research* involves the research concerning quality or kind and is concerned with phenomena that cannot easily be quantified.

(iv) Conceptual vs. Empirical
  - *Conceptual research* is related to abstract ideas or theory, and generally concerns the development of new concepts or reinterpreting existing ones.
  - *Empirical or experimental research* is a data-based approach with the aim to come up with conclusions that can be verified relying on experience and observation alone. Empirical evidence is considered the most powerful support possible for a given hypothesis.

In addition, Kothari (2004) discusses other types of research which are variants of one or more of the above-stated research types. These can be based on for example the purpose of the research, the time it takes to conduct the research or the environment in which the research is done. Some of these types include:

(v) Other research types:
  - *One-time vs. longitudinal research* – depending on whether the research is confined to a single time-period or several time-periods respectively.
  - *Field-setting, laboratory, or simulation research* – depending upon the environment in which the research is done.
  - *Clinical or diagnostic* – when the research follows case-study methods or in-depth approaches to go deep into the causes of things or events, using very small samples.
  - *Exploratory vs. formalized* – the aim of exploratory research is the development of hypotheses rather than their testing, whereas formalized research has a substantial structure with specific hypotheses to be tested.
  - *Conclusion-oriented vs. decision-oriented* – in contrast to decision-oriented research, conclusion-oriented research is characterized by the freedom of a researcher to pick up, redesign and conceptualize a problem. In decision-oriented research, the researcher is always in need for an external decision maker, and an example of this would be the field of operations research.

The difference between qualitative and quantitative research is specifically addressed by Creswell (2014), who also include *mixed* research methods. It can be argued, that to formulate quantitative research approaches, qualitative research is usually needed, and thus all research is at least mixed to some degree. Quantitative and qualitative are also outlined as the two main approaches to research by Kothari (2004). The quantitative approach can be further sub-classified into *inferential, experimental* and *simulation* approaches to research. Inferential involves the formation of a database from which to infer characteristics and relationships. Experimental is characterized by higher control over the research environment, where variables can be manipulated to observe their effects on others. Simulation involves the construction of an artificial environment enabling the study of dynamic behavior of a system under controlled conditions – which can be useful for building models for understanding future potential conditions. The *qualitative approach* concerns subjective assessments of attitudes, opinions, and behavior, and is a function of the insights and impressions of the researchers. An example of qualitative research is group interviews. The outcomes of qualitative research can be results in either quantitative or non-quantitative form.

A differentiation between types of decision-oriented research can be attributed to whether it is descriptive, normative or prescriptive (Bell, Raiffa, and Tversky 1988). *Descriptive decision theory* involves the study of how decision makers (potentially irrational) *actually* make decisions. *Normative decision theory* is the contrast to descriptive decision theory. Normative decision theory involves the analysis to determine optimal decisions of ideal rational agents. Thus, while descriptive concerns the "is", the normative concerns the "ought". The third class, *prescriptive decision theory,* is somewhere in between normative and descriptive. Prescriptive decision theory has the aim to be useful for real, potentially non-ideal decision makers: to help them make good decisions and prepare for future decision situations (S. Grant and Van Zandt 2009).

A differentiation can be made between *research method* and *research methodology*. Kothari (2004) characterizes the difference between *research methods* and the broader term *research methodology* as follows: Research methodology is the science of how research is done scientifically and can be considered as the way to systematically solve the research problem. Research methods concern all those methods and techniques that are used for conducting research, i.e., when researchers are performing research operations.

3.2. Classification of Research and Research Design

To address the research question and objectives, we discuss the research methodology and research methods that are utilized in this research project. In this context, research methodologies are used as a broader term to which the overall research problem is systematically solved, while research methods refer to the specific techniques used.

Few research projects fit neatly into only one of the research types presented but draw on elements from several categories. However, in the following, we attempt to classify this research project as concise as possible. In terms of characterizing the research objective within one of the four objectives proposed by Kothari (2004), it would best fit with: *To gain familiarity with a phenomenon or to achieve new insights into it* – primarily by gaining insights into how changeability explicitly can be designed for to handle future contextual uncertainty in conceptual ship design.

3.2.1. Research methodology

The research type of this project can be classified at multiple levels. To our best judgment, the overall classification is *applied, conceptual, mixed qualitative and quantitative, prescriptive research*. *Applied,* since we solve a problem manifested in the real world. C*onceptual,* since it relates to the search and development of new concepts, methods, and models to solve a real-life problem. *Mixed qualitative and quantitative,* as the underlying goal is the development of quantitative decision support methods. Moreover, as significant *qualitative* research is needed to develop quantitative models for *wicked* (Rittel and Webber 1973) ship design problems, the project is considered mixed qualitative and quantitative (Creswell 2014). *Prescriptive,* in that we aim to provide tools that can be helpful for guidance in practical ship design decision applications.

In that the research project is indented to support design *decisions* under uncertainty, it is worth making a note on the type of decision theory orientation that it concerns. For design decision support, it is *prescriptive.* The research project generally concerns the following decision-research:

- *Prescriptive design decisions*: The goal of the research is to develop quantitative models in support for conceptual design decisions under uncertainty. Thus, the project is generally connected to decision theory, as the design process is a decision-based process (Hazelrigg 1998).
- *Prescriptive operational decisions:* The development of an evaluation model for a ship often involves simulating the lifecycle management of the vessel, and thus this type involves operations research. Focus here is prescriptive in that we seek to identify the "optimal" operations, but we recognize that this may be naïve for applications to complex real-life ship design problems. Therefore, we also take a more applied approach – potentially involving in-use managerial strategies through analyses of *design-strategy pairs* (Schaffner 2014). In relation to flexibility exercise decisions, ensuring that the management recognizes and follows up with the potential exercise can be done by the development of *game plans* (de Neufville 2009).

To solve the main research questions stated, we break it down into smaller pieces that are easier to address. These smaller sub-research parts can, however, be classified in multiple ways inspired by Kothari (2004):

- *Analytical:* Large parts of the research, in general, is of an analytical type, i.e., developing models to analyze the technical and economic performance of each design alternative.
- *Empirical*: Empirical research is conducted both to gather and analyze market data, fuel price data, and data of earlier retrofits of ships in the industry. The main purpose is to generate design alternatives and simulation models to study the design alternatives.

- *Simulation*: Simulation models are developed to study and evaluate the design alternatives generated. *S*imulation methods are used to create artificial environments in which we study simplified conceptual design alternatives subject to changes in the environment. This approach is typically used for studying lifecycle properties (ilities) of systems that may be difficult to quantify otherwise.
- *Longitudinal:* To characterize the behavior of the ship throughout its lifecycle, emphasizing temporality.
- *Diagnostic: S*ignificant time is spent studying in-depth one single offshore ship case in the industry, which experienced to be physically changed during the design and building processes.
- *Fundamental*: The research is to some degree of fundamental type (although not being natural science), as significant time is spent to understand and generalize the rather diffuse ilities in the literature (despite being constructed descriptions for both artifacts and natural systems) – especially in terms of what changeability is, and how it can be quantified.

3.2.2. Research methods

The inherent complexities of the research problem forced the initial adoption of a broad systems perspective. Multiple methods have been utilized to address the research objectives, and in the following, we briefly address the most important overall research methods:

- *A literature review* is central for the general development and structuring of the research project, to position the contribution within the existing literature (Pruzan 2016), and to characterize changeability which has a fundamental role in this research project.
- *Systems thinking* is relevant for the systematic decomposition, analysis, and synthesis of the ship as a complex system. Although important to focus on the constituent parts of the system to understand it, the priority is the study of the system as a whole (Blanchard and Fabrycky 2011).
- *Interdisciplinary research* is essential in this research since the topic of ship design spans across several disciplines: technical aspects, such as hydrodynamics, structural mechanics and machinery, and economic aspects involving market dynamics and simulation of managerial decision-making.
- *Case studies* are important in this research project. Motivating examples are collected from various sources and briefly studied to gain insights into the dynamics of changeability in the industry. Additionally, one in-depth case study of an offshore ship is conducted, which formed the basis Article 1 and inspired multiple derivative projects.
- *Interviews* are conducted in the in-depth case study to learn from the experiences of the people who were directly involved in the project.

- *Collaborative learning* has been central in this research project, as multiple of the contributions are results of collaborative synergies. Two other PhD students (Sigurd Pettersen and Jose Garcia) and I have worked closely together.
- *Statistical analyses* are performed on time-series data primarily for understanding the maritime market dynamics and fuel prices.

3.3. Methods for Design Decision Support

Multiple methods for design and decision support have been utilized in this research project, in addition to the methods addressed in the literature review in Chapter 2. This is partly as the underlying motivation of this research project is to develop methods and models for supporting design under uncertainty, but also because methods for design naturally are needed for conducting design analyses. An overview of methods used in the research project is given below.

- *Monte Carlo simulation* is used as a generic tool for sampling contextual scenarios from probability distributions. An overview of the applications of Monte Carlo methods is given by Kroese et al. (2014).
- *Search, and mathematical optimization* methods are used, albeit relatively simple, for the selection among sets of discretized alternatives, for example for tactical contract selection in the lifecycle simulations for the evaluation of design alternatives. Computational optimization methods are not utilized for the overall strategic design problem, due to the general lack of a well-defined problem to optimize. Instead, tradespace methods are used. General references for optimization in design are Arora (2004) and Papalambros and Wilde (1988) and for operations research by Hillier and Lieberman (2010). Methods for search, specifically tree-search, are covered by Russell and Norvig (1995).
- *Tradespace exploration methods* are widely used throughout this research project. A tradespace "*is the space spanned by the completely enumerated design variables, which means given a set of design variables, the tradespace is the space of possible design options.*" (Ross and Hastings 2005). It is a type of *set-based design*, where multiple solutions are explored – especially useful for *strategic* (long-term) problems of *wicked* or *ill-structured* nature, as for these problems there is not a well-structured objective function nor solution space description that can be effectively optimized and solved. A tradespace lets the user study the Pareto fronts of design alternatives that simultaneously optimize two variables that trade off against each other, for example, value and costs. Fuzzy Pareto fronts are "thicker slices" of the classical Pareto front, which can be useful for analyzing tradespaces in multiple contexts (epochs) (Smaling and de Weck 2004). Interactive

visualizations of tradespaces can be useful for designers to gain insights (Curry and Ross 2015), which is utilized in this research project.

- *The Responsive System Comparison (RSC) method* is utilized in detail in this research project. RSC is developed by Ross et al. (2008, 2009) as a generic system design framework mainly classified into three stages: information gathering, alternatives evaluation, and alternatives analysis. The RSC method typically involves the use of multi-attribute tradespace exploration (MATE) and Epoch-Era Analysis (EEA), but is generic and open for multiple analytical methods and models within its structure.

3.4. Research Approach and Timeline

The interdisciplinary nature of the overall research problem made it necessary to take a comprehensive approach, exploring concepts, methods, and models from multiple fields. A mind map from the initial phase of the research project is presented in Figure 3-1. Here we can see the three main methodological areas that were assumed relevant to investigate in the initial literature review: systems engineering, finance/economics, and mathematical optimization. Additionally, there were multiple other smaller aspects that could be explored - outlined in white boxes.

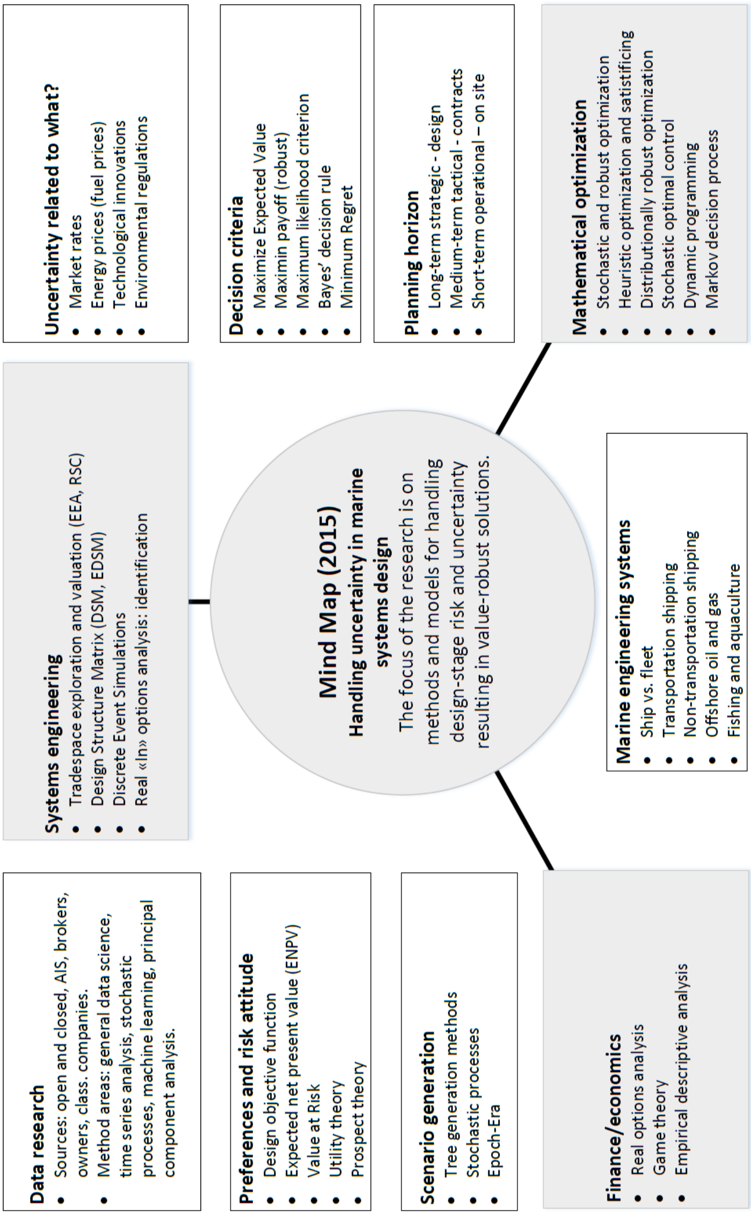

Figure 3-1: Initial mind map of the research project (ca. 2015), highlighted areas are main areas of methodological research, while the white boxes are other brainstormed aspects that may be of importance.

The mandatory coursework was designed to capture the three main fields outlined in Figure 3-1. A conceptual timeline for the research project is outlined in Figure 3-2. The initial exploratory research primarily resulted in two conference papers a) and b) presented at PRADS in 2016. The point was to get more familiar with real options and systems engineering methods to assess their use for ship design applications. However, stochastic optimization methods were initially explored for conceptual design applications but were rejected as a central concept of this research project mainly due to the generic difficulties in the characterization of a well-defined strategic design problem to solve. This is in line with the *wicked* nature of physically large and complex systems (Andrews 1998). Computational optimization methods were however kept open for more well-defined tactical and operational ship design considerations. In fact, this is one of the insights that became manifest in the first main article (Article 1). Article 1 was also based on the in-depth case study that was conducted in collaboration with Ulstein. This general insight from the collaborative in-depth study resulted in the updated outline of the main research architecture to which the research model was adapted, as illustrated in Figure 3-4. Another outcome of the collaborative research project was the general focus on complex non-transport vessels in the main articles.

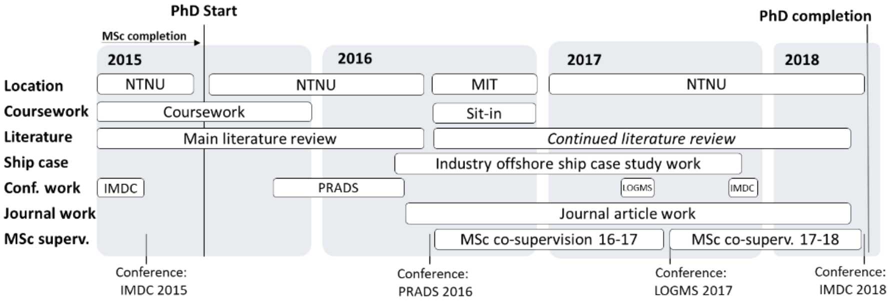

Figure 3-2: Conceptual research timeline (continuously revised - ex-post).

Three main articles are developed in addition to Article 1, as illustrated in Figure 3-3 and Figure 3-4. One of the important aspects of Article 1 was that it briefly covered all five aspects of complexity in design outlined by Rhodes and Ross (2010). The following three articles started more narrowly, before gradually expanding the horizon as illustrated in Figure 3-3 (right).

Article 4 is more directly connected to one of the motivating examples in this research project regarding the design of flexible non-transport vessels. Should they be point-optimized for the first mission, designed with additional characteristics making them retrofittable, or designed with additional equipment making them versatile? It was rather clear from the beginning this paper would be produced, however, what was initially unclear was the path that would take us there. Therefore, a systematic breakdown of the various aspects of design under uncertainty was conducted.

First, we were interested in the technical details of offshore ships with various types and levels of changeability. The result of this was the production of Article 2, covering mainly aspects of structural and behavioral complexity, as illustrated in Figure 3-3 (right). Article 2 utilized an established metric for quantification of changeability level (filtered outdegree), but the general lack of an established characterization and quantification of changeability lead to the development of Article 3. This was also motivated by collaborative research with Massachusetts Institute of Technology (MIT), as the fall semester of 2016 was spent as a visiting researcher at the Systems Engineering Advancement research initiative (SEAri).

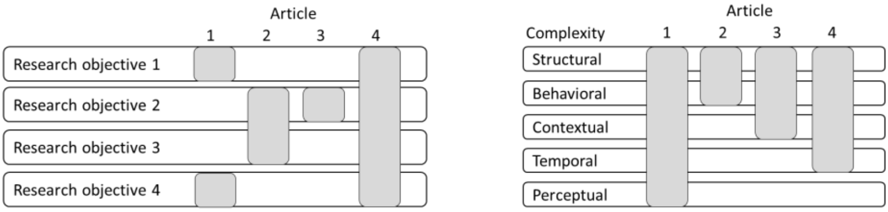

Figure 3-3: Illustration of the relationship between the individual articles with the research objectives (RO) and five aspects of complexity (Rhodes and Ross 2010).

Article 3 presents a comprehensive literature survey on changeability in design. The goal of the paper is to present a generic approach to how changeability can be described and designed for, and how the level of changeability can be measured. Article 3 extends the aspects of complexity covered further to include the contextual domain. In the end, Article 4 presents a comprehensive ship design approach also including temporal aspects of uncertainty. The goal here is to understand the economic tradeoffs for the vessels motivated in the example earlier, mainly regarding retrofittability vs. versatility. Perceptual complexity is not explicitly addressed.

In addition to the main articles, several supporting papers and presentations are produced. For example, several interesting MSc research projects have been co-supervised at NTNU, resulting in multiple presentations at LOGMS 2017 and two papers to IMDC 2018.

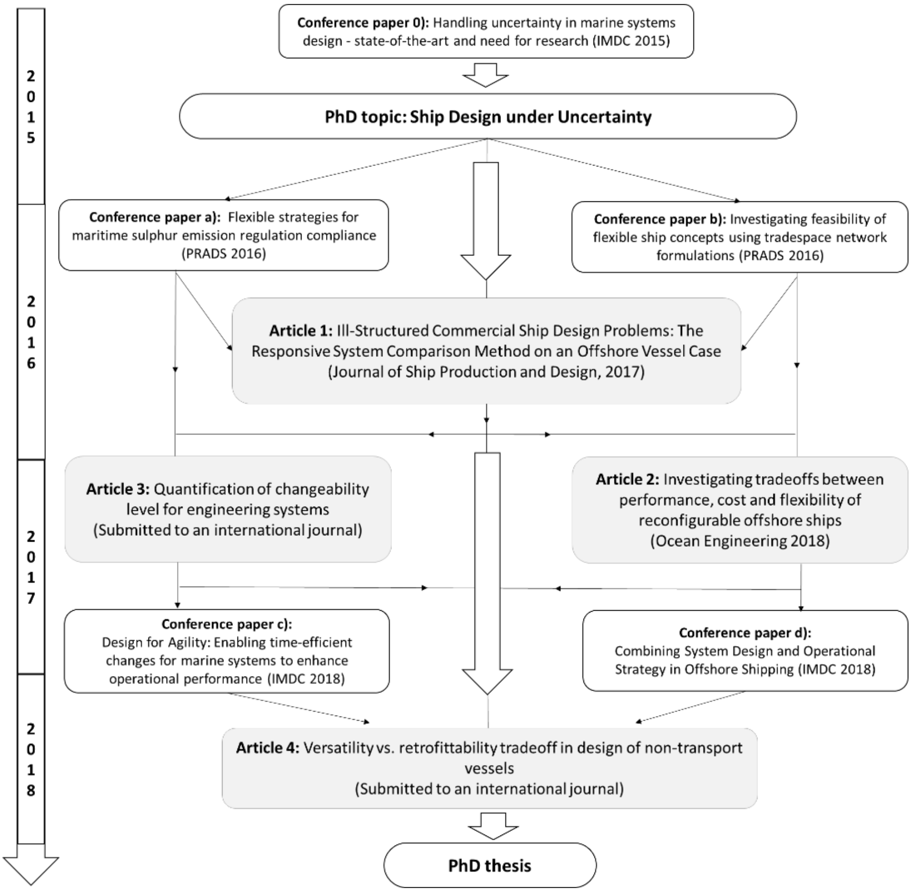

Figure 3-4: Research architecture for publications (ex-post), not exhaustive.

4. Summary of Publications

4.1. Articles

4.1.1. Article 1

Ill-Structured Commercial Ship Design Problems: The Responsive System Comparison Method on an Offshore Vessel Case

Pettersen S.S.; Rehn, C.F.; Garcia J.J.; Erikstad, S.O.; Brett, P.O.; Asbjørnslett, B.E.; Ross, A.M.; Rhodes, D.H.

Journal of Ship Production and Design,34(1), 72-83, 2018

Abstract:

In this paper, we address difficulties in ill-structured ship design problems. We focus on issues related to evaluation of commercial system performance, involving perceptions of value, risk, and time, to better understand trade-offs at the early design stages. Further, this paper presents a two-stakeholder offshore ship design problem. The Responsive Systems Comparison (RSC) method is applied to the case to untangle complexity, and to address how one can structure the problem of handling future contextual uncertainty to ensure value robustness. Focus is on alignment of business strategies of the two stakeholders with design decisions through exploration and evaluation of the design space. Uncertainties potentially jeopardizing the value propositions are explicitly considered using epoch-era analysis. The case study demonstrates the usefulness of the RSC method for structuring ill-structured design problems.

Relevance to the thesis:

This paper lays the foundations for the multiple offshore ship studies performed in this research project, from which multiple derivative papers are developed. This paper explicitly assesses the applicability of the RSC method for maritime cases, investigates the use of multi-attribute utility functions for evaluation, and the use of Epoch-Era Analysis for comparing design alternatives under uncertainty – explicitly covering Research Objective 1, and partly Research Objective 4 (Figure 3-3 left). The paper also illustrates the collaboration between NTNU, MIT, and Ulstein.

Declaration of authorship:

Jose Garcia, Sigurd Pettersen, and I together developed and wrote the paper under the supervision of Adam Ross and Donna Rhodes at MIT during and after a workshop in early 2016. Per Olaf Brett, Stein Ove Erikstad and Bjørn Egil Asbjørnslett supervised the continued development of the paper.

4.1.2. Article 2

Investigating tradeoffs between performance, cost and flexibility of reconfigurable offshore ships
Rehn, C.F.; Pettersen, S.S.; Erikstad, S.O.; Asbjørnslett, B.E.
Ocean Engineering, 147, 546-555, 2018

Abstract:

This paper investigates tradeoffs between technical performance, cost, and flexibility level for reconfigurable offshore ships. An offshore ship can be configured with various types of equipment; thus, its base structure constitutes a platform from which several end ship design configurations can be derived. A ship with equipment retrofit flexibility will typically have excess stability, deadweight, and deck area to ensure physical compatibility. However, there are complex system interactions that need consideration, such as the effects of flexibility on cost and technical performance. To tackle this problem, we capture technical performance using a multi-attribute utility function, based on a ship's capability, capacity, and operability, and utilize a tradespace representation of the system to quantify flexibility using the filtered outdegree metric. Findings indicate that increased platform flexibility does increase capacity but comes at a complex compromise with operability as resistance is increased, and roll periods become unfavorable due to high accelerations. Furthermore, the analysis confirms the applicability of multi-attribute utility, tradespace exploration and filtered outdegree for understanding the implications of flexible offshore ships.

Relevance to the thesis:

This paper quantifies the level of changeability in a design, contributing to Research Objective 2, and explores technical tradeoffs for incorporation of changeability in design, contributing to Research Objective 3.

Declaration of authorship:

Sigurd Pettersen and I developed and wrote this paper as a continuation of supporting paper b): *Investigating feasibility of flexible ship concepts using tradespace network formulations.* I conducted the quantitative analyses. Stein Ove Erikstad and Bjørn Egil Asbjørnslett supervised the paper through discussions.

4.1.3. Article 3

Quantification of Changeability Level for Engineering Systems

Rehn, C.F.; Pettersen, S.S.; Garcia, J.J.; Erikstad, S.O.; Brett, P.O.; Asbjørnslett, B.E.; Ross, A.M.; Rhodes, D.H

Under review in an international journal

Abstract:

This paper outlines a generic method for quantifying changeability level, to support better decision making in the early stages of design of engineering systems. Changeability represents the ability of a system to change form, function, or operation, and is a collective term for characteristics such as flexibility, adaptability, and agility. Quantification of changeability level must not be confused with valuation of changeability. The level of changeability in a design is essentially under the control of the designer. Two aspects of changeability are discussed, the first being how to structure changeable design alternatives using the Design for Changeability (DFC) variable. The DFC variable represents combinations of path enablers built into a design. Path enablers are characteristics of systems enabling them to change more easily. The second aspect is to quantify the level of changeability for a given design alternative, based on change cost and time. For the latter, we propose two measures for quantification: 1) bottom-up, measuring the reduction of cost and time enabled for each relevant change, and 2) top-down, measuring the span of change opportunities at given cost and time thresholds. A case study of a ship is presented to demonstrate the proposed generic method.

Relevance to the thesis:

This paper presents a generalized contribution characterize and quantify the level of changeability for a design alternative, strongly contributing to Research Objective 2.

Declaration of authorship:

I developed and wrote the majority of this paper, which was initiated under the supervision of Adam Ross and Donna Rhodes at MIT the spring of 2017. Sigurd Pettersen and Jose Garcia contributed significantly to the continued development of the paper, Sigurd supported specifically with the framing of the paper and Jose worked specifically with the case study. Per Olaf Brett, Stein Ove Erikstad and Bjørn Egil Asbjørnslett supervised the continued development of the paper.

4.1.4. Article 4

Versatility vs. retrofittability tradeoff in design of non-transport vessels
Rehn, C. F.; Garcia, J. J.; Erikstad, S. O.; de Neufville, R.
Submitted to an international journal

Abstract:

In this paper, we study the relationship between economic performance and flexibility for non-transport vessels. More specifically, we investigate the difference between two means of achieving flexibility: retrofittability and versatility, i.e., the ability of a vessel to satisfy diverse needs with or without change of physical form, respectively. A model is presented to study this relationship, where we first generate design alternatives with relevant, flexible properties before we subsequently evaluate the design alternatives based on their discounted economic lifecycle performance. The evaluation model is based on a two-level decomposition of the planning horizon to handle temporal complexity, using scenario planning and Epoch-Era analysis (EEA) for long-term strategic considerations, and Monte Carlo simulation and optimization for medium-term tactical ship deployment. The proposed model is applied to an offshore construction ship design case. Findings indicate that retrofittability significantly can increase economic performance for non-transport vessels operating in an uncertain heterogeneous context.

Relevance to the thesis:

This paper is based on earlier articles and findings, and thus comprises a more comprehensive contribution to the research project. All four research objectives are addressed in this paper, extending the contribution from Articles 2 and 3 to the evaluation domain signified by Research Objective 4.

Declaration of authorship:

I developed and wrote the majority of this paper. Jose Garcia supported the development of the case study. I conducted the quantitative analyses. Richard de Neufville supported in detail with the framing of the paper, and Stein Ove Erikstad supervised the general development of the paper.

4.2. Supporting Papers

Supporting paper a)

Flexible strategies for maritime sulphur emission regulation compliance
Rehn, C.F.; Haugsdal, A.; Erikstad, S.O.
PRADS 2016 - Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures

Abstract:
This paper presents an analysis of different strategies for compliance to maritime sulphur emission regulations. Abatement options mainly involve using heavy fuel oil with scrubber, distillate fuels or LNG. Flexible strategies are introduced by explicitly considering how shipowners can switch or retrofit between abatement options, in order to reduce costs and improve performance. Deciding which alternative that is most preferable for a ship is a complex task, which depends on ship-specific factors such as annual fuel consumption and part of time in emission control areas, and on uncertain parameters such as fuel prices and environmental regulations. A decision support model based on Monte Carlo simulation is developed to assess different strategies for compliance. We can conclude that flexible abatement strategies show superior performance and should hence be considered for new ship projects today.

Relevance to the thesis:
This paper explores and contributes to characterize design alternatives with various levels of changeability, addressing Research Objective 2. Additionally, the paper explores value tradeoffs to identify the best solution, contributing to Research Objective 4.

Declaration of authorship:
I developed and wrote the majority of this paper. Annette Haugsdal contributed with data for the quantitative analyses, which were conducted by me. Stein Ove Erikstad supervised the general development of the paper.

Supporting paper b)

Investigating feasibility of flexible ship concepts using tradespace network formulations
Rehn, C.F.; Pettersen S.S.; Erikstad, S.O; Asbjørnslett, B.E.
PRADS 2016 - Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures

Abstract:
In this paper, we investigate the technical feasibility of flexible offshore ship design concepts with respect to retrofits. Flexibility is intended to improve performance, but there are often complex system interactions that are difficult to assess at the early design stage related to stability, resistance, hydrodynamic behavior, and payload capacity. These aspects need to be understood and assessed at the conceptual stages. In this paper, we develop a tradespace network model and define transition rules to describe feasible retrofits. A multi-criteria utility function is used to assess the tradeoff between performance and cost. We demonstrate our approach using a case from offshore vessel design, where we investigate the feasibility and impact of retrofits. The low-fidelity quantitative analysis indicates that the beam is the least flexible design parameter. This knowledge can be important when defining a flexible marine platform "prepared" for future retrofits.

Relevance to the thesis:
This paper quantifies the level of changeability in a design, contributing to Research Objective 2, and explores some technical aspects of incorporation of changeability in design, contributing to Research Objective 3.

Declaration of authorship:
Sigurd Pettersen and I developed and wrote this paper. Stein Ove Erikstad and Bjørn Egil Asbjørnslett supervised the research through discussions.

Supporting paper c)

Sulphur abatement globally in maritime shipping
Lindstad, H.E.; Rehn, C.F.; Eskeland, G.S.
Transportation Research Part D: Transport and Environment, Vol. 57, Dec. 2017, pp. 303-313

Abstract:
In 2016, the International Maritime Organization (IMO) decided on global regulations to reduce sulphur emissions to air from maritime shipping starting 2020. The regulation implies that ships can continue to use residual fuels with a high sulphur content, such as heavy fuel oil (HFO), if they employ scrubbers to desulphurise the exhaust gases. Alternatively, they can use fuels with less than 0.5% sulphur, such as desulphurised HFO, distillates (diesel) or liquefied natural gas (LNG). The options of lighter fuels and desulphurization entail costs, including higher energy consumption at refineries, and the present study identifies and compares compliance options as a function of ship type and operational patterns. The results indicate distillates as an attractive option for smaller vessels, while scrubbers will be an attractive option for larger vessels. For all vessels, apart from the largest fuel consumers, residual fuels desulphurised to less than 0.5% sulphur are also a competing abatement option. Moreover, we analyze the interaction between global SO_X reductions and CO_2 (and fuel consumption), and the results indicate that the higher fuel cost for distillates will motivate shippers to lower speeds, which will offset the increased CO_2 emissions at the refineries. Scrubbers, in contrast, will raise speeds and CO_2 emissions.

Relevance to the thesis:
Although not explicitly addressing changeability, the paper concerns the characterization and modeling of the uncertain future operation context (Research Objective 1) and evaluation of design alternatives (Research Objective 4). This includes explicitly addressing details of operational patterns and a potential “hidden” response from the operating agents to maximize their contribution margins.

Declaration of authorship:
H. Elizabeth Lindstad initiated the paper and led the development and writing of the paper. I contributed with the development of figures and paper formatting, in addition to general discussions with Lindstad regarding the outline and formulation of the paper. Gunnar S. Eskeland contributed to the general development and writing of the paper.

Supporting paper d)

Design for Agility: Enabling time-efficient changes for marine systems to enhance operational performance
Christensen, C.; Rehn, C.F.; Erikstad, S.O.; Asbjørnslett, B.E.
13th International Marine Design Conference (IMDC2018)

Abstract:
In this paper, we propose a model for quantifying the value of operational agility in shipping, i.e., the value of being able to exploit possible profitable market opportunities quickly. For a system operating in a dynamic context, the ability to be able to adapt and change is essential. However, for real-world applications, exploiting this flexibility comes with a time delay. If we are not taking the time delay into account, we may be biased towards estimating a higher value of flexibility than what is realizable, as well as failing to properly design the system to be able to change within an adequate time span. A real option valuation model based on Monte Carlo simulation is proposed, where we consider the time delay as a model parameter. The proposed methodology is applied to a bulk shipping case. Bulk fleet capacity expansion is currently achieved mainly through new-building or the 2nd hand market, but designing versatile and reconfigurable ships and fleets are also an alternative. The results indicate that significant value can be enabled by being agile, and potential design solutions enabling agility are proposed, both for fleets and single ship cases.

Relevance to the thesis:
This paper is relevant for all four research objectives, however with a focus on the temporal dimension of changeability.

Declaration of authorship:
This paper is based on the MSc thesis by Carsten Christensen at NTNU the spring of 2017. Carsten and I had multiple meetings to explore this subject, and the paper was written together during the fall semester of 2017. Stein Ove Erikstad and Bjørn Egil Asbjørnslett supervised the research mainly through discussions.

Supporting paper e)

Combining System Design and Operational Strategy in Offshore Shipping
Strøm, M.A.; Rehn, C.F.; Pettersen, S.S.; Erikstad, S.O.; Asbjørnslett, B.E.; Brett, P.O.
13th International Marine Design Conference (IMDC2018)

Abstract:

This paper presents the design-strategy planning (DSP) procedure as a framework that integrates life cycle strategies of a ship into the early stages of the design process. We argue that understanding strategic, tactical and operational strategies is essential when it comes to design of complex systems under uncertainty. Unfortunately, these are often neglected in ship design problems today. Using a Markov Decision Process Methodology, we demonstrate the gained insight from the concurrent exploration of system configurations and strategies, to better understand what actions to do when. A case study is presented, where different tactical strategies of an offshore vessel are characterized. The results indicate that there are significant advantages in explicitly addressing ship owner strategy through DSP, when designing offshore ships that may be reconfigured in their lifetime.

Relevance to the thesis:

This paper contributes to the evaluation of design alternatives (Research Objective 4). A new quantitative approach is attempted to the management of a vessel in the operational phase, and the paper addresses strategic aspects of management.

Declaration of authorship:

This paper is based on the MSc thesis by Morten A. Strøm at NTNU the spring of 2017. Morten, Sigurd, and I had multiple meetings to explore this subject, and the paper was written together during the fall semester of 2017. Stein Ove Erikstad, Bjørn Egil Asbjørnslett, and Per Olaf Brett supervised the research.

5. Results Overview

This chapter presents a discussion on how the research objectives are fulfilled and a detailed description of the three contributions from this research project.

5.1. Fulfilling the Research Objectives

Research Objective 1

Develop models that effectively capture relevant aspects of the future uncertain operating context.

Research Objective 1 is met through identification of multiple methods and models used in the literature for scenario characterization and modeling, which are applied to maritime cases through the papers. An overview of the literature on these methods is given in Chapter 2.2. In Supporting papers a) and d), we model fuel prices and market rates (respectively) using stochastic processes and Monte Carlo simulation. In Article 1, we explore the use of epochs for characterizing context variables and needs and construct eras using narrative methods. In supporting paper c), three manually generated scenarios are developed for achieving model-transparency to easily communicate insights. Finally, in Article 4, we combine epoch-era methods and Monte Carlo methods: we use epoch-era constructs for the strategic (long-term) planning problem and Monte Carlo for the tactical (medium-term) planning problem. As conceptualized in Article 4, we emphasize the importance of the planning horizon for the choice of methods.

Research Objective 2

Define and quantify the level of changeability for a system.

Research Objective 2 is met through the development of a generic framework for characterizing and quantifying changeable design alternatives, presented in Article 3. This is based on a comprehensive review of various approaches used in the literature, as presented in Chapter 2.3.2. The essence is that multiple characteristics (path enablers) can be included in a design alternative to enhance changeability. The degree to which these characteristics collectively reduce the cost and time for the system to perform a state-change is then quantified, either by a bottom-up or top-down approach. Articles 2, 4 and supporting paper b) utilize one or more of the methods and models discussed in Article 3.

Research Objective 3

Develop an understanding of technical tradeoffs for the realization of changeable ship design solutions.

Research Objective 3 is met through the development of technical ship design models and collaboration with Ulstein ship design company, leveraging on their experience. Article 2 presents the insights from the technical modeling, where simple feasibility models concerning, e.g. hydrodynamics and structural mechanics are developed. These models help in the study of which technical ship factors that are important for the ship to serve as a platform – enabling multiple derivative end-design alternatives to be developed without retrofit of the main dimensions, as a change of main dimensions is costly and time-consuming. For non-transport vessels, this typically involves having *margins* for stability, deck area, and deadweight. These characteristics can be described as path enablers enhancing changeability, as addressed in Research Objective 2. Article 2 leverages on the model and findings originally developed in supporting paper b). In Articles 1 and 4, the simple technical models describing feasible ship design alternatives are developed in collaboration with Ulstein ship design company.

Research Objective 4

Develop models to evaluate changeability in design – operationalizing the link between uncertainty, design variables, and operational strategies.

Research Objective 4 is met through the development of multiple evaluation models identified in the literature review, as discussed in Chapter 2.3.3. Supporting paper a) uses an “in” option inspired real options pricing approach based on Monte Carlo simulation, which also is the case for Supporting paper d). Supporting paper e) presents an alternative evaluation approach that also addresses shipowner strategies. Article 4 integrates multiple aspects for evaluation, utilizing Monte Carlo and optimization at the tactical planning horizon, and epoch-era and tradespace exploration at the strategic planning horizon. Common for the above-mentioned approaches is that they use economic discounted net present value as a measure to evaluate changeability in design. An alternative approach to evaluation using multi-attribute utility theory is utilized in Articles 1, 2 and supporting paper b), although this is not directly utilized for the evaluation of changeability.

5.2. Contributions

The key contributions of the research project can be summed up in three main points.

5.2.1. Contribution 1

A framework for describing and quantifying changeable design alternatives, applicable to ship design as well as engineering design in general.

Contribution 1 was motivated by the continuously addressed questions: *What is a flexible design, and how flexible is one design alternative compared to another?* Contribution 1 is in line with Research Objective 2, which is prioritized as a key research contribution due to its novelty (arguably). Research Objective 2 was the most difficult objective to address, as there is a lack of an established framework in the generic systems engineering literature which could be readily adapted to ship design applications. The reason there is a lack of a general framework to address this issue is, possibly, that characterizing and quantifying changeability in design quickly becomes case specific. There are however various approaches presented in the literature in a fragmented manner, which this contribution is based upon. An attempted well-structured review of the literature on changeability in design is presented in Chapter 2.3.2, and the general framework is presented in Article 3. Table 8 in Chapter 2.3.3 is designed to help clarify the difference between the quantification of changeability level and evaluation of changeability.

The generic framework is inspired by the literature addressed in Chapter 2.3.2, and can be summarized in the following two main points:

- *Characterize and describe changeable design alternatives*

  Based on a state-space system representation (Ross, Rhodes, and Hastings 2008), the change between two system-states can be made cheaper and quicker by including specific characteristics (path enablers) in the design. For a design otherwise similar, e.g., 3500 twenty-foot equivalent unit (TEU) container ship, multiple characteristics enhancing changeability can be added for, e.g., the potential upgrade to 4500 TEU. Several changeable alternatives can thus be generated by combining path enablers. Sets of path enablers can be conceptualized in the design for changeability (DFC) design variable. This framework can be used for changes in form, function, and operation.

- *Quantify the level of changeability for a design alternative*

  For design alternatives with different sets of path enablers included (to enhance a state-change in form, function, or operation), we are interested in quantifying their collective effect on change cost and time. This is so we can answer the question: how flexible is one design alternative compared to another? Two approaches are proposed:

(i) *Bottom-up,* measuring the reduction of cost and time enabled for each relevant change, for example, measured as normalized relative reduction. The bottom-up approach can help clarifying questions such as: how much can we reduce the cost of adding a crane to the ship by pre-reinforcing the hull? Or, for operational cases without change of form: How much more operationally agile would a ship be by adding 10% extra engine power?

(ii) *Top-down*, measuring the span of change opportunities at given cost and time thresholds, generally measured using filtered outdegree (FOD) (Ross, Rhodes, and Hastings 2008), of which one representation is lateral cargo mobility (LCM) (Stopford 2009). This approach can help answer questions such as: How versatile is the ship, i.e., how many missions in the market can be served without reconfiguration of the ship itself? How large fraction of possible equipment retrofits can be made on the ship within one week?

5.2.2. Contribution 2

An assessment of the applicability of methods and models for handling uncertainty in ship design, primarily from the real options and systems engineering domains.

A central contribution of this research project is the assessment of established generic methods in the literature can be used to design better ships. This also includes the application of methods developed in this research project, addressed in Contribution 1. Contribution 2 is generally supported by all the articles and supporting papers. Multiple methods for characterization of changeable design alternatives, for evaluation of design alternatives, and for selection among design alternatives are covered in Research Objectives 1 to 4 and addressed in the literate review in Chapters 2.2, 2.3 and 3.3. A short overview follows:

- *Characterize and quantify changeable design alternatives*

  Described in Contribution 1.

- *Evaluation of changeable design alternatives*

  For the evaluation of changeable design alternatives, the general approach is based on real options evaluation. However, we recognize that important assumptions may not hold for ship design considerations. Instead of “risk-neutral valuation,” the general approach for evaluation of real options “in” projects is by “actual valuation” – using actual probabilities and risk-adjusted discount rates

(Wang and de Neufville 2005). For these problems, the main insights are gained through the comparison of design alternatives with, and without, changeability built in. Monetary discounted value measures are generally used. The methods for generating scenarios are based on the planning horizon. For complex strategic (long-term) planning problems epoch-era methods are identified as specifically useful. For tactical and more well-defined problems (medium-term, e.g., months to years) Monte Carlo methods are identified as useful.

- *Selection among changeable design alternatives*

  For the selection among design alternatives, multiple methods have been used. Complex strategic (long-term) ship design problems under uncertainty are typically *ill-structured* and *wicked* (Andrews 1998), which is addressed in Article 1. This means that the main issue is to formulate the problem to solve, instead of solving the well-formulated problem representation. If the design alternatives to optimize are not well-defined, (naïve) use of optimization methods is logically not recommended. This is signified by the general difficulties of characterizing changeable design alternatives to select from (Contribution 1). Instead, more transparent *tradespace exploration* methods (Chapter 3.3) are utilized for strategic (long-term) design problems. For more well-structured problems, typically characterized by the shorter planning horizons, optimization is used – e.g., for the selection of tactical decisions, such as contract selection, for optimal operational management. Separating between methods based on the planning horizon is utilized in Article 4. In general, obviously, if a well-defined representation of the problem can be defined, optimization methods may be useful, or even by far superior – especially if the solution space is large.

5.2.3. Contribution 3

An identification of potentially valuable changeable ship design solutions, specifically being "prepared for retrofits" for two cases: fuel flexibility for transport ships and mission flexibility for non-transport vessels.

The value of changeability to handle future uncertainty for conceptual ship design cases is demonstrated. We identify being "prepared for retrofits" as of particular potential value, as this can enable upside opportunities at a relatively low up-front capital cost. The papers demonstrate the value of being "prepared for retrofit" for two cases in detail (but not limited to):

- Ability to change between markets in non-transport shipping. This is specifically addressed in Article 4, indirectly building on Articles 2 and 3.

- Ability to change between engine fuel sources for general transportation ships. This is demonstrated through a case study presented in supporting paper a).

This contribution is interesting, especially it can be backed up by empirical data suggesting that equipment retrofits for non-transport vessels, in fact, take place in the industry (Table 1) – also addressed in Article 4. These retrofits are even potentially conducted for ships not prepared for retrofits. As a recent study points out: several conversion projects in the industry are discarded due to too high retrofit costs (Ullereng 2016). This further supports the significance of being “prepared for retrofits”. These findings are also aligned with Buxton and Stephenson (2001) results from their study on design for upgradeability for container ships.

6. Discussion

This chapter supplements the discussions of the individual publications, focusing more on the scientific and practical implications of the research project. First, we discuss practical implications of the research, before evaluations of contributions and research objectives are presented.

6.1. Practical Implications

The research is considered as *applied* (Chapter 3.2), as the goal is to solve a problem manifested in the real world. Several motivating empirical cases from the industry are presented in the introduction, demonstrating earlier retrofits of ships (Table 1), examples of versatile ships (Table 5), and examples of ships prepared for retrofits (Table 6). Further, there is a growing interest for being prepared for retrofits, exemplified with the introduction of the *Gas Ready* classification notation by DNV GL (2015). A recent study pointed out that several conversion projects in the industry are discarded due to too high retrofit costs (Ullereng 2016). These comments are consistent with the findings from the case studies in this research project, materialized in Contribution 3.

The practical takeaways from the research can be summed up as follows: changeability in ship design can be of significant value and should hence be addressed in practical ship design cases. However, one should take care so that flexibility only is designed for where it is of significant value for the stakeholders. Insights from this research project indicate that flexibility in design, specifically being prepared for retrofits, could be of value for fuel switching for transport ships, and market switching for non-transport ships. The applications are obviously not limited to these two fields. Furthermore, empirical evidence indicates that cruise ship elongation occurs with noticeable frequency.

It would be of interest to study other maritime cases to gain a better understanding of where flexibility *is* (and maybe more importantly is *not*) good engineering practice. Stopford (2009) discusses the critical tradeoff between cost and operational performance for flexible ships. Ships that generally operate with slim profit margins perhaps cannot afford to take the extra cost to invest in the “insurance” provided by flexibility. This can at least be seen for versatility cases, with relatively expensive flexibility, i.e., multi-purpose transport ships. Most transport ships in the industry are single-purpose built (Stopford 2009). This may suggest that the economic benefit of specialization outweighs the economic benefit of multi-functional flexibility in general. However, Contribution 3 mainly concerns the flexibility provided by being prepared for retrofits (retrofittability), which rather is *supported* by the arguments of Stopford, as ships can be optimized for the single-purpose but prepared for other purposes.

6.2. Evaluation of Contributions

Contribution 1 concerns the development of a generic framework to characterize and quantify changeability. The contribution is identified as the most novel part of this work, as it arguably contributes not only to the ship design literature but also to the general systems engineering literature. The framework sets out to structure a case-specific and abstract phenomenon, and we want to emphasize that we do not consider this issue solved yet. We recognize that there may be multiple other methods to characterize and quantify changeability, which we encourage to be addressed in continued research.

Contribution 2 involves the investigation, application, and evaluation of the usefulness of methods and models for handling uncertainty for ship design applications. The research procedure involved a literature survey, and a qualitative judgment for what *does* and potentially *does not* work well, and why. The extensive state-of-the-art literature review covers most of the insights we have gained throughout Contribution 2. We do recognize, obviously, that it is impossible to evaluate the applicability of all possible methods and models potentially useful. The approach taken was top-down, focusing on the problem that was intended to be solved, rather than bottom-up by force-fitting methods and models to our problem in the spirit of Maslow's hammer. The methods and models that were probably useful for our needs were mostly identified by the literature addressing similar problems, but for other engineering systems than ships.

As the problem of ship design under uncertainty generally is an *ill-structured* problem, significant time was spent to structure the problems to solve in concert with the testing of various methods and models. As multiple methods and models have been identified as useful for the individual sub-parts of the ship design problem, the resulting outcome is not a quantitative evaluation of methods and models, but rather a qualitative judgment of where and how they are applicable. For example, several methods and models have been identified for scenario generation, and our insights are in the lines of that the model of choice should be dependent on the relevant planning horizon that is to be modeled, and the degree of complexity and uncertainty in the context. For many purposes, a scenario model can comprise multiple methods and models, e.g., exploratory epoch-era narrative scenario method for the long-term strategic problem, and computational Monte Carlo methods for the medium-term tactical scenario modeling problem.

Contribution 3 involves the insights gained in reach for the goal of better ship design under uncertainty. More specifically, the most influential insights were obtained from the empirical research of retrofits and "design for retrofits" in the industry, and the simulation case studies developed in this project. This research contribution is essential for the potential transfer of knowledge to practitioners, demonstrating the "proof-of-concept." What would be of significant strong research value would be to "flip the table" and demonstrate cases where flexibility is not valuable. However, as flexibility brings the *right but not the obligation*, the downside cannot be larger than the cost of the option – if the cost can be properly measured. Further discussions on practical implications are given in Chapter 6.1.

6.3. Evaluation of Research Approach

Several motivating research questions were posed in the outline of this research project, such as: What is a flexible ship? How can flexibility be designed for, to increase performance? What is the relationship between the ability of a ship to change form, function, and operation, and key characteristics of the uncertain future operating context? These questions were formalized into four research objectives that were systematically addressed throughout the research project.

The research objectives were initiated at the beginning of the research project and developed continuously throughout the project as more insights were gained. The research objectives should ideally be clearly developed and defined in the beginning of the research project. This was however not realistic for this project. It would, in general, be beneficial, but I believe that the adaptive process, in this case, was beneficial for the outcome of the project. Infinitely many approaches could have been made to solve this research problem, on a relatively abstract level, and thus, some time was needed to absorb the literature and structure the research project.

The research was highly conceptual and anchored in exploring and applying methods from the literature. However, in retrospect, I believe that significant insights also could be gained through descriptive empirical research from the industry. Empirical data can provide support for arguments in the most powerful form. There would however potentially be an issue with the availability of relevant data. To some degree though, this research project has gathered data to motivate the research project – as demonstrated in Tables 1, 5 and 6, and summarized in Rehn and Garcia (2018).

7. Conclusions and Further Work

This chapter concludes the research project and presents insights towards relevant future work.

7.1. Overall Conclusion

The purpose of the thesis to develop knowledge to design better ships. More specifically, it concerns the development and application of effective methods and models for handling future contextual uncertainty in the early design stages. The thesis further studies the relationship between future contextual uncertainty affecting the economic performance of a system, and the ability of the system to change form, function, and operation. As such, we gain insights into whether and how system-level properties such as flexibility and versatility (generalized as changeability) will be of key importance for the next generation ocean systems. This is considering both satisfying the immediate demands of the market, while at the same time being value-robust towards changes in the future operating context.

The research goals are addressed through systematically addressing four research objectives, resulting in the following three key contributions (C):

C1 A framework for describing and quantifying changeable design alternatives, applicable to ship design as well as engineering design in general.
C2 An assessment of the applicability of methods and models for handling uncertainty in ship design, primarily from the real options and systems engineering domains.
C3 An identification of potentially valuable changeable ship design solutions, specifically being “prepared for retrofits” for two cases: fuel flexibility for transport ships and mission flexibility for non-transport vessels.

Albeit only touching on the tops of a vast domain of methods and models that can result in improved ship design processes, we conclude that proactively addressing changeability in ship design can be of significant value. This is demonstrated in this thesis for fuel flexibility for transport vessels, and equipment retrofittability for non-transport vessels. This conclusion is fueled by several factors, where market uncertainty, long project time horizons and project capital intensity are three of vital importance.

The primary goal of this research project is fulfilled within the time and resource boundaries provided. This research project has contributed to the knowledge on conceptual ship design under uncertainty, and for the general knowledge of design of changeable engineering systems. Nevertheless, there is a need for continued research for further improvement.

7.2. Further Work

The research objectives group the research effort into four main points, which could and should be studied further.

Research Objective 1 concerns the development of methods and models for effectively capturing relevant aspects of the future uncertain operating context. This thesis highlights the importance of the planning horizon for the choice of method. This should be taken into consideration in terms of further research. For the more ambiguous long-term strategic issues, proper case studies in collaboration with industry actors are recommended. This is, mainly, as the purpose of such scenarios often are at a higher level of abstraction, where model simplicity and transparency for effective communication between analysts and decision makers are of high importance. For the more well-defined scenario cases, e.g., market rate modeling short-term, more data-centric research should be performed.

Research Objective 2 concerns the definition and quantification of the level of changeability for a system. The framework developed relies on estimating the cost and time of performing specific state changes. As the cost and time of construction projects often are exceeded, further development of this framework could include uncertainty in those parameters. This could be an area further of study relating to the developed framework. Of course, the framework itself may be flawed, and continued research directed towards developing meaningful ways to characterize changeable design alternatives is encouraged. The validity of the proposed framework can be investigated through case studies. Further research should also be directed towards properly estimating the carry cost of flexibility in design. In addition to the direct increased capital cost that a path enabler may incur, the variable costs of the path enablers are important and are to a low degree covered in this thesis, or in general. This is probably because it is case dependent, and thus, carry costs should be explored in concert with detailed case studies.

Research Objective 3 concerns technical aspects of incorporation of changeability in a ship. This is important, as in order to generate changeable design alternatives, one needs to understand whether they are technically feasible, and whether there are any non-intuitive tradeoffs in technical performance. A proper understanding of this area is essential and recommended for further research. I believe that the most efficient way to bring this further is through realistic case studies, preferably with industrial applications.

Research Objective 4 concerns the development of models to evaluate changeability in design – operationalizing the link between uncertainty, design variables, and operational strategies. In terms of following through with the studies of flexibility in design, this is perhaps the most important objective. Further research is recommended towards the investigation of other evaluation models proving to be useful for ship design applications. Further, a promising area to follow up on is the untangling of “optimal” operational decisions into multiple strategies, and the subsequent study of "design-strategy pairs". Robust real-life anchored case studies would be beneficial here. A critical point that was not followed up on in detail in this project is the calibration of the models towards the preferences of the stakeholders. For the models to be useful, this is an important area that must be addressed, and should hence receive more focus.

At last, in terms of the type of case studies, cruise shipping is an exciting area that did not receive attention in this project, even though cruise ships have a proven record of multiple elongations and retrofit project. In terms of making the complex, ambiguous concept of flexibility in design easier to communicate to practitioners and researchers, I recommend the consideration of the development of "classes of flexibility" in shipping. This is exemplified by the flexible class notation called *Gas Ready* from DNV GL. As classification societies are omnipresent in the maritime industry, I believe that the development of additional flexible classes could serve as an enabler for the industry to appropriately adapt the material. Thus, I recommend further research to consider closely collaborating with classification societies.

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Appendix A: Glossary

Term	**Definition**
Changeability	Ability of a system to change form, function, or operation (de Weck, Ross, and Rhodes 2012).
Complexity	The complexity of an object is often referred to as the amount of information needed to describe it (Kolmogorov 1983). In the context of systems engineering, Rhodes and Ross (2010) classify five aspects of complexity. The first two, *structural* and *behavioral*, are related to state-of-the-practice for systems design. That means, traditional design practices of mapping from function to form. The latter three relate to state-of-the-art, extending the system boundary to also include *contextual*, *temporal*, and *perceptual* aspects.
Concept design	Part of the early-phase design process, where the goal is to determine the specifications of a principal solution, a concept (Pahl and Beitz 1988).
Design	The process of *designing (verb)* is as an open-ended process where plans for useful artifacts and processes are created (de Weck, Roos, and Magee 2011). Plans refer to e.g. drawings, software, protocol definitions, verbal, and visual material. Design can in general be described as a mapping process from *function* to *form* (Coyne et al. 1990). A *design (noun)* is also used as a noun referring to the plan of the artifact itself.
Engineering system	A "class of systems characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society" (de Weck, Roos, and Magee 2011). The additional social dimension differentiates engineering systems from purely *technical systems.*
Flexibility	Ability of a system to be changed by a system-external change agent with intent (de Weck, Ross, and Rhodes 2012). This contrasts with *adaptability* – with an internal change agent.
Form	Form "is what the system *is*; it is the physical or informational embodiment that exists or has the potential to exist. Form has shape, configuration, arrangement and layout. Over some period of time, form is static and perseverant (even though form can be altered, created, or destroyed). Form is the thing that is built; the creator of the system builds, writes, paints, composes, or manufactures is. Form is

	not function, but is necessary to deliver function” (Crawley, Cameron, and Selva 2016).
Function	Function “is what the system *does;* it is the activities, operations, and transformations that cause, create, or contribute to performance. Function is the action for which a thing exists or is employed. Function is not form, but function requires an instrument of form. Emergence occurs in the functional domain. Function, performance, the “ilities”, and emergence are all instances of functionality. Function is more abstract than form, and because it is about transitions, it is more difficult to diagram than form” (Crawley, Cameron, and Selva 2016).
Ilities	The ilities “are desired properties of systems, such as flexibility or maintainability (usually but not always ending in ility), that often manifest themselves after a system has been put to its initial use. These properties are not the primary functional requirements of a system’s performance, but typically concern wider system impacts with respect to time and stakeholders that are embodied in those primary functional requirements. The ilities do not include factors that are always present, such as size and weight (even if these are described using a word that ends in ility)” (de Weck, Roos, and Magee 2011).
Lifecycle	The “sequence of phases that an engineering system undergoes, which can be divided into three major parts: conceiving, developing, and deploying.” (de Weck, Roos, and Magee 2011).
Operations research (OR)	Research dealing with the management of systems in the *operational phase* of the lifecycle. OR is important for system design considerations, as it can be central for *evaluating* design alternatives - alternatively manifested through *requirements engineering*.
Platform	A “module or set of components that splits a system into two parts so that changes can, in principle, be made on either side of the platform interface without affecting the other side as long as appropriate standards are followed; platform implementation: All parts or components on the side of the platform interface farther from the end user, namely, the parts or components needed to achieve the desired abstract interface” (de Weck, Roos, and Magee 2011).
Property	A “term used to describe all characteristics of a system that determine its usefulness to a variety of stakeholders and this includes all function (and performance), ilities and factors such as size, weight and cost” (de Weck, Roos, and Magee 2011).

Requirement	"The properties that an engineering system is supposed to achieve, deliver or exhibit" (de Weck, Roos, and Magee 2011).
Requirements engineering / elicitation	The process of identifying and defining the functional requirements in the engineering design process, sometimes related to the conceptual design phase itself.
Retrofittability	Ability of a system to satisfy diverse needs *by* change of form.
Risk	"The level of hazard combined with the likelihood of the hazard leading to an accident, and the duration or exposure of the hazard; a combination of likelihood, severity, and lack of detectability of an accident or loss event." (de Weck, Roos, and Magee 2011).
System	"A set of interacting components having well-defined (although possibly poorly understood) behavior or purpose; the concept is subjective in that what is a system to one person may not appear to be a system to another." (de Weck, Roos, and Magee 2011).
System architecture	"Is an abstract description of the entities of a system and the relationship between those entities" (Crawley, Cameron, and Selva 2016).
Systems architecting	"The process by which standards, protocols, rules, system structures, and interfaces are created in order to achieve the requirements of the of the system; trade-off studies may precede the determination of system requirements." (de Weck, Roos, and Magee 2011). Comment: Although there seems to be no consistent differentiation between system architecture and system design/engineering, according to de Weck, Roos, and Magee (2011) "systems architecting creates a system design at a high, abstract level, whereas systems engineering is often associated with refining such as design; by blending the two processes, one accomplishes the assignment of functions to physical or abstract entities, and the definitions of interactions and interfaces between entities"
Systems design	"The process of defining the components, modules, interfaces, and data for a system to satisfy specified requirements. System development is the process of creating or altering systems, along with the processes, practices, models, and methodologies used to develop them." (MITRE Corporation, 2014)
Systems engineering	"An interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the

	development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem” (INCOSE[2]).
Uncertainty	“Things that are not known, or only known precisely. They may be characteristics of the universe (e.g. statistical processes) or characteristics of the design process (e.g. information not yet collected); in either case they are factual. Many uncertainties are measurable, although some are not (e.g. future events). They are value-neutral; they are not necessarily bad.” (McManus and Hastings, 2005).
Versatility	Ability of a system to satisfy diverse needs *without* change of form (de Weck, Ross, and Rhodes 2012).

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[2] International Council on Systems Engineering (INCOSE), 7060 Opportunity Road, Suite 220 San Diego, CA, USA.

Appendix B: Main Articles

Article 1

Ill-Structured Commercial Ship Design Problems: The Responsive System Comparison Method on an Offshore Vessel Case
Pettersen S.S.; Rehn, C.F.; Garcia J.J.; Erikstad, S.O.; Brett, P.O.; Asbjørnslett, B.E.; Ross, A.M.; Rhodes, D.H.
Journal of Ship Production and Design,34(1), 72-83, 2018

Article 2

Investigating tradeoffs between performance, cost and flexibility of reconfigurable offshore ships
Rehn, C.F.; Pettersen, S.S.; Erikstad, S.O.; Asbjørnslett, B.E.
Ocean Engineering, 147, 546-555, 2018

Article 3

Quantification of Changeability Level for Engineering Systems
Rehn, C.F.; Pettersen, S.S.; Garcia, J.J.; Erikstad, S.O.; Brett, P.O.; Asbjørnslett, B.E.; Ross, A.M.; Rhodes, D.H
Under review in an international journal

Article 4

Versatility vs. retrofittability tradeoff in design of non-transport vessels
Rehn, C. F.; Garcia, J. J.; Erikstad, S. O.; de Neufville, R.
Submitted to an international journal

Article 1

Ill-Structured Commercial Ship Design Problems: The Responsive System Comparison Method on an Offshore Vessel Case

Pettersen S.S.; Rehn, C.F.; Garcia J.J.; Erikstad, S.O.; Brett, P.O.; Asbjørnslett, B.E.; Ross, A.M.; Rhodes, D.H.

Journal of Ship Production and Design,34(1), 72-83, 2018

Ill-Structured Commercial Ship Design Problems: The Responsive System Comparison Method on an Offshore Vessel Case

Sigurd S. Pettersen[a], Carl F. Rehn[a], Jose J. Garcia[a,c], Stein O. Erikstad[a], Per O. Brett[a,c], Bjørn E. Asbjørnslett[a], Adam M. Ross[b], Donna H. Rhodes[b]

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Abstract: *In this paper, we address difficulties in ill-structured ship design problems. We focus on issues related to evaluation of commercial system performance, involving perceptions of value, risk and time, to better understand trade-offs at the early design stages. Further, this paper presents a two-stakeholder offshore ship design problem. The Responsive Systems Comparison (RSC) method is applied to the case to untangle complexity, and to address how one can structure the problem of handling future contextual uncertainty to ensure value robustness. Focus is on alignment of business strategies of the two stakeholders with design decisions through exploration and evaluation of the design space. Uncertainties potentially jeopardizing the value propositions are explicitly considered using epoch-era analysis. The case study demonstrates the usefulness of the RSC method for structuring ill-structured design problems.*

Key words: Systems Design, Naval Architecture, Multi-Attribute Utility Theory (MAUT), Uncertainty, Complexity

1. Introduction

In a competitive maritime industry, there is a need to design, develop and deliver systems able to sustain value throughout a multi-decade lifetime. However, design of ocean engineering systems remains a difficult task, mainly due to the complexity and uncertainty governing these systems and their sociotechnical contexts. Even a clear definition of what is a better ship is ambiguous (Ulstein and Brett 2015) - it all depends. Understanding the relation between business strategies and corresponding marine design decisions, is not straight-forward, and the ship design task could be considered a wicked problem (Andrews 2012), or an ill-structured problem (Simon 1973). An ill-structured problem lacks a specified beginning and goal states, and the relation between these are unknown. More information must be gathered to enrich the problem definition and take informed decisions. A differentiation can hence be made between the problem of defining the problem to solve, and the problem of solving this problem. In this paper we stress the importance of understanding both of these aspects when it comes to design of complex systems.

The driving forces behind ocean engineering systems are often commercially oriented, introducing risks due to high market volatility. High oil prices and large ultra-deepwater discoveries have spurred the development of offshore oil and gas fields. Offshore construction vessels (OCVs) have taken part in this arena, particularly in the development of marginally profitable fields. More recently, the oil price collapse has had significant impact on this industry, rendering recent large multi-functional, *gold-plated* design solutions unprofitable.

However, there are multiple other sources of contextual uncertainty that can affect the initial value propositions, and hence need to be considered in ship design, including technical, regulatory and operational factors. Risk and uncertainty are usually associated with negative consequences, but it is also important to acknowledge the upside opportunities uncertainty can introduce (McManus and Hastings 2006). Actively considering uncertainty in the design process can result in solutions that reduce downside risk and increase upside exposure, hence increasing the expected system performance over its lifetime. Design solutions that continue to provide value in a variety of contexts are known as *value robust* solutions, which can be achieved by either active or passive value robustness strategies, relating to whether the system actively can change in response to uncertainty or not. Active change involves implementation of changeability, characterized by the ability of a system to alter its form and function for the future. This involves system properties such as robustness, flexibility, agility, scalability and upgradeability, often also referred to as *ilities* (Fricke and Schulz 2005; Ross, Rhodes, and Hastings 2008; Niese and Singer 2014; Chalupnik, Wynn, and Clarkson 2013). The current situation in the offshore industry serves as a perfect example of the importance of focusing on value robustness and flexibility as key factors for success in a volatile industry.

Research on design of complex offshore engineering systems under uncertainty has recently gained momentum, as researchers have called for taking a broader view to engineering systems design processes (de Weck, Roos, and Magee 2011; Fet, Aspen, and Ellingsen 2013). With the current state of the offshore market, Erikstad and Rehn (2015) address the need for approaches for handling uncertainty in ship design. As a response to such calls, recent research within marine design focuses on novel methods, including methods from operations research and systems engineering (Garcia et al. 2016). Operations research methods include stochastic programming applied to issues in ship design like machinery selection under uncertainty (Balland et al. 2013; Patricksson and Erikstad 2016). Another recent approach uses Markov decision processes for evaluating ship design performance under uncertainty (Kana and Harrison 2017).

In this paper, we use the Responsive Systems Comparison (RSC) method to understand the decision making process in ship design. The RSC method is based on two systems engineering methods; i) multi-attribute tradespace exploration and ii) epoch-era analysis (Ross et al. 2009; Ross et al. 2008). Specific RSC applications include the design of an anchor handler tug and supply vessel (Gaspar et al. 2012), environmental regulation compliance in a lifecycle perspective (Gaspar et al. 2015), ship design for naval acquisition affordability (Schaffner, Ross, and Rhodes 2014), and a simplified offshore construction vessel (OCV) case (Keane, Brett, and Gaspar 2015).

The current paper explores the ship design process using the RSC method based on a real industrial case. It represents an analysis of the design of an offshore construction vessel for a joint venture of two stakeholders with different preferences. Following this, the most significant contribution are the theoretical insights to ill-structured design problems, and its formulation as a two-stage abduction process.

2. Evaluation of Commercial System Performance

Commercial engineering systems are typically selected on basis of economic decision criteria like net present value (NPV), or based on decision models allowing managerial flexibility, such as real options. A shortcoming of economic approaches is the number of assumptions one has to make. What are the future revenue streams? What are future market conditions? What discount rate should we choose? Microeconomic theory separates between risk averse, risk neutral and risk seeking behavior, normally assuming a risk averse attitude among stakeholders. This is not reflected in the use of NPV, or other economic measures of merit alone (Erichsen 1989; Benford 1970). Prospect theory (Kahneman and Tversky 1979) goes further, proposing that decision makers are loss aversive, and value losses as more negative than an equivalent win positively.

Value may vary over time, hence there are differences between the perceived value at the time of a decision and the value of that decision as actually experienced (Ross and Rhodes 2008). Investments in the commercial shipping industry are made in order to receive expected future benefits. Do we really know how to discount such perceived value? Empirical research in behavioral economics show that time inconsistent discount models, such as hyperbolic discounting, often account better for the preferences of stakeholders than the common assumption of time consistent discounting, as in financial NPV calculations (Frederick, Loewenstein, and O'Donoghue 2002). If we do not know which discounting model that best represents stakeholder perception of value, how can we then discount?

Taking future uncertainty into account in the cash flows by simulation based on historical data and extracting measures like value-at-risk, may help mitigate going into the *flaw of averages* (Savage 2009), but still does not take into account situations where a ship owner competes against other agents for different contracts, i.e. alternative, uncertain cash flows. Game theory may guide us some of the way, but it assumes that other agents act rationally. If agents are not rational, what is then the probability of winning a contract? What do the customers offering a contract actually care about when they select a specific bid among several? For complex systems facing uncertainty in their future operating context and in their perceived value to the stakeholder, economic decision criteria should be amended with other value attributes that better capture the things that stakeholders actually care about.

2.1. Profit as a subset of value

There are multiple examples of what may be perceived as value in commercial shipping today, in addition to profitability. Recently, there has been increased focus on environmentally friendliness. Several ship owners market themselves as "green". One may on the other hand, argue that for many profit-oriented players, green marketing is one way to increase profits further by making the product/service more attractive for customers and not because they care about the environment *per se*. However, it is difficult to reliably quantify the effect of this green marketing (Dahle and Kvalsvik 2016). It has also been proposed that the ultimate goal of some ship owners may be *prestige*, rather than pure profit. This may be signified by actions that drive costs, without really adding any "value" in economic terms. For example, 40% of platform supply vessels (PSVs) in the North Sea has been built with Ice Class, without really needing it (Garcia, Brandt, and Brett 2016). Again, it is possible to argue that ship owners believe this design choice will drive long-term profitability of their operation, as the vessel becomes more *versatile* with respect to operating region. These attitudes separate owners with a strong relation to the technical and operational aspects from ship owners with a purely commercial mind-set.

For commercial applications, in which profitability is the only objective, one may rephrase and say that profitability then is the (only) element of what the stakeholders perceive as value and success. Therefore, *value-focused thinking* (Keeney 1992) remains central, and value can hence be seen as a superset of profitability. If the preferred value attributes replicate profit-seeking stakeholders, this disaggregated approach nevertheless helps us untangle the complexity of the profit dynamics, which enables a better understanding of value trade-offs in various contextual settings.

2.2. Multi-attribute utility theory

Several methods for making decisions based on multiple value attributes exist (Ross et al. 2010; Papageorgiou, Eres, and Scanlan 2016). In this paper, we use multi-attribute utility theory, as presented by Keeney and Raiffa (1993). The attributes must adhere with the following criteria; i) *completeness*, representing all important aspects of decision making, ii) *operational*, possible to measure, iii) *decomposable*, so that they can be broken into parts for easier evaluation, iv) *non-redundant*, so that the same attributes are not counted twice, and v) *minimal*, so that the dimensionality of the problem is kept as small as possible. We here use an additive multi-attribute utility function, on the following form:

$$U(X) = \sum_{i=1}^{I} k_i U_i(X_i) \tag{1}$$

U here refers to the overall utility over all attributes. k_i are the weights for each attribute i, with an attribute value X_i. The value attributes selected for the model should be the things the stakeholders really care about, limited by short-term memory to seven, plus minus two (Miller 1956). Additional complexities can be handled by decomposition, making a value hierarchy adding structure to the utility function (Keeney 1992).

3. Methodology

The Responsive Systems Comparison (RSC) method is used in this paper. The RSC method was originally presented in Ross et al. (2009) and Ross, McManus, et al. (2008), but evolved to its current form in later papers, a recent reference being Schaffner et al. (2014). The stated purpose of the RSC method is “to take a designer or system analyst (RSC practitioner) through a step-by-step process of designing and evaluating dynamically relevant system concepts” (Ross et al. 2009). To fulfil this, the framework uses several other methods such as multi-attribute tradespace exploration (MATE) and epoch-era analysis (EEA). The RSC method is a generic approach to design decision making. A key heuristic for the method is to reduce the number of assumptions to a minimum. This makes it suited for combination with other tools and methods. Figure 1 illustrates the current layout of the RSC method, consisting of 9 steps clustered into 3 modules. Note that several feedback loops exist between the steps. As the understanding of the system increases, the stakeholders may perceive the system differently from their initial perspective.

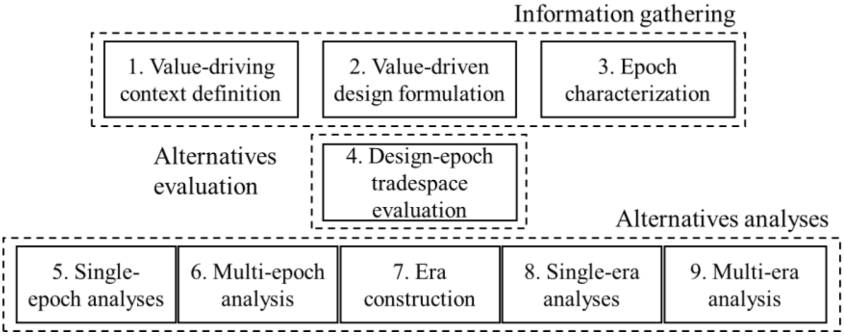


Figure 1: The Responsive System Comparison (RSC) method (adapted from Schaffner et al. (2014)).

The RSC method has been considered for implementation in this offshore case study due to its suitability to consider system design cases with changes in user needs and expectations, context and the system itself (Ross et al. 2009).

3.1. Information gathering

The initial steps of the RSC method collect the information used throughout the analysis. These steps should be supported by interviews with the decision-makers and other stakeholders in the project (Ross et al. 2009). First, in the "Value-driving context definition" the context of the system must be defined, in terms of how the context drives value. The "problem" in the environment is recast into an "opportunity", where an initial state can be turned into a desired state (Simon 1996). The outcome of the "Value-driving context definition" can be a value proposition. The value proposition will thus provide the link between the scope of the system design process and the business strategy of the stakeholders.

In the second step, "Value-driven design formulation", a set of value attributes are extracted from the value proposition. The attributes should be narrowed to the factors that stakeholders really care about. Having specified value attributes, the process of mapping from objectives and overall value statements to design descriptions can start. By abducting specific design instances and generalizing them into design variables that matter for system value, we map from the value space to the physical space driving costs (Ross, Rhodes, and Hastings 2008).

"Epoch characterization" is the final information gathering process where exogenous uncertainties are encapsulated within well-defined epoch variables. Every combination of epoch variables represents an epoch, a static short-run scenario. An epoch can be described as "a period of time for which the system has fixed context and fixed value expectations" (Ross and Rhodes 2008). Typically, epoch variables are technology or infrastructure changes, economic and market forces, policy and regulation, and resources and budgetary constraints.

3.2. Alternatives evaluation

The "Alternatives evaluation" defines the tradespace model upon which the designs are evaluated. The exact model which maps the connection between the value space, possibly via a performance space, to design and epoch spaces, is defined in this step. The modelling in this step relates to the causal mechanisms that were seen as "black box" in the information gathering. The aim of this evaluation process is to gain insight in how possible system architectures provide value, given important contextual uncertainties (Ross et al. 2009). The outcome of this stage are utility measures and costs for all design alternatives in all epochs. The required mapping between the value and design spaces is shown in Figure 2. In the figure, MAU refers to multi-attribute utility, while MAE refers to multi-attribute expense, a generalized cost representation.

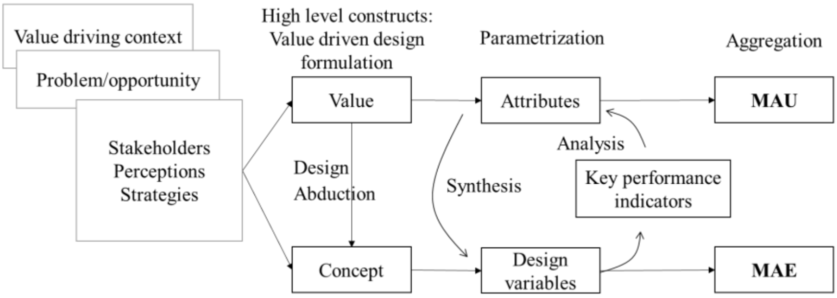


Figure 2: Relating value and design concept to the tradespace.

3.3. Alternatives analyses

"Alternatives analyses" consists of five steps concerned with producing metrics that let us compare and get insight of alternative designs in and across epochs and eras. In "Single-epoch analyses" tradespaces are explored with the Pareto efficient frontier of non-dominated solutions as the criteria of design goodness of fit (Keeney and Raiffa 1993). For the "Multi-epoch analysis", Fitzgerald and Ross (2012) propose additional metrics to identify value robust designs across changing contexts and needs. These measures can be extended to consider active value robustness and changeability.

To be able to analyse design performance in a lifetime perspective, eras are constructed. Eras are scenarios representing the long run system context, consisting of sequences of epochs assembled along a timeline (Ross and Rhodes 2008). In accordance with microeconomics, the long run is signified by holding no factors constant (Varian, 2006). Era construction is an example of scenario planning, allowing for strategic planning for the medium to long-term, as they seek to answer from the stakeholder's perspectives "What can conceivably happen?" and "What would happen if…?" (Lindgren and Bandhold 2003). Eras thus enable assessment of the lifecycle performance of various designs in different contextual operating conditions.

"Single-era analyses" and "Multi-era analysis" are the two final steps of the RSC method. In the "Single-era analyses" time-dependent effects of unfolding eras are investigated for interesting design alternatives (Schaffner, Ross, and Rhodes 2014). "Multi-era analysis" explores dynamic system properties by identification of patterns across multiple eras, exploring design-strategy pairs, to understand how we for example can implement changeability to ensure value robustness.

4. Case study

The case study centres on the design of an offshore construction vessel, following the RSC method. The information gathering phase was informed by interviews with decision-makers from a real ship design project, and a retrospective Accelerated Business Development (ABD) process. This process is described by Brett et al. (2006).

4.1. Step 1: Value-driving context definition

The business opportunity for a new offshore ship design emerges from a set of trends in the oil and gas industry. Increasing world population and economic growth is believed to lead to an increased demand for energy. While there are alternatives to oil and gas emerging, both due to the depletion of most easy-access resources and the threat of global warming, the offshore oil and gas markets are expected to be strong for a long time despite a characteristic high short-term volatility.

Two shipping companies form a joint venture to introduce novel offshore technologies to a new operational region. Their strategies and goals are different, while one provides a wide range of services within the Gulf of Mexico, the other is a world-wide operator with principal focus on light well intervention (LWI) services. The involvement of more than one key stakeholder increases intrinsically the difficulty of selecting a single design to build (Fitzgerald and Ross 2013). The merger of shared and competing goals into one system concept, calls for a collaborative engineering approach combining coordination, cooperation and collaboration between stakeholders. The intention of this approach is to attain more together than what would be possible apart. While the ship design project that results from the business opportunity is to be done by a joint venture between the two stakeholders, the preferences of each ship owner should be kept separate. This strategy makes it easier to understand which trade-offs and compromises are made through the decision-making process. For this reason, we keep the value propositions of each main stakeholder separate. The outcome of Step 1 is thus the two following value propositions:

> **Stakeholder 1:** *"Being the first subsea contractor in the Gulf of Mexico by building and operating a fleet of profitable OCVs."*
>
> **Stakeholder 2:** *"Being the leading provider of high quality solutions for the offshore oil industry, by adding advanced, environmentally friendly and profitable OCVs to the existing fleet."*

4.2. Step 2: Value-driven design formulation

Once the value-driving context has been defined, which helps us outline the problem to be solved, we can start formulating the value-driven design. The value attributes are derived from the value propositions, and therefore align with the business opportunity that was identified in Step 1. Interviews with key decision makers are an important ingredient when collecting the appropriate statements of needs, and expressing them in terms of objectives (Ross et al. 2009). We separate between monetary and non-monetary aspects of value, which are assessed independently in the model, due to their temporal differences. Profitability is incorporated indirectly in the model, through cost minimization for feasible designs for a mission with a given rate, and is considered a value attribute at the era level. See Chapter 4.4 and Chapter 5.2 for further information and discussions on profitability. The non-monetary value attributes of the two key decision-makers are at the epoch level, and are summarized in Table 1. The associated single-attribute utility functions for the non-monetary value attributes of each stakeholder are given in Figure 3.

Table 1: Stakeholder value attributes.

Stakeholder	Value att.	Level	Units	Worst	Best	Description
1	Originality	Epoch	[-]	0	10	First mover with advanced equipment in GoM.
1	Replicability	Epoch	[-]	0	10	Easiness to replicate at different yards.
1	Profitability	Era	[$]	-	-	Net cash flow from the investment.
2	Eco-friendliness	Epoch	[-]	0	10	Environmental friendly transit and operations.
2	Fleet integrability	Epoch	[-]	0	10	Integrability with current advanced fleet.
2	Profitability	Era	[$]	-	-	Net cash flow from the investment.

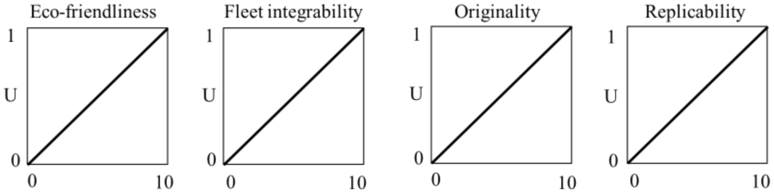


Figure 3: Single-attribute utility functions.

Originality represents the ability of being the first mover with advanced equipment into the Gulf of Mexico (GoM) market. Originality is a measure of how technically advanced a vessel is compared with the current operational fleet in this area, physically operationalized through the crane lifting and light well intervention capability on a scale from 0 to 10 where higher is better. Replicability represents a measure on the simplicity to which a design can be reproduced by another yard. It reflects the building complexity, in this maritime context operationalized by the gross tonnage (GT) on a defined 0 to 10 scale, where a lower GT represents a higher number on the scale. Complex ships are assumed to be more difficult to copy and reproduce compared to simpler ones, as more information is needed to describe complex systems. Eco-friendliness represents the ability of a design to perform with as low environmental footprint as possible. This is defined on a scale from 0 to 10, dependent on aspects of eco-friendliness of a design in transit and operation operationalized through the water resistance of the design and the fuel type used. Fleet integrability represents the degree to which the design integrates into the current advanced light well intervention fleet of stakeholder 2. The attribute is defined on a scale from 0 to 10 based on the LWI capability of the current fleet of stakeholder 2.

Table 2 presents the design variables generalized from common parametrizations of offshore vessel designs. The design variables represent the aspects of the physical design concepts with stronger influence on the value attributes. To avoid disregarding a-priori designs of high potential value, we do not check for basic feasibility requirements at this stage, like stability or minimum freeboard.

Table 2: Design variables.

Design variable	Units	Values
Length	m	[120, 140, 160, 180]
Beam	m	[20, 25, 30, 35]
Depth	m	[8, 11, 14]
Installed power	MW	[5, 10, 15, 20, 25]
Accommodation	persons	[50, 150, 250, 350]
Main crane capacity	tonnes	[0, 200, 400, 600, 800]
Light well intervention	tonnes	[0, 300, 600]
Moonpool	[-]	[No, Yes]
Fuel type	[-]	[MGO, Dual Fuel (DF)]
Dynamic positioning	[-]	[DP2, DP3]
Remotely operated vehicle	[-]	[No, Yes]

4.3. Step 3: Epoch characterization

The epoch characterization phase elicits exogenous uncertainties perceived by the stakeholders as potentially impacting the value of the system. For the offshore vessel in this case study, we define the system boundary around the ship itself, and hence eight epoch variables are predicted to affect the vessel, as illustrated in Figure 4.

Figure 4: Ship system boundaries and epoch variables.

The eight epoch variables, classified in contract parameters and technical requirements are presented in Table 3. Additionally, we define each of the four operational areas as a combination of water depth and sea state, represented by the significant wave height (Hs), as described in Table 4. Further, the possibility that the ship is in lay-up is also included.

Table 3: Epoch variables representing important sources of exogenous uncertainty.

	Epoch variable	Unit	Values
Contract parameters	Contract rate	k$/day	[50, 70, 120, 170, 220]
	Operational area	[-]	[1, 2, 3, 4]
Technical requirements	Light well intervention req.	tonnes	[0, 300, 600]
	Module weight req.	tonnes	[0, 200, 400, 600]
	Accommodation req.	POB	[50, 150, 250, 350]
	ROV req.	[-]	[0, 1]
	Dynamic positioning req.	[-]	[0, 1]
	Deck area req.	m^2	[0, 1000]

Table 4: Characteristics of depth and sea state (Hs) for the four operational areas.

Operational area	Epoch var. value	Depth [m]	Hs [m]
Gulf of Mexico	1	1600	2.0
Brazil	2	2500	2.5
North Sea	3	200	3.0
West Africa	4	1800	1.0

4.4. Step 4: Design-epoch tradespace evaluation

This step enables the representation of all designs from the design space in terms of utility and costs in the tradespace, to gain an understanding of how system concepts provide value given important contextual uncertainties (Ross et al. 2009). At this stage, we model the mapping between the value space and the design space. Some of this mapping takes place by going through modelling of physics and economics, via "key performance indicators" (KPIs). The outcome of Step 4 is a measure of multi-attribute utility (MAU), and a cost measure, multi-attribute expense (MAE).

There are various intermediate performance indicators in the model, which are central in the mapping between value and physical design. At an early design stage, we want to evaluate multiple designs in different epochs, hence the models need to be low fidelity in order to make it computationally feasible. Therefore, in absolute terms, the estimated properties may not be correct, but for comparisons in relative terms indicate the main relationships between the relevant parameters. The physical calculations include lightweight, deadweight, deck area, speed, acquisitional and operational costs.

This paper focuses on design of commercial systems, where profitability is central. It is important to understand that even though profitability is not assessed as a value attribute in a particular epoch, it is incorporated indirectly because we want to minimize the costs in a mission with a given day rate. Hence, when we seek Pareto optimal designs, we also find the designs that maximize the profitability for each epoch, and this way of structuring the problem opens up for easy exploration of the trade-off between profitability and other value attributes such as eco-friendliness. In order to assess profitability, a financial model is used to calculate the cash flows. The financial system boundary is around the ship itself, and hence we do not include financial details on the fleet level for the ship owners. Fuel costs are not included in this model, since they are assumed paid by the charterer. The system boundary in this analysis does not include specific aspects of the market, such as supply and demand, and we hence just work with contracts, with their rates and requirements. Assessment of these underlying dynamics remains outside the scope of this analysis.

Figure 5 illustrates the architecture of the methodological approach in this paper, comprising mainly four elements: the design space, the system modelling, the epoch space and the resulting evaluation criteria: value and cost. What is particularly important to consider, is how an epoch can be decomposed into information regarding the context and needs. Both, context and needs may change over time, randomly, or one may see more casual relationships. Proper investigation of these dynamics is important in order to make value robust design decisions, for example through interviews with the stakeholders. In this analysis, we assume that the set of value attributes remains constant in different epochs. Further, in the process of calculating the MAU, we assume that the weights remain static at 0.5 for each of the two value attributes for each of the two stakeholders. The different costs components are aggregated to a multi-attribute expense (MAE) function for each stakeholder, where acquisition costs and operational costs are weighted equally. When a design does not satisfy the requested technical requirements in an epoch, it is considered infeasible. No direct limitations are imposed on the newbuilding price.

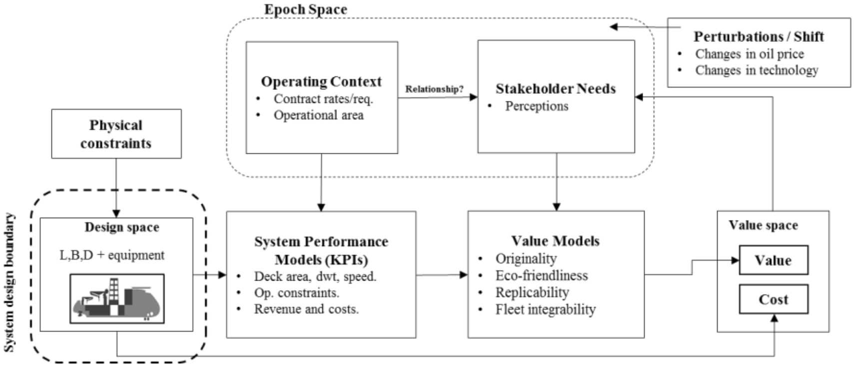


Figure 5: Illustrating the design-value mapping model.

Once the value-epoch model is defined, all design solutions can be plotted in terms of MAU versus MAE, creating a tradespace for a given epoch. Taking the view that we investigate a trade-off between utility and cost, the non-dominated solutions become those designs that for each possible budgetary constraint maximizes utility. Since we maximize utility and minimize costs for a given contract with a given day rate, we indirectly find the designs that maximize the profit for that particular epoch and contract.

Table 5: Sample designs for further assessment.

Design name		I	II	III	IV	V	VI
Design ID	[-]	116454	114843	110835	128020	111081	128356
L, B, D	[m]	140,25,8	160,30,11	160,20,8	180,20,8	120,30,8	180,20,8
Main crane	[tonnes]	200	400	800	400	800	800
Accommodation	[POB]	150	250	150	150	250	250
Engine power	[MW]	15	25	15	15	15	15
Light well intervention	[tonnes]	300	0	600	600	600	600
Moonpool	[-]	Yes	Yes	No	No	No	No
Fuel type	[-]	Diesel	Diesel	Diesel	DF	Diesel	DF
Remotely operated vehicle	[-]	Yes	Yes	Yes	Yes	Yes	Yes
Dynamic positioning	[-]	DP3	DP3	DP3	DP3	DP3	DP3
Deck area	[m^2]	1200	2000	1000	1300	1000	1000
Dwt	[tonnes]	7300	19000	4500	6700	5400	5400
Max speed	[knot]	18	20	18	18	17	18
Acquisition cost	[m$]	164	210	215	236	223	247

To gain better insight in this design problem, six designs are studied more in detail in the following analyses, as illustrated in Table 5. Since we do not check for technical feasibility on the design variables, to reduce the number of assumptions, we may get solutions that seem unrealistic to ship designers. This is especially true for designs III and IV.

4.5. Step 5: Single-epoch analyses

In this step, we analyze and explore the tradespaces for each stakeholder in different epochs, gaining insight into the trade-offs among alternative designs. This process is carried out with the means of learning about the complex system behavior in different static contexts. Tradespace yield is a useful metric for evaluating single epochs, which takes the feasible designs within the epoch, as the percentage of the total number of enumerated designs (Ross et al. 2009). This also gives a hint of whether the attribute ranges should be redefined to make it easier for designs to fulfil requirements. For illustration, we assess the system behavior under three epochs, represented in Table 6.

Table 6: Three relevant example epochs for the Gulf of Mexico.

	Low case	**Base case**	**High case**
Epoch ID	981	6813	6889
Contract rate	$70 000/day	$170 000/day	$220 000/day
Operational area	Gulf of Mexico	Gulf of Mexico	Gulf of Mexico
LWI	0 tonnes	600 tonnes	600 tonnes
Module weight	200 tonnes	200 tonnes	400 tonnes
Accommodation	50 people	150 people	250 people
ROV req.	Yes	Yes	Yes
Dynamic positioning	DP2	DP3	DP3
Deck area req.	0	1000	1000
Tradespace yield	0.20	0.02	0.01

The tradespace yield measures are in this case identical for the two stakeholders. Only the designs that have the technical equipment to satisfy the requirements in an epoch are defined as feasible. Due to the structure of the model, and the high number of designs generated, the tradespace yield measures becomes relatively low.

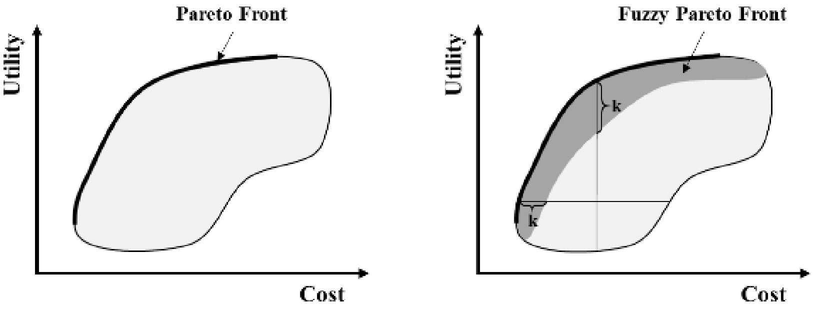


Figure 6: Pareto optimality and Fuzzy Pareto optimality with k% fuzziness, for a tradespace defined by utility and cost.

There exist multiple metrics to measure the performance, mostly based on Pareto efficiency. Figure 6 demonstrates the concept of the Pareto efficient frontier, with and without fuzziness, as introduced by Smaling and Weck (2004). The Fuzzy Pareto Number (FPN) is a metric that can be used to quantify the distance to the Pareto front for each design. FPN is defined as the smallest fuzziness percentage for which a design is in the fuzzy Pareto set (Fitzgerald and Ross, 2012). The FPN of the six designs followed in this analysis for both stakeholders are illustrated in Table 7. FPN of 101 represents infeasibility, while FPN of 0 stands for Pareto optimality.

Table 7: Fuzzy Pareto Number (FPN) for the six designs in three considered epochs for stakeholder 1 and 2.

	Stakeholder 1			Stakeholder 2		
Design	Low case	Base case	High case	Low case	Base case	High case
I	101	101	101	101	101	101
II	22	101	101	16	101	101
III	3	0	101	4	1	101
IV	8	8	101	0	0	101
V	5	3	0	9	6	2
VI	7	3	0	0	0	0

4.6. Step 6: Multi-epoch analysis

The purpose of multi-epoch analysis is to find value robust systems across changing contexts and needs, by measuring system value across multiple epochs. A separation can be made between actively and passively value robust systems (Ross, Rhodes, and Hastings 2008):

- **Passively value robust** systems are relatively insensitive to changing conditions, and continue to deliver value above an acceptable level, while maintaining the initial design configuration.
- **Actively value robust** systems can benefit from dynamically taking actions in response to changing conditions that may deteriorate the system performance, such as implementation of changeability.

In this analysis, we only consider passive value robustness. An overview of metrics for assessing design performance across multiple epochs is presented by Fitzgerald and Ross (2012). The Fuzzy Normalized Pareto Trace (fNPT) identifies passively value robust designs. In its “unfuzzy” form (0% fuzziness), it is simply the fraction of epochs in which a design is located on the Pareto front. With a fuzziness above 0, it represents the fraction of epochs in which the design is within the fuzzy Pareto set. If active value robustness is achieved through changeability, *effective* fNPT may be used as a measure of improved performance. The feasible design space is changing in size for each epoch. The fNPT metric is assumed only based on the feasible designs in an epoch.

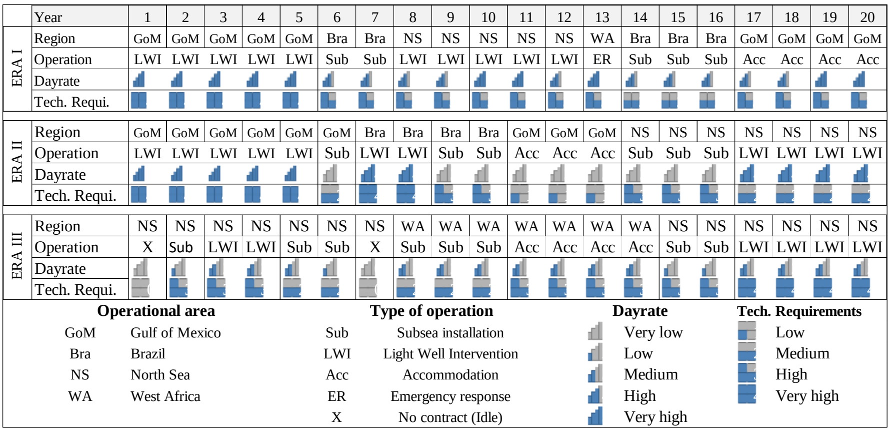
Table 8: NPT and k% fNPT for the six designs for stakeholder 1 and 2.

		Stakeholder 1			Stakeholder 2		
Design	Feasible	NPT	10% fNPT	20% fNPT	NPT	10% fNPT	20% fNPT
I	0.06	0.00	0.02	0.06	0.00	0.03	0.06
II	0.07	0.00	0.00	0.00	0.00	0.00	0.00
III	0.35	0.01	0.34	0.35	0.00	0.27	0.35
IV	0.17	0.00	0.01	0.14	0.00	0.17	0.17
V	0.45	0.00	0.31	0.44	0.00	0.04	0.33
VI	0.45	0.00	0.27	0.44	0.00	0.44	0.45

The passively value robust metrics are relatively low due to the structure of the problem. There are no static designs that perform well over all the epochs considered. Large multi-functional vessels will be able to take different missions, but require higher rates to be profitable than smaller designs that are optimized for single missions. This reasoning indicates that changeability could be valuable. For a proper assessment of the active value robustness of the designs, weighting and filtering based on probability may be considered.

4.7. Step 7: Era construction

The entire era space for this problem would be extremely large, considering the sizeable epoch space. While simulation methods could be applied to sample eras based on historical data following simple logical rules, a narrative approach is here used to represent likely system lifecycle scenarios. This enables simple “what if”-analyses that are easily communicated among stakeholders. Epoch durations through an era could be dynamic, but in this case we simplify and assume a static time span of 1 year per epoch. This intends to capture the volatility of the oil and gas industry, and to include the possibility for shorter "accident-driven" missions. For the case, the following three eras are specified for a 20-year system lifecycle, encapsulating stakeholder beliefs. The three eras are presented in Figure 7, in terms of operational areas, types of operation, day rates and technical requirements. Era I represents a baseline scenario, with an initially targeted tender contract and a strong offshore market continuation. Era II represents a similar start with the targeted tender contract, followed by a weakened market ending with offshore decommissioning in later years. Era III represents a market collapse where the initial targeted tender contract is not won.



	Year	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
ERA I	Region	GoM	GoM	GoM	GoM	GoM	Bra	Bra	NS	NS	NS	NS	NS	WA	Bra	Bra	Bra	GoM	GoM	GoM	GoM
	Operation	LWI	LWI	LWI	LWI	LWI	Sub	Sub	LWI	LWI	LWI	LWI	LWI	ER	Sub	Sub	Sub	Acc	Acc	Acc	Acc
	Dayrate	Very high	Very high	Very high	Very high	Very high	High	High	High	High	Very high	Very high	High	Very high	High	High	High	High	High	Very high	Very high
	Tech. Requi.	Very high	Very high	Very high	Very high	Very high	High	High	High	High	High	High	High	High	Medium	Medium	Medium	High	High	High	High
ERA II	Region	GoM	GoM	GoM	GoM	GoM	GoM	Bra	Bra	Bra	Bra	GoM	GoM	GoM	NS	NS	NS	NS	NS	NS	NS
	Operation	LWI	LWI	LWI	LWI	LWI	Sub	LWI	LWI	Sub	Sub	Acc	Acc	Acc	Sub	Sub	Sub	LWI	LWI	LWI	LWI
	Dayrate	Very high	Very high	Very high	Very high	Very high	Very low	Very high	Very high	Very low	Very low	Very low	Very low	Very low	Very low	Very low	Very low	Very high	Very high	Very high	Very high
	Tech. Requi.	Very high	Very high	Very high	Very high	Very high	Medium	Very high	Very high	High	High	Low	Low	Low	High	High	High	Medium	Medium	Medium	Medium
ERA III	Region	NS	NS	NS	NS	NS	NS	NS	WA	WA	WA	WA	WA	WA	WA	NS	NS	NS	NS	NS	NS
	Operation	X	Sub	LWI	LWI	Sub	Sub	X	Sub	Sub	Sub	Acc	Acc	Acc	Acc	Sub	Sub	LWI	LWI	LWI	LWI
	Dayrate	Very low	Low	Medium	Medium	Medium	Low	Very low	Medium	Medium	Medium	Medium	Medium	Medium	Medium	Low	Low	Medium	Medium	Medium	Medium
	Tech. Requi.		High	High	High	Medium	Medium		Medium	Medium	Medium	High	High	High	High	High	High	Very high	Very high	Very high	Very high

Operational area

GoM	Gulf of Mexico
Bra	Brazil
NS	North Sea
WA	West Africa

Type of operation

Sub	Subsea installation
LWI	Light Well Intervention
Acc	Accommodation
ER	Emergency response
X	No contract (Idle)

Dayrate

- Very low
- Low
- Medium
- High
- Very high

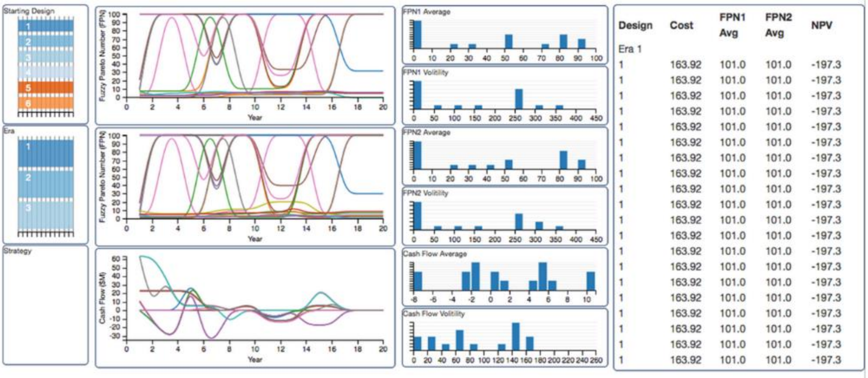
Tech. Requirements

- Low
- Medium
- High
- Very high

Figure 7: Description of three narrative eras.

4.8. Step 8: Single-era analyses

Single-era analyses focus on long-term value sustainment through dynamic scenarios with changing contexts and needs. Insight is gained through investigation of time-dependent effects that emerge through various sequences of epochs. For passively value robust designs, one can better identify strengths and weaknesses for different eras, and understand value trade-offs in various realizations of the future. For actively value robust designs, long run strategies can be examined as means to exercise changeability, and identify path dependencies. Visualization of these datasets remains difficult, but is an essential tool for gaining insights and communicating the results to stakeholders (Curry et al. 2017). Figure 8 illustrates an interactive map of the performance of various designs in the three narrative eras constructed in this case.



Design	Cost	FPN1 Avg	FPN2 Avg	NPV
Era 1				
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3
1	163.92	101.0	101.0	-197.3

Figure 8: Illustration of candidate designs over different single eras with supporting metrics (adapted from Curry et al. (2017)).

Tracking of monetary performance metrics such as net present value and return on investment through each scenario, are particularly interesting to commercial system stakeholders. Monetary and non-monetary performance metrics can be concurrently illustrated in a lifecycle performance plot, as shown in Figure 8. Additionally, we are interested in evaluating the risk of defaults and the financial survivability of a design, which becomes visible the era level of the analysis. We may for example be willing to accept short periods of loss, in order to have higher overall probability of survival.

4.9. Step 9: Multi-era analysis

Multi-era analysis is a parallel process to the multi-epoch analysis. While multi-epoch analysis seeks to identify value-robust designs across the epoch space, the aim of multi-era analysis is to do the same in the era space. Considering the magnitude of the era space, it is computationally infeasible to find metrics parallel to those found in multi-epoch analysis. Smarter search mechanisms are needed to perform viable multi-era analyses, including methods for sampling epochs to eras, for example based on strategic system management decisions. The propagation of the era will be dependent on the trajectory of system decisions, especially when considering active value robustness and changeability. In addition, perturbations creating a shift from one epoch to the next will create path dependencies. For this reason, rolling horizon heuristics could be of interest in further research. A rolling horizon approach would not consider a fully rolled out scenario tree from the beginning, but continuously update the scenario tree as future uncertainties are resolved and decisions are made.

5. Discussion

5.1. On problem structuring

Design of engineering systems involves simplification of an initial ill-structured problem. There is a significant difference between the task of defining the ill-structured problem in terms of well-structured representations, and the task of solving a well-structured representation of the design problem. The Responsive Systems Comparison (RSC) method facilitates the problem definition processes, in addition to laying out a structured approach for solving the subsequent well-structured design problem. Taking relatively abstract business propositions into a more well-structured problem space represents in itself a design problem, as many alternative well-structured problems can be formulated. Thereafter, the well-structured problem can be solved, and resulting recommendations can be communicated to decision makers. Hence, this can be considered a two-stage abductive reasoning process, as illustrated in Figure 9.

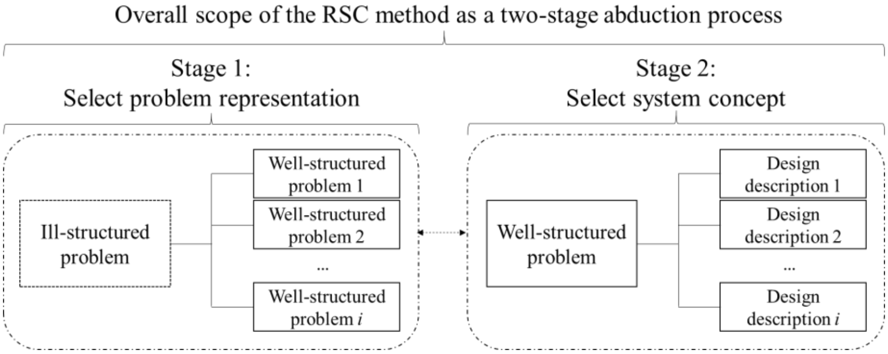


Figure 9: Making ill-structured problems well-structured, and solvable through two abductive stages.

Structuring an ill-structured problem represents in itself a result, as it reduces the ambiguities surrounding stakeholder preferences. For instance, the knowledge generated by explicitly relating a value proposition to the design space by producing a model, defines the design problem in such a way that it finally can be solved. The case study shows that the RSC method generates useful insights that will influence how design problems are framed, and thus how they are made solvable. Even incomplete RSC analyses provide value in early stage design problems, as they help structure the design process.

5.2. Profitability in a multi-attribute utility model

Evaluating commercial systems naturally require some attention given to monetary measures of value, beyond the trade-off between utility and cost. The model proposed in this case study incorporates profitability at the era-level, where non-dominated solutions are explored for a given contract with a fixed day rate. This enables identification of solutions that reduce costs for a given revenue, hence implicitly maximizing profitability. Two of the criteria of multi-attribute utility theory are violated when attempting to incorporate profitability as an epoch-level value attribute, namely non-redundancy and operationalization (Keeney and Raiffa 1993).

What generates value and what demands resources, or costs, should be kept separate according to the non-redundancy criteria. Since profitability already incorporates the costs, double counting becomes an issue when using profitability as an epoch-level value attribute. In the case of epochs with fixed revenue, attempting to use revenue alone as an epoch-level value attribute will not add differentiation among designs. However, use of an alternative well-structured problem representation, as illustrated in Stage 1 in Figure 9, may render revenue a meaningful epoch-level value attribute. Further, it is challenging to operationalize profitability as an epoch-level value attribute. One could argue that the perceived value of some profit depends on the size of the investment, rather than just the amount of money gained. A stakeholder would perhaps perceive the relative return on investment (ROI) as more important than the cash flows. However, issues with double counting again makes this approach troublesome. Additionally, running a loss is not easily modelled in a utility function, where contributions to utility are measured on a positive scale. A loss cannot be understood as adding positively to utility. Hence, a weakness when applying multi-attribute utility theory to commercial engineering systems design is that the profit cannot be rationally modelled within the framework.

In general, the value attributes selected depend on the location of system boundaries and level of abstraction, and not only on the stakeholder preferences. Inclusion of profitability at the era-level is found to be most meaningful for the case presented in this paper. This enables meaningful incorporation of short periods with negative profitability, with the aim of maximizing the overall profitability. Further, use of profitability as an era-level value attribute allows other interesting aspects of profitability to be considered, such as incorporation of constraints on losses and assessment of the effects of different stakeholder risk attitudes for the alternative designs.

6. Conclusion

In this paper, we show the applicability of the Responsive Systems Comparison method for structuring ill-structured design decision problems, making design problems more tangible. The strengths in the method with respect to the more well-structured design problem lie in the reduction of assumptions, supporting the decision-making process by communicating the trade-offs and compromises between multiple aspects of value. By applying the RSC method to a design case of an industrial offshore construction vessel, we show that commercial systems performance models can be integrated within the framework.

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Article 2

Investigating tradeoffs between performance, cost and flexibility of reconfigurable offshore ships

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Investigating tradeoffs between performance, cost and flexibility for reconfigurable offshore ships

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Abstract

This paper investigates tradeoffs between technical performance, cost and flexibility level for reconfigurable offshore ships. An offshore ship can be configured with various types of equipment; thus, its base structure constitutes a platform from which several end ship design configurations can be derived. A ship with equipment retrofit flexibility will typically have excess stability, deadweight and deck area to ensure physical compatibility. However, there are complex system interactions that need consideration, such as the effects of flexibility on cost and technical performance. To tackle this problem, we capture technical performance using a multi-attribute utility function, based on a ship's capability, capacity and operability, and utilize a tradespace representation of the system to quantify flexibility using the filtered outdegree metric. Findings indicate that increased platform flexibility does increase capacity, but comes at a complex compromise with operability as resistance is increased, and roll periods become unfavorable due to high accelerations. Furthermore, the analysis confirms the applicability of multi-attribute utility, tradespace exploration and filtered outdegree for understanding the implications of flexible offshore ships.

Keywords

Ship Design; Platform; Flexibility; Uncertainty; Systems Engineering; Tradespace

1. Introduction

1.1. Motivation

In contrast to traditional deep-sea cargo transportation ships, offshore ships comprise a set of ships that are designed to provide different operational services, such as platform supply, offshore construction and light well intervention. These ships are usually build either for a particular long-term contract, which impose specialization, or on speculation, which impose multi-functionality. At early design stages, the future needs of an offshore ship are typically uncertain, due to volatile and heterogenous market conditions (Erikstad and Rehn, 2015). For this reason, there is a need to understand how offshore ships can embed flexibility to be reconfigured in response to emerging needs, and how flexibility affects technical performance and acquisition costs.

From a design perspective, it may be useful to think of offshore ships as comprised of two main groups of subsystems: ship systems and mission-related systems (Erikstad and Levander, 2012). Ship systems are similar across a wide range of final designs, and may include the main hull, accommodation unit and bridge. Mission-related systems can include cranes, remotely operated vehicle units and light well intervention towers. In this way, we adopt the notion of *platforms*, representing the subsystems that provide a common basis from which a stream of end-design configurations can be derived. An interesting aspect of reconfigurable offshore ships is that compatibility between the platform and the mission-related modules moves beyond the consideration of the platform-module interface alone. By adding mission-related modules to the ship, the behavior and performance of the whole system is changed. Such a reconfiguration may change the hydrodynamic properties of the ship, and impact compliance with stability requirements, rendering some useful reconfigurations infeasible.

1.2. Platforms and flexibility

There exists a wide body of research on platforms in the systems engineering literature. The segment of product family design and platform-based product development has received particular attention (Jiao et al., 2007; Jose and Tollenaere, 2005; Meyer and Lehnerd, 1997; Simpson et al., 2006). Research on product platforms are rooted in the development of product families, representing a set of similar products derived from a common platform, while still having specific functionality to meet different customer requirements. Meyer and Lehnerd (1997) define a product platform as *"a set of subsystems and interfaces developed to form a common structure from which a stream of derivative products can be efficiently developed and produced"*. Product platforms have traditionally been discussed in the context of manufacturing, related to mass customization of product families. This mode of platform thinking is especially useful for ship yards. Erikstad (2009) discusses modularization, product platforming and modular production in shipbuilding. Semini et al. (2014) take the perspective of customer order decoupling points to define customized and standardized designs, and discuss strategies for customized ship design and construction linked to different market characteristics. Early stage ship design research frequently discuss modularization as a way to incorporate all necessary ship subsystems within the hull, examples being the Design Building Blocks (Andrews, 2012), and the Packing Approach (van Oers, 2011). An alternative view of the platform notion is on design of large, complex systems subject to temporal uncertainty of future use and demand, such as offshore ships. This represents the ship owners' point-of-view, as ship owners need to handle uncertainty throughout a vessel's lifecycle. In this paper, we take the latter approach, and use *platform* instead *product platform* notation to be specific. However, in the literature, there seems to be overlapping definitions.

A challenge in platform and product platform design is the tradeoff between the degree of modularity, and the performance of products based on the same platform. A generic platform may work for multiple purposes, but will perhaps not be a successful design in competition with optimized alternatives. D'Souza and Simpson (2003) present a method for balancing these design properties, studying a general aviation aircraft case. Hölltä et al. (2005) use several metrics to quantify the degree of modularity for products that face both technical and business-related constraints, finding that technical constraints limit the degree to which a design should be modularized. In a more thorough study, Hölttä-Otto and de Weck (2007) find that designs driven by technical constraints in fact often exhibit integral architectures, compared to less constrained designs. These results are in partial opposition to the independence axiom of Suh (1990), and the notion that modularization is always a positive.

Several methods for design of product platforms under uncertainty exist. These include the Product Platform Concept Exploration Method (PPCEM) (Simpson et al., 2001), Design for Variety (DFV) (Martin and Ishii, 2002), and a design process for a product line design under uncertainty and competition (Li and Azarm, 2002). Gonzalez-Zugasti et al. (2000) present a method for architecting product platforms, which are evaluated using a real options approach in Gonzalez-Zugasti et al. (2001). Flexible product platform designs are addressed by Suh et al. (2007), coupling real options valuation with a structural model for the platform. A real option is in this context normally defined as the right, but not the obligation, to change system configuration at a future time (De Neufville, 2003). As there are technical limitations to using real options analysis in engineering compared to financial applications, it has been necessary to device new methods for evaluation of options "in" physical engineering systems (Wang and De Neufville, 2005). As opposed to real options "on" projects, real options "in" projects require understanding of underlying technical constraints. Identification of these options becomes equivalent to finding the design elements that should be flexible. Kalligeros et al. (2006) present a method for identifying the system elements that should constitute the platform design.

Beyond options theory, flexibility is discussed from a broad perspective by Saleh et al. (2009), reviewing the literature on flexibility from a multi-disciplinary perspective including management, manufacturing, engineering and design. Flexibility is considered as the ability of a system to be modified to meet new requirements (Chalupnik et al., 2013). Ross et al. (2008) suggest that flexibility require an external change agent to actively intervene, considering it beneath the umbrella term changeability, along with adaptability; the ability of the system to change itself through an internal change agent. Fricke and Schulz (2005) outline design principles for changeability aimed at reducing complexity, and present a framework for identification and implementation of characteristics that enable future system configuration changes. In their paper, they further discuss the difference between changeability and product platforms, and point out that changeability can be incorporated into the platform itself, which is appropriate when there is temporal uncertainty to the demand of the overall product family.

There is an important difference between valuation of changeability and quantification of the level of changeability. In traditional real options literature, focus is usually on the valuation of a given real option. When it comes to systems design, before we can evaluate the flexibility of a design alternative, we need to be able to describe a design's level of flexibility, in addition to understanding the technical implications of different levels of flexibility. In this paper, we focus on flexibility level quantification by use of the graph theoretical filtered outdegree metrics (Ross et al., 2008). We do not focus on monetary valuation of flexibility, but rather address the technical performance of the whole offshore ship, to be able to understand impacts of increased levels of flexibility. The approach applied for assessment of ship performance in this paper is based on multi-criteria decision making methods, in which a set of conflicting objectives are traded (Keeney and Raiffa, 1993). Multi-objective decision making methods have become popular within ship design, investigating multiple technical (Caprace et al., 2010; Klanac et al., 2009; Martins and Burgos, 2009) and commercial compromises (Gaspar et al., 2012; Temple and Collette, 2016). In multi-attribute tradespace exploration, the point is not merely to identify a set of Pareto optimal design, but also to understand how the set of Pareto optimal designs change with changing context and needs (Ross and Rhodes, 2008).

From this discussion, we address an interesting problem from the naval architects' point of view: How to identify good design alternatives that satisfy performance expectations, while still being flexible to change in the future? We will demonstrate a method for quantifying the level of flexibility of an offshore ship using filtered outdegree based on tradespace network system representations, and use this for understanding the technical limitations and tradeoffs in performance and cost that platform flexibility leads to.

2. Multi-attribute decision-making

2.1. Multi-attribute tradespace exploration for evaluating designs

Multi-attribute tradespace exploration is a technique for evaluation of many alternative designs against a set of value attributes reflecting the preferences of the stakeholders (Ross et al. 2004). Founded in multi-attribute utility theory, the utility function is a function of a set of single-attribute utility functions adhering to several requirements. The attribute set should be *complete*, representing all important properties; *operational*, possible to represent in the analysis; *decomposable*, meaning that the utility function can be broken down to parts that can be analyzed more easily; *non-redundant*, suggesting that the aspects of importance should not be double-counted; and *minimal*, meaning that the set of attributes should be kept as small as possible (Keeney and Raiffa, 1993).

The multi-attribute utility function is often represented as a linear weighted sum of all the single-attribute utility functions, as shown in Equation (1). In this function, U_j represents the multi-attribute utility estimate for a design alternative j in the design set J, while the single-attribute utility function u_{ij} scores design alternative j with respect to value attribute i in the set of attributes I. k_i denotes the weight for attribute i.

$$U_j = \sum_{i \in I} k_i u_{ij,} \; \forall \, j \in J \tag{1}$$

In the tradespace, the multi-attribute utility for each design alternative is plotted against a measure of costs. The costs can be readily estimated for each design alternative. In Figure 1, we see an example of a tradespace. The Pareto front of non-dominated designs is highlighted.

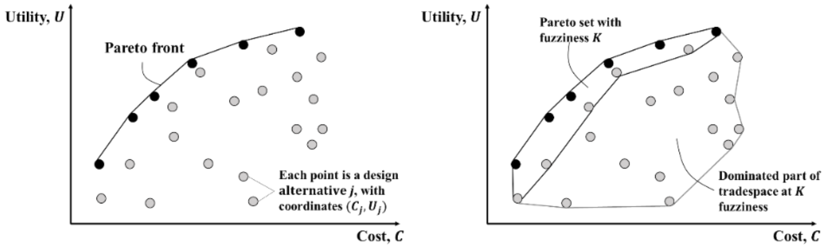

Figure 1: Illustration of a tradespace left (a), with fuzzy Pareto set included right (b).

A significant difference between multi-attribute tradespace exploration and similar forms for multi-criteria decision making methods, is the focus on further concept exploration rather than directly finding an "optimal" solution. There are two primary reasons for this. First, we do not have much knowledge about the design alternatives at this stage beyond the low fidelity analysis done. Therefore, we should seek out more information before reducing the number of system concepts to explore. Second, future uncertainty may manifest itself in changes in the context and stakeholder needs, effectively changing the utility function. Solutions that once looked bad, may now look better. This line of thinking is captured in epoch-era analysis (Ross et al., 2008; Ross and Rhodes, 2008).

2.2. Extending the Pareto set with fuzziness

A compromise between keeping all solutions for exploration of the tradespace, and identifying solutions on the Pareto efficient frontier, is to retain some of the dominated designs for further analysis. Smaling and de Weck (2004) developed a framework for extending the set of Pareto efficient design to a fuzzy Pareto set, by introducing a relaxation factor for dominance. The relaxation factor K is a number between 0 and 1, where 0 will mean that we only consider the set of designs at the Pareto front, and 1 meaning that the whole feasible solution space is kept for consideration. A design alternative falling within the fuzzy Pareto set when $K = 0.1$, can be considered to be within 10% of the range of costs and utility relative the Pareto front (Fitzgerald and Ross, 2012). The fuzzy Pareto number $FPN(j)$ for a design alternative j is defined by Fitzgerald and Ross (2012), as the minimal K for which the design alternative j is still contained within the fuzzy Pareto set P_K, as shown in Equation (2).

$$FPN(j) = \min\{K \mid j \subset P_K\} \tag{2}$$

The concept of fuzzy Pareto sets is illustrated in Figure 1 (b). The tradespace is divided into a region that is within the fuzzy Pareto set, and the solutions that are still considered dominated under the relaxed condition for Pareto optimality. Keeping an extended amount of design alternatives for further investigation reduces the probability that potentially value robust solutions are discarded before a proper evaluation has been done, considering that the performance may change under future operating conditions.

2.3. Tradespace networks for quantification of changeability level

Physical reconfiguration changeability between point designs in the tradespace is considered next, where changeability simply represents an umbrella term from flexibility, as discussed by Ross et al. (2008). If a design from the tradespace has been selected as the preferred concept to build and deploy, the stakeholders could still reconfigure the design at a later stage in the lifetime, by adding or removing features. The addition or removal of a feature will be equivalent to moving from one system state to another. In theory, all designs can change into each other, but not all such changes between two designs are rational, when accounting for the cost and time of implementing the change.

In graph theoretical terms, each design alternative is a node, while a set of arcs represents feasible reconfigurations from the considered start node to nodes representing the new systems after reconfigurations. Multiple paths may exist between two nodes comprising an arc, as different physical ways (mechanisms) of making the state transition exist resulting in the same change effect. Details of this concepts are described in the agent-mechanism-effect framework presented by Ross et al. (2008). Associated with each transition path, there is a cost and time. Ross et al. (2008) introduce filtered outdegree (FOD) a measure quantifying the level of changeability by counting the outgoing paths or arcs from a design, counting either change mechanisms or end-states respectively reachable at a given cost and time. In this paper, we only consider counting the number of end-states for simplicity. Figure 2 illustrates a tradespace network in which a cost and time filter is applied, resulting in a reduced set of feasible arcs. An arc is thus defined to exist if there is a path between the nodes within the acceptable cost and time threshold. The node representing an initially selected design (j) that may have previously been located on the Pareto front is shown in Figure 2 (a). In Figure 2 (b), arcs which symbolize feasible transitions for given cost and time thresholds are illustrated.

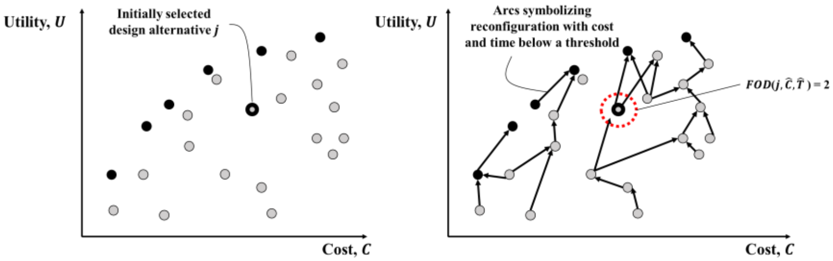

Figure 2: Tradespace network representation left (a), and filtering for cost and time right (b).

Using the graph theoretical constructs outlined above in combination with the notion of a tradespace network, Ross et al. (2008) present a framework for quantification of changeability.

The central metric for changeability in this framework is based on the Outdegree of the system. The Outdegree is the number of outgoing arcs from a node. By applying a threshold cost and time for a state change between two nodes, the Filtered Outdegree (FOD) is defined. The $FOD(j,\hat{C},\hat{T})$ metric quantifies the number of feasible outgoing arcs from node j to all nodes in the set J, under given cost $\hat{C}$ and time $\hat{T}$ thresholds, as given by Equation (3).

$$FOD(j,\hat{C},\hat{T}) = \sum_{d \in J} H(C_{j,d}, T_{j,d}), \ \forall\, C_{j,d} < \hat{C}, \ \forall\, T_{j,d} < \hat{T} \tag{3}$$

$C_{j,d}$ and $T_{j,d}$ are cost and time for transitioning from node j to d, and H is the Heaviside function defined as 1 if there exist a path where both change cost and time for the node transition are below the thresholds, and 0 else. Thus, we only count end-state changeability in this particular case. However, the metric can easily be altered to counting the number of change paths between states, if that is more relevant for the analysis. Counting end-states enables easy analysis of the space of possible reconfigurations, while counting paths is a more complex measure that enables detailed analyses of the state transitions, i.e. analyses of the change mechanisms. Counting paths can be relevant for e.g. equipment slot modularization or steel reinforcement analyses on an offshore ship. This level of fidelity remains outside the scope of this paper, and thus we proceed to count end-states. The filtered outdegree allows an understanding of which real options “in” the design that should be evaluated. The measure can also be adapted by fixing certain design variables that can constitute integral to a platform design.

3. Methodology

To investigate tradeoffs between performance, cost and flexibility of offshore vessels, we follow a stepwise procedure as outlined in Figure 3.

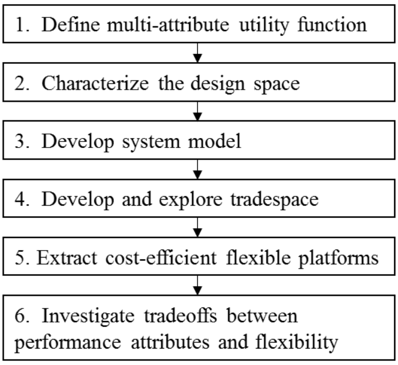

Figure 3: Methodological flowchart.

The first three steps comprise the initial part, where the problem is outlined. This involves defining the multi-attribute utility function, characterizing the design space and developing a model of the system. To be able to evaluate the performance of a design, it is necessary to connect the multi-attribute utility function with the possible design alternatives in a system model. Depending on the chosen approach for design characterization, it is important to screen alternatives to make sure they are physically viable.

The latter three steps comprise the analysis part. First, to get an overall understanding of the model, a tradespace should be developed and explored. For model verification purposes, one can benchmark against ships that are built to see their modelled performance. A separation is made between ships without equipment, i.e. "platforms", and with equipment, as we are interested in analyzing the retrofit flexibility of the platforms. To investigate the impact of cost, we reduce the tradespace and extract cost-efficient solutions by use of a fuzzy Pareto filter on the tradeoff between flexibility and cost. This reduces the set of designs to analyze, simplifying the problem. Last, we investigate the tradeoffs between various performance attributes and flexibility, for these cost-efficient designs.

4. Case study

This case study uses the multi-attribute tradespace network theories to generate insights into the design of reconfigurable offshore ships. The design of offshore construction vessels has been chosen due to the spatial complexity of the design space, the heterogeneity of the markets in which they operate, and the ambiguities in perceived ability to generate value. This case study presented builds on material in Rehn et al. (2016).

4.1. Define multi-attribute utility function

4.1.1. Offshore ship generalized performance attributes

When assessing the performance of an offshore ship, the question *"what is a better ship?"* must be explored (Benford, 1970; Ulstein and Brett, 2015). First, when considering commercial systems, it is reasonable to argue that a good ship is a profitable ship. The ability to generate profits depends on the market situation and is not easy to untangle in terms of describing individual system substructures contributing to profitability.

From a technical point of view, we can still identify a few generalized performance attributes defining valuable systems. For example, in the consumer car industry, disregarding the price, generalized attributes that define a good car include comfort, driving capabilities such as traction and acceleration, transportation capacity in terms of people and luggage, ECO-friendliness, aesthetics and safety. If all these are met, we have a good car. However, as one may find, these attributes eventually meet a physical tradeoff. Either you get a sports car, or you get an SUV. Further, not to mention that increasing attributes together quickly increases the price of the car.

For offshore ships, we can follow the same analogy. A ship designer is interested in developing designs that can be sold to their potential customers; the ship owners. What is desired of an offshore ship is the ability to meet the customer requirements, to drive profitability. We propose three generalized technical performance attributes that are assumed to serve as proxies for profitability, and thus define a better ship, as presented in Table 1.

Table 1: Offshore ship generalized performance attributes.

Attribute	**Description**
Capability	Capability to perform various tasks with equipment: crane, tower, ROV.
Capacity	Transport and storage capacity: deck area, deadweight, tank type/sizes.
Operability	Ability to operate: stability, hydrodynamic behavior, speed.

However, even when disregarding costs, bigger is not always better. For example, issues with external physical constraints may occur, such as maximum lengths at ports and canals. In addition to these three performance attributes several others may be defined, such as safety and reliability (Papanikolaou, 2009). These are more difficult to quantify at the conceptual design level, and were hence not included in this analysis. In general, it is important not to span too many attributes, as short term memory limits the number of attributes to seven, plus minus two (Miller, 1956). Further, the proposed performance characteristics are physical descriptive measures, that are important for most ship concepts. These attributes must not be confused with the "-ilities", such as flexibility and adaptability, which are system characteristics on the lifecycle level. These enter the discussion when we consider the filtered outdegree in later parts of the analysis.

4.1.2. Multi-attribute utility (MAU) function

The multi-attribute utility (MAU) function for offshore construction vessels is decomposed into a set of three single-attribute utility functions, connected to the three aspects of performance: capability, capacity and operability. The structure of the utility function is shown in Figure 4. For simplicity, the utility function is assumed a linear weighted sum as presented in Equation (1), with equal weights. However, other representations of value are possible. The hierarchy in Figure 4 represents a generalized set of performance attributes for offshore construction and well intervention vessels, and does not necessarily represent the multi-attribute utility function of a particular industry actor.

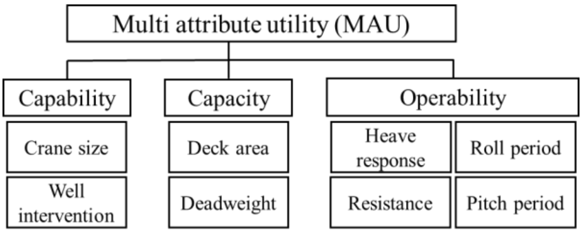

Figure 4: Three performance attributes contributing to the multi-attribute utility function.

The single-attribute utility functions for capability and capacity are easily estimated, as these are decomposable to descriptive elements of the ship topside equipment types and size measures. The single attribute utility for operability is decomposed into further performance attributes based on hydrodynamic characteristics, which map onto ship concepts through the knowledge base of naval architects.

4.2. Characterize the design space

4.2.1. Generating feasible designs

A set of designs is enumerated on basis of design variables that are related both to the main dimensions of the ship, and to the systems installed on board. The six design variables that provide description of the design alternatives, are provided in Table 2.

Table 2: Design variables with ranges describing the set of designs assessed.

Design variable	Description	Unit	Values
L	Length	*m*	70, 80, 90, 100, 110, 120, 130, 140, 150, 160
B	Beam	*m*	15, 18, 21, 24, 27, 30, 33
D	Depth	*m*	7, 9, 11, 13, 15
M	Moonpool	m^2	0, 49
C	Main crane	*Metric ton (MT)*	0, 100, 200, 300, 400, 500
T	LWI tower	*Metric ton (MT)*	0, 250, 500, 750

Only design alternatives that adhere to some basic constraints on physical feasibility in naval architecture are enumerated. Ship concepts need to comply with stability, freeboard and structural integrity criteria. Stability is incorporated based in the requirement of that initial metacentric height (GM) must exceed a minimum required $GM_{MIN} = 0.15\ m$. The freeboard (F) must exceed a minimum required $\mathrm{F}_{MIN} = \ 1.5\ m$. A model that ensures structural integrity in the hull is included to prevent unreasonably slender ships. A simplified structural model is assumed, and the maximal material stress allowed is $\sigma_{MAX} = 220\ MPa$ for an assumed maximum bending moment condition, including a safety factor. In addition, we require that if well intervention tower is installed, a moonpool is required. Initial design space enumerates to 16800 designs, which reduces to 5803 after the physical compatibility screening.

4.2.2. Parametric assessment for ship properties

The analysis relies on various physical parameters, which are given in Table 3. Assumed parameters for the properties of the equipment that can be installed on the vessel are given in Table 4. The ship platform represents the ship without equipment.

Table 3: Physical parameters for the analysis.

Parameter	Description	Unit	Value
k_{LS}	Lightweight per LBD	[kg/m^3]	0.23*
k_{cost}	Cost per lightweight platform	[k$/MT]	8
k_{DA}	Deck area per LB	[m^2/m^2]	0.55*
C_B	Block coefficient	[-]	0.65*
T_P	Wave peak period	[s]	10
H_S	Significant wave height	[m]	4

** Obtained from comparison with real offshore vessels. MT= Metric tons.*

Table 4: Assumed weight, center of gravity (CoG), deck area and cost of equipment.

Equipment	Weight [MT/MT]	CoG [m]	Deck area	Costs [m$/MT]
Crane	2.5*	10	$capacity_{crane}^{0.45}$ [m^2]	0.022
Well int.	4	30	0.45 [m^2/MT]	0.13

**Including heave compensation equipment. MT= Metric tons.*

The acquisition cost C_{SHIP} for the ship is calculated using Equation (5) by adding two cost elements: the cost of the ship without equipment, and the cost of the equipment. The scaling constant k_{cost} represents the cost per metric tonnes of the ship without equipment, and is given in Table 3. C_{equip}^{e} is the cost of including equipment e in the set E of possible equipment types that can be installed on the ship.

$$C_{SHIP} = k_{cost}\, W_{LS} + \sum_{e \in E} C_{equip}^{e} \tag{5}$$

The lightweight of the platform ship, W_{LS}, is given in Equation (6). k_{LS} is a scaling constant given in Table 3.

$$W_{LS} = k_{LS}\, LBD \tag{6}$$

4.3. Develop system model

Performance attributes representing the single attribute utility functions are defined on a 0 to 1 scale, where 1 is the best, and 0 is the worst. For every performance attribute, the individual subcomponents are included using a linear weighted sum, as shown in Equation (1). The defined ranges for the individual performance subcomponents are given in Table 5.

Table 5: Single attributes utility ranges.

Performance attributes		Unit	Utility = 0%	Utility = 100%
Capability	Crane size	MT	0	500
	Well intervention size	MT	0	750
Capacity	Deck area	m^2	500	2 500
	Deadweight	MT	1 000	15 000
Operability	Heave response variance	m^2	0.5	0
	Roll period	s	10	20
	Pitch period	s	4	10
	Resistance	kN	500	0

4.3.1. Capability

Capability is based on the equipment installed on the vessel, and is for simplicity assumed a linear combination of crane lifting capacity and well intervention tower lifting capacity. No additional calculations are needed, since the capability can be estimated directly from the design description, and connects to the utility function as shown in Table 5.

4.3.2. Capacity

The deck area, A_{DECK}, for a design is estimated by Equation (7). The scaling constant k_{DA} is given in Table 3. A^e_{equip} is the area that equipment e, in the set E of possible equipment types, takes up on deck. In other words, we care about the free deck area. In accordance with Table 5, the deck area should be maximized.

$$A_{DECK} = k_{DA}\, LB - \sum_{e \in E} A^e_{equip} \tag{7}$$

The deadweight, dwt, of a design is estimated by Equation (8). Δ_{max} is the maximum weight displacement of the ship, defined by the main dimensions, maximum freeboard, block coefficient and water density. W^e_{equip} is the weight of equipment e on deck, in the set E, given in Table 4, and W_{LS} is the lightweight of the platform ship given by Equation (6).

$$dwt = \Delta_{max} - \sum_{e \in E} W^e_{equip} - W_{LS} \tag{8}$$

4.3.3. Operability

Offshore ships should be operable in rough seas. Hence, the hydrodynamic ship response in waves is simplified and estimated. The heave response is determined from the main ship characteristics, in sea states described by a Bretschneider wave spectrum. To simplify, only the translational vertical response is considered. The ship is modelled as a damped mass-spring system including added mass from water (Faltinsen, 1990). The excitation force in the vertical direction is the sum of the Froude-Krylov force, and the diffraction forces. Added mass is represented by 2D strip theory. Assuming the ship as a simplified box shape, we obtain Equation (9) describing the transfer function for heave response $H_3(\omega)$.

$$|H_3(\omega)| = \left|\frac{x}{\zeta_a}\right| = \frac{\frac{2}{k}\sin\left(\frac{kL}{2}\right)[\rho B g e^{kz_{bottom}} - \omega^2 A_{33}^{2D} e^{kz_{middle}}]}{\sqrt{(C_{33} - (M + A_{33})\omega^2)^2 + (B_{33}\omega)^2}} \tag{9}$$

Here, M is the ship mass, A_{33} is the added mass, B_{33} is the damping coefficient, and C_{33} is the spring constant. ρ is the sea water density and g is the gravitational acceleration. ζ_a is the wave amplitude, ω is the wave frequency, and k is the wave number. L and B refer to the length and beam of the ship. $S(\omega)$ is the Bretschneider wave spectrum. Maximization of operability implies minimization of the heave variance (σ^2), obtained by integrating the heave response spectrum, as shown in Equation (10).

$$\sigma^2 = \int_0^\infty |H_3(\omega)|^2 S(\omega) d\omega \tag{10}$$

When it comes to roll and pitch movement, it is reasonable to desire a high period, as slow vessel accelerations are assumed beneficial for operations. The estimates for the pitch and roll period are given in Equation (11).

$$T_i = \frac{2\pi k_g^i}{\sqrt{g \cdot GM_i}} \tag{11}$$

Here, i represents the degree of freedom, either 4 for roll or 5 for pitch. k_g^i is the radius of gyration, and GM_i is the initial metacentric height. Under the objective of maximizing operability, we further seek to minimize the total ship resistance shown in Equation (12).

$$R_{tot} = \frac{1}{2}\,\rho\, V^2 A\, C_{tot} \tag{12}$$

Where, V is the speed of the ship and C_{tot} is the total resistance number. The wet surface area A is estimated using Equation (13).

$$A = a\sqrt{\nabla\, L} \tag{13}$$

Where, a is a constant assumed to be 2.6. ∇ is the volume displacement of the vessel, estimated as $\nabla = C_B \cdot LBT$, where C_B is the block coefficient, and L, B and T refer to the length, beam and draft of the ship. The non-dimensional total resistance number is assumed to follow the relation in Equation (14), in which F_N is the Froude number, given by $F_N = V/\sqrt{g \cdot L}$, assuming a constant design speed of 15 knots.

$$C_{tot} = \ 3.99\, {F_N}^{5.59} + \ 0.00206 \tag{14}$$

To account for the vessel being equipped with a moonpool, the resistance is assumed to increase by 10%. Keep in mind, the potential inaccuracy of the above-mentioned estimations may not be that of an issue, as they are included for enabling comparisons between the alternative vessel concepts, and not for absolute estimations.

4.4. Develop and explore tradespace

A design space of 5803 alternative designs is generated and analyzed. These designs include ship platforms both with and without equipment installed. The corresponding tradespace is shown in Figure 5, where each point represents a design alternative. The designs that are on the Pareto frontier are highlighted, as are the designs that are within the 3% fuzziness Pareto set.

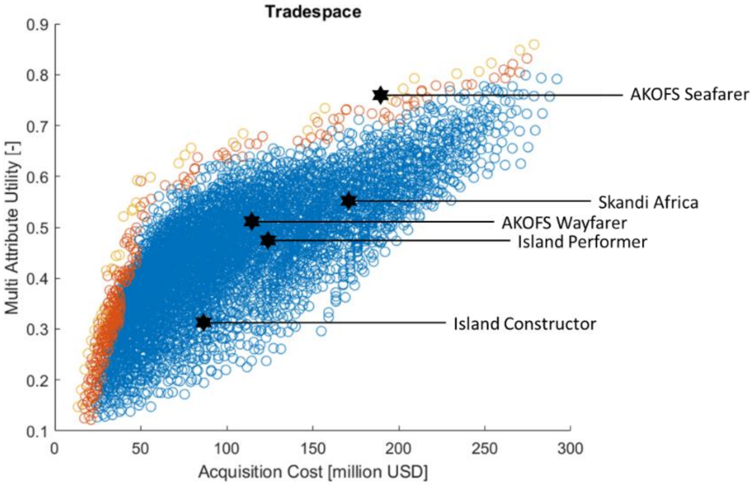

Figure 5: Tradespace of offshore ship designs alternatives.

Five existing offshore construction vessels in the industry are included in Figure 5 to benchmark and validate the model. Detailed information about these vessels is given in Table 6, where cost, MAU and performance attributes are estimated by the model. Two of these vessels are previous winners of the award for the Norwegian Ship of the Year. Note that the results for these five vessels only reflect their value to the hypothetical ship owner in the case, and are not indicative of their value to their actual owners in terms of profitability.

Table 6: Evaluating recent offshore construction and light well intervention vessels in the tradespace model.

			Performance Attributes			Design variables					
Name	Cost [m$]	MAU [-]	Capability	Capacity	Operability	L	B	D	M	C	T
Skandi Africa	165	0.53	0.50	1.00	0.41	161	32	13	1	900	0
AKOFS Seafarer	187	0.73	0.86	0.76	0.72	157	27	12	1	400	450
Island Performer	123	0.47	0.49	0.48	0.43	130	25	10	1	250	300
Island Constructor	81	0.31	0.11	0.48	0.25	120	25	10	1	140	100
AKOFS Wayfarer	114	0.50	0.36	0.85	0.39	157	27	12	1	400	0

In Table 7, the details of four Pareto efficient (0% fuzziness) designs identified from Figure 5 are shown, including the design variables, performance attributes, MAU and acquisition cost. These designs are selected based on their spread along the Pareto front, as can be seen on the increasing cost and MAU values. We look at these designs to better understand our model and the tradespace. Findings are discussed in Chapter 5.

Table 7: Four Pareto optimal ship designs, from least to most expensive.

			Performance Attributes			Design variables					
Design ID	Cost [m$]	MAU [-]	Capability	Capacity	Operability	L	B	D	M	C	T
4118	17	0.22	0.00	0.12	0.33	90	15	7	0	0	0
2636	48	0.59	0.50	0.23	0.72	140	15	7	0	500	0
1322	151	0.72	0.67	0.68	0.72	150	24	13	1	500	250
7	279	0.86	1.00	0.93	0.71	160	30	15	1	500	750

4.5. Extract cost-efficient flexible platforms

The most significant retrofit cost drivers are changes in the main dimensions of the ship, that is, changing the size of the ship platform. We therefore fix platform parameters (length, beam, depth and moonpool) and only investigate change of equipment on deck (crane and tower). This enables a more meaningful comparison between platforms, since they are similar in the functional space. This reduces the platform design space to 640 alternatives.

The 5% fuzzy Pareto optimal designs in the tradeoff between filtered outdegree and acquisition cost reduces the size of the set of platform designs from 640 to 158. These are the most cost effective flexible platforms available at a given cost. These 158 platform designs are plotted in a tradespace in Figure 6, where we can see the tradeoffs between platform flexibility as measured by filtered outdegree (FOD), acquisition cost and multi-attribute utility. The threshold cost and time for the calculation of FOD are in this case manipulated so that it only enables retrofit of equipment and not of the platform, which enables us to analyze physical aspects of retrofit feasibility.

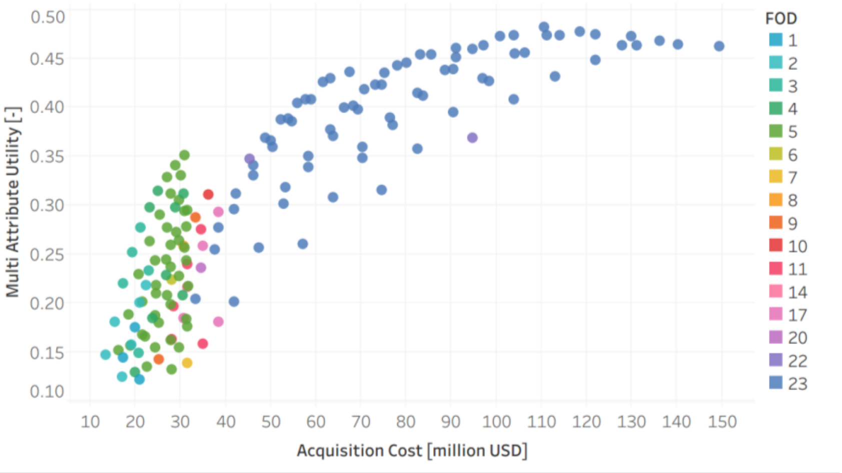

Figure 6: MAU, cost and FOD for cost-effective flexible maritime platforms.

Table 8 presents more detailed information of interesting Pareto optimal platforms in Figure 6. The platforms analyzed do not have any equipment, hence their capability levels are zero, indicated with a "-". These can obviously be changed in the events of adding equipment, which is what we analyze here. The maximum filtered outdegree for a platform in this analysis is 23, which represents being able to take all potential equipment configuration states, as predefined in the tradespace network model.

Table 8: Cost effective ship platforms.

				Performance Attributes			Design variables					
Design ID	Cost [m$]	FOD	MAU [-]	Capability	Capacity	Operability	L	B	D	M	C	T
4120	14	2	0.15	0	0.06	0.23	70	15	7	0	-	-
4111	31	5	0.35	0	0.32	0.45	160	15	7	0	-	-
5747	33	23	0.20	0	0.28	0.23	70	33	7	1	-	-
5739	67	23	0.44	0	0.74	0.40	150	33	7	1	-	-

4.6. Investigating tradeoffs between performance attributes and flexibility

Being on the fuzzy Pareto front in the tradeoff between filtered outdegree and acquisition cost is preferable, to enable maximum potential retrofit upside at the minimal initial cost. Figure 7 untangles the multi-attribute utility measure of the designs plotted in Figure 6, to enable further investigation of the implications of platform flexibility on capacity and operability.

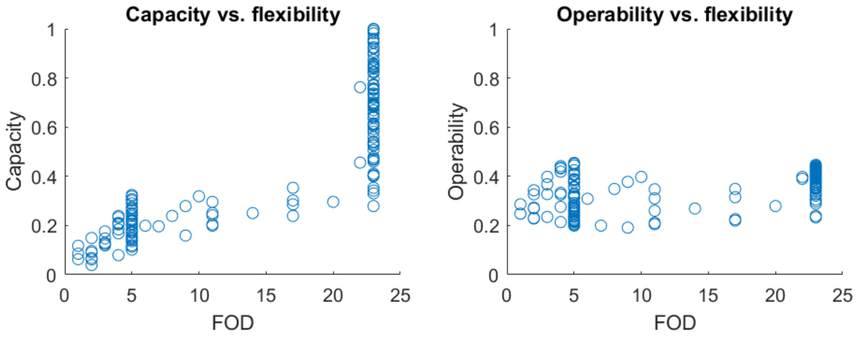

Figure 7: Capacity and operability utilities plotted against flexibility measured in filtered outdegree (FOD).

Figure 7 illustrates single utility attribute values for the platforms as a function of the level of flexibility quantified by the FOD metric. There is a relatively clear correlation between capacity and flexibility, however, operability seems to have a more complex relationship with flexibility, and hence it is of interest to investigate operability vs. flexibility further to its individual sub-attributes. Figure 8 plots FOD against roll, heave response, resistance, and pitch.

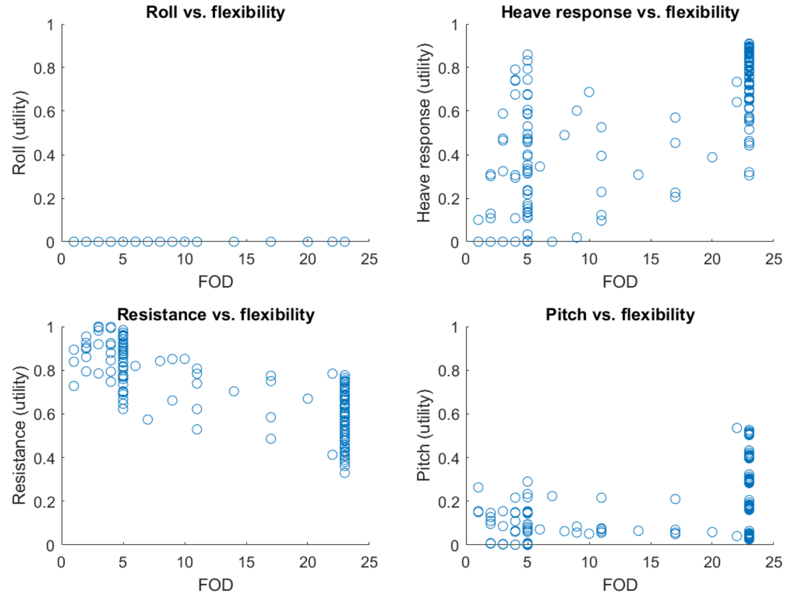

Figure 8: Subcomponent utilities of operability plotted against flexibility measured in filtered outdegree (FOD).

Flexible platforms with high operational performance at low cost are of interest to identify and understand. Three selected platforms at this complex Pareto front are given in Table 9, with best individual single subcomponent operability levels. We can see that these designs are significantly different, supporting the hypothesis of that conflicting objectives must be traded off against each other, i.e. no solution is best at all performance metrics at the same time.

Table 9: Flexible maritime platforms at low cost with high operational performance.

					Performance Attributes			Design variables					
Best attr.	Design ID	Cost [m$]	FOD	MAU [-]	Capability	Capacity	Operability	L	B	D	M	C	T
Res	5759	49	23	0.37	0	0.51	0.40	130	27	7	1	0	0
Heave	5669	91	23	0.46	0	0.87	0.41	160	33	9	1	0	0
Pitch	5494	104	23	0.41	0	0.85	0.42	110	33	15	1	0	0

5. Discussion

Pareto optimal results in Table 7 represent the offshore ships that give the highest performance for the lowest cost in the tradespace plotted in Figure 5. Design 2636 in Table 4 is closest to utopia. This design is long and slender, has a large crane installed and a low acquisition cost. Compared to ships in the industry today, this ship has a high length-to-beam ration, of 9.3. It could be interesting to investigate further why this is not found in the market today. It is just a modelling oversimplification, or a so far unexplored opportunity? This points to the need for an iterative analysis process, where we for example can revisit the assumption of equal single-attribute weights. Further, the physical compatibility models in this analysis for structural integrity and stability are very simple, and high fidelity analyses should be used to further investigate the potential use for such a design.

For deeper insights in the model and results, Figure 5 also includes five real offshore ships, of which two are previous winners of the award for Norwegian Ship of the Year. These ships are mainly included for model validation purposes, but it also allows us to investigate differences between them. Information about cost, technical performance and design variables for these are estimated by the model and given in Table 6. AKOFS Seafarer is the only of the four designs that is Pareto optimal based on our model. Island Constructor represent a first generation LWI vessel, and has substantially lower technical performance compared to the other ships in Table 6. We do not aim to criticize any of the designs, and recognize that our model may be flawed to give wrong estimates. Our estimation approach is though transparent, as presented in the paper, and the results follow directly from this. Our goal with the comparisons is to provide insight to improve decision making in offshore ship design.

In Figure 6, we can see the tradeoff between platform flexibility, measured in filtered outdegree, and platform multi-attribute utility and acquisition cost. If a platform is supposed to handle crane and tower retrofits, extra stability and deck area is needed, which comes at a cost. We are therefore interested in identifying the most flexible designs at the lowest cost. A key characteristic of the most cost-effective flexible maritime platforms presented in Table 8, is the non-slenderness of these designs. They are wide and short, indicating that cheap flexibility compromises operability.

Figure 7 illustrates the relationships between the individual performance attributes and flexibility. We can see that in terms of capacity, we have a positive correlation with flexibility.

This is intuitive, as a larger platform can take on more equipment retrofits, and has a larger deck area and deadweight which increases the capacity. However, the relationship between operability and flexibility is more ambiguous, as shown in Figure 8. We observe that all 158 prescreened cost effective flexible platform designs perform poor in terms of rolling. These designs have low roll periods (<10s), contributing to unfavorably high accelerations. Further, Figure 8 shows that a compromise must be made between resistance and flexibility, as excess stability, deadweight and deck area are needed for a high FOD. The heave response and pitch still have an ambiguous relationship with flexibility, as they seem relatively independent from FOD. For the 158 prescreened cost-effective flexible designs, however, all have relatively undesirable roll periods. For heave motion, however, good dynamic behavior should be able to be achieved independently of the degree of flexibility. Table 9 presents three interesting platform designs at low cost which have one highest individual subcomponent operability attribute, while still being able to take on all possible types of equipment (FOD = 23). The fact that these three designs are significantly different supports our conclusion that operability is a complex performance attribute with conflicting sub-attributes. To decide which platform design that is better, one needs to determine what is more important to be able to find a compromised "optimal" solution. This ties back to our comment in the introduction about the difference between valuation of changeability, and quantification of changeability level. The former will aid in determining what to do, while we focus on the latter in this paper. Thus, attempts at deciding the best tradeoff between the conflicting objectives remains outside the objectives of this paper. These results leave us with some insight about the properties of flexible offshore ship platforms. Multiple compromises must be made in the design, between enabling reconfigurations through excessive platform size and stability, roll period, and resistance. Ship slenderness is a critical factor that must be traded against flexibility when designing offshore ship platforms with reconfigurable topsides.

We have shown how tradespace exploration lets us study the trade-offs between utility and costs. However, the single attribute utility weights in the model are assumed constant. By considering explicitly what happens when the system context or stakeholder needs change in an epoch-era analysis (Ross and Rhodes, 2008), strategies could be elaborated for exercising specific reconfiguration opportunities. The tradespace network using filtered outdegree to quantify the level of flexibility can thus lead us to designs providing promising redesign alternatives in the dynamic setting. However, outdegree is only one measure of centrality in network theory. Further insight can be obtained by exploring other measures of centrality, such as betweenness and closeness. Curry et al. (2017) briefly include some other metrics of centrality in their tradespace analysis. Nevertheless, we demonstrate that filtered outdegree represents a good measure for quantifying the level of flexibility for offshore ship platforms.

In terms of flexible platform analysis, it could be interesting to further investigate sensitivities in terms of the design variables of the platform. For the ships in this analysis, this involves the length, beam, depth and moonpool. However, it is important to realize that it is also possible to change the platform, with for example elongation (Knight et al., 2015) and moonpool readiness. While the design study presented in this paper has taken a parametric approach, other methods researched in the maritime literature could provide valuable for flexibility analyses. These include using Design Building Blocks (Andrews, 2012), Packing Approach (van Oers, 2011) or optimization of modular adaptable designs (Choi and Erikstad, 2017). With such higher fidelity design methods involving the internals of the ship, one can potentially approach the operability concerns from for the flexible ships from new angles, which can offset the unfavorable aspects identified from the simple approach presented in this paper.

6. Conclusion

This paper investigates tradeoffs between performance, cost and flexibility of offshore ship platforms. For measuring technical performance, a generalized maritime model is defined based on capability, capacity and operability. A tradespace representation is used to explore the design space, and to define the tradespace network that enables the quantification of flexibility level by use of filtered outdegree. Two main conclusions can be drawn from this work. First, we conclude that tradespace exploration methods and filtered outdegree are good methods to understand the design space and investigate tradeoffs between performance, cost and flexibility. It is particularly helpful to see which aspects of technical performance are affected by increasing the level of flexibility. The second conclusion is regarding the insights gained from analyzing the flexible ship platforms with these methods. Flexible platforms are characterized by having excess stability, deadweight and deck area to take on equipment retrofits. Increased platform flexibility does increase capacity, but comes at a complex compromise with operability as resistance is increased, and roll periods become unfavorable due to high accelerations. Although this latter conclusion may seem obvious from an experienced naval architect's point of view, it is still beneficial to systematically quantify these tradeoffs with the aim of designing better ships under uncertainty.

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Article 3

Quantification of Changeability Level for Engineering Systems

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Quantification of Changeability Level for Engineering Systems

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Abstract

This paper outlines a generic method for quantifying changeability level, to support better decision making in the early stages of design of engineering systems. Changeability represents the ability of a system to change form, function, or operation, and is a collective term for characteristics such as flexibility, adaptability, and agility. Quantification of changeability level must not be confused with valuation of changeability. The level of changeability in a design is essentially under the control of the designer. Two aspects of changeability are discussed, the first being how to structure changeable design alternatives using the Design for Changeability (DFC) variable. The DFC variable represents combinations of path enablers built into a design. Path enablers are characteristics of systems enabling them to change more easily. The second aspect is to quantify the level of changeability for a given design alternative, based on change cost and time. For the latter, we propose two measures for quantification: 1) bottom-up, measuring the reduction of cost and time enabled for each relevant change, and 2) top-down, measuring the span of change opportunities at given cost and time thresholds. A case study of a ship is presented to demonstrate the proposed generic method.

Key words: changeability, flexibility, systems design, uncertainty

1. Introduction

1.1. Introduction

Engineering systems operate under contextual uncertainties from economic, physical, technical, and regulatory domains. Life-cycle properties, such as flexibility, agility, and robustness, often termed the “ilities”, are increasingly popular in the literature [de Weck et al., 2011], and are essential for handling uncertainty. Many of these system properties involve change of some sort, which can be generalized to the term changeability. When it comes to designing for changeability, there is an important differentiation between quantification of the level of changeability, and valuation of a given level of changeability. One can say that a design alternative is flexible, without saying anything about the value of this flexibility. For example, when designing a new airport, one of the most important early stage decisions is to determine the capacity. If future demand for capacity is uncertain, two alternatives are to build excess capacity into the system, or to build the system smaller but flexible to be able to expand easily. This example illustrates the importance of considering changeability already at the early design stages, as it will significantly influence the choice of design concept. The example motivates the following research question: How can we measure the degree to which one design alternative is changeable, compared to another? The focus of this paper is to address means of quantifying changeability level on a general basis for engineering systems. We argue that this is important for two main reasons: (1) to be able to structure design alternatives with different levels of changeability, on which evaluation can be subsequently performed, in order to decide *how much changeability* we should design into a system, and (2) for providing means for communicating system changeability between decision makers.

This paper presupposes that there is a lack of clarity of the fundamentals of changeability level quantification in the literature. The contribution of this paper is to present a generalized method for quantifying changeability level for engineering systems. We take the initial perspective that all systems inherently are changeable, it is just a matter of how much effort it will take to change; thus, the level of changeability should be measured based on how it reduces the change effort [Ross, Rhodes, and Hastings, 2008, Fricke and Schulz, 2005]. We argue that change effort can be meaningfully operationalized through two main dimensions for engineering systems: Cost and time, i.e. increased system changeability enables a design alternative to change more quickly and at lower cost. However, increased changeability level usually comes at an extra investment cost. What is central to understand is that changeability essentially is within the control of the designer, as he or she can specify an explicit changeability level for an engineering system at the conceptual design stage.

1.2. Literature review

There exist a wide body of literature defining “ilities”, recent references include Beesemyer [2012]; Chalupnik, Wynn, and Clarkson [2013]; de Weck, Ross, and Rhodes [2012]; Ross and Rhodes [2008]; Ross et al. [2008]; Ryan, Jacques, and Colombi [2013]; Saleh, Mark, and Jordan [2009]. Various definitions of the different “ilities” exist, and this paper does not aim to provide additional definitions to this topic. Rather, the focus is on exploring the fundamentals of changeability, where central contributions include Fricke and Schulz [2005] and Ross et al. [2008]. Fricke and Schulz [2005] define changeability and discuss principles indicating which features systems should incorporate to be changeable, such as modularity and scalability. Ross et al. [2008] propose that change can be described by an alteration between two system states, and present a design-neutral framework to define changeability through three aspects: change agents, change mechanisms and change effects.

Alternatively to the collective term changeability, one can identify individual research tracks in the literature focusing on specific “ilities”, such as adaptability [Gu et al., 2004; Engel, and Browning, 2008; Fletcher et al., 2009], flexibility [Nilchiani et al., 2005; Chang, 2007; Giachetti et al., 2003; Baykasoğlu, 2009; Swaney, and Grossmann, 1985; Broniatowski, and Moses, 2016], upgradeability [Buxton, and Stephenson, 2001], evolvability [Tackett et al., 2014], and agility [Giachetti et al., 2003]. An extensive contribution on flexibility in engineering design is given by de Neufville, and Scholtes [2011]. The use of specific ilities has also become integrated with different focus areas, for example: manufacturing flexibility [Slack, 1983; Gerwin, 1993; Browne et al., 1984; Chang, 2007], machinery flexibility [Chang et al., 2001; Baykasoğlu, 2009] and product flexibility [Rajan et al., 2005]. Other applications of changeability in the literature include oil and gas systems [Lin et al., 2013; Cardin et al., 2015], ships [Niese, and Singer, 2014], power systems [Lund et al., 2015], and spacecrafts [Silver, and de Weck, 2007], to mention a few. This illustrates the wide application area of changeability. However, the definitions of the various “ilities” are often overlapping and ambiguous, which may hinder researchers in reaching meaningful consensus on this subject. The aim of using the collective term changeability instead, is to avoid this problem of ambiguity.

When it comes to literature on changeability, and its derivative “ilities”, few contributions clearly differentiate between quantification of the level of changeability and the separate topic of changeability valuation. Perhaps the most significant contribution in the systems engineering literature towards quantifying the level of changeability in a design is by Ross [2006] and Ross et al. [2008], who introduced the filtered outdegree (FOD) metric. FOD quantifies changeability level within a networked tradespace, which for example is used further in research by Fitzgerald, Ross, and Rhodes [2012]; Shah, Wilds, Viscito, Ross, and Hastings [2008]. Further insights on changeability level quantification in the literature can be gained from investigating the direct effects of incorporation of changeability in design. Changeability enables systems to change more easily. This is elaborated on for example in the manufacturing literature, where range, time and cost are identified as three important dimensions of flexibility [Chang, 2007]. The effect on change costs has received much focus, for example through work by Fletcher et al. [2009], Gu et al. [2004], Ross [2006] and Spackova et al. [2015]. Some authors measure changeability level based on the expected reduction of change cost. Gu et al. [2004] and Spackova et al. [2015] measure adaptability level by normalized cost savings of performing a change. Change time and range have received less attention in the literature on changeability level quantification. Range is to some degree measured through FOD – as it counts space of change opportunities. Olewnik, and Lewis [2006] propose a measure of flexibility based on the possible change range in the performance of the system.

It can be difficult to estimate the consequences of making physical changes to systems, as change may propagate and have unforeseen effects. Thus, changeability is closely related to change propagation and prediction, for which an extensive literature review is found in Jarratt et al. [2011]. A notable contribution is by Clarkson, Simons, and Eckert [2004], who present the Change Prediction Method to predict the risk of change propagation in terms of both change likelihood, and impact. This model builds on the Design Structure Matrix (DSM) system representation to model component interdependencies. For a review of DSM see Eppinger and Browning [2012]. Eckert, Clarkson, and Zanker [2004] describe and analyze how change is handled. They discuss strategies for coping with change, including adding adequate margins in a design which can absorb changes. For example, an engine might be powerful enough to support a certain increase in weight of an aircraft, but if the weight increase is too large, the engine must be modified. Suh et al. [2007] use a Change Propagation Index (CPI) to measure the degree to which a system component amplifies or reduces the change propagation. Hence, one can identify suitable components that can be made changeable. The authors use CPI for flexible product platform design. An alternative approach to develop more changeable systems is presented by Kalligeros, de Weck, and de Neufville [2006]. They identify platform components based on their sensitivity to exogenous changes using the Sensitivity Design Structure Matrix (SDSM), which was introduced by Yassine and Falkenburg [1999]. The differentiation between change propagation, and assessment of system changeability is also pointed out by Koh, Caldwell, and Clarkson [2013]. Building on Clarkson, Simons, and Eckert [2004], they present a method to assess the changeability of a system based on change likelihood and impact. Two aspects of making components more changeable are discussed, whether it should be made less likely to change, or easier to change. This work is extended by Koh et al. [2015] in terms of using change forecast to identify and prioritize product components for modularization. An important aspect of changeability level quantification is the level of granularity chosen by the analyst, which is discussed by Chiriac et al. [2011]. They conclude that the level of system granularity can have a significant impact on the degree of modularity, measured for the same system.

The work presented in this paper is positioned at the early stage of the design process. Thus, this research differentiates itself from the research focusing on change propagation of existing systems. In addition, building on Mekdeci, Ross, Rhodes, and Hastings [2011], we expand the system boundaries beyond only considering change of physical design variables, to also include changes in the operational space. Research on operational changeability is often connected with real options (RO) (see Trigeorgis [1996] for an overview of RO). Real options literature involves assessment of pure operational options, such as layup and reactivation of an asset, in addition to options more connected to the technical characteristics of an asset, such as market switch and capacity expansion. The former options involve no change of physical design variables, while the latter options may do. For example, does the asset have the required multi-functionality to switch markets? Or can the asset be expanded easily? These strategic questions should be addressed at the early design stages, and are specifically characterized by the level of changeability of the asset. To address this issue, Wang and de Neufville [2005b] introduce the terms real options "on" and "in" systems, where in contrast to "on" options, "in" options do not treat technology as a black box. "In" options are not necessarily predefined, which leads to the field of real options identification [de Neufville et al., 2008; Wang, and de Neufville, 2005b].

As we can see through the review of recent literature, a spectrum of methods and measures exists for quantifying the level of changeability for a design. Unfortunately, there seems to be no consensus reached. Thus, we address the need for the development of a generalized approach for quantification of changeability level for conceptual system design.

2. What is changeability?

2.1. Concepts and definitions of changeability

Changeability represents the ability of a system to change form, function, or operation [de Weck et al., 2012], and represents a collective term for system characteristics including, but not necessarily limited to, flexibility, adaptability, evolvability, scalability, upgradeability, versatility, and agility. In this paper, we adopt the changeability terminology presented by Ross et al. [2008]. They propose three aspects to describe changeability: change agents, change mechanisms, and change effects. The change agent instigates a change, and can be represented by human or nature. Change mechanisms describe the means by which the system is able to change, i.e. the path taken by the system in a change event. The mechanisms changing the system can be operational changes, replacement of a deteriorated system component, or a redesign of the system. The change effect quantifies the difference in state before and after the change. Further, a path enabler is a system characteristic that gives the opportunity to execute some change more easily. One or more path enablers may make possible a change mechanism at a reduced effort, and consequently, each path-enabling variable may allow the creation of one or more change mechanisms and end states at reduced effort [Beesemyer et al., 2012; Ross et al., 2009]. Path enablers correspond with what Fricke and Schulz [2005] generally call "principles" characterizing changeability. Path enabling variables differ from design variables in their purpose; while design variables directly drive value generation, path enablers are defined to enhance changeability and can be considered as dynamic change opportunities. State change, change effects and change mechanisms are illustrated in Figure 1, with an illustrative example from a ship expansion case. In Figure 1, only three out of several change mechanisms are considered. In theory, there are potentially infinitely many change paths, as there are also potentially infinitely design alternatives that can satisfy functional requirements. However, for all practical considerations, one must construct a feasible set of change paths to make analyses viable. Path enablers, such as a reinforced hull, can be directly connected to using margins as a strategy for handling changes [Eckert et al., 2004], hence reducing the potential for change propagation.

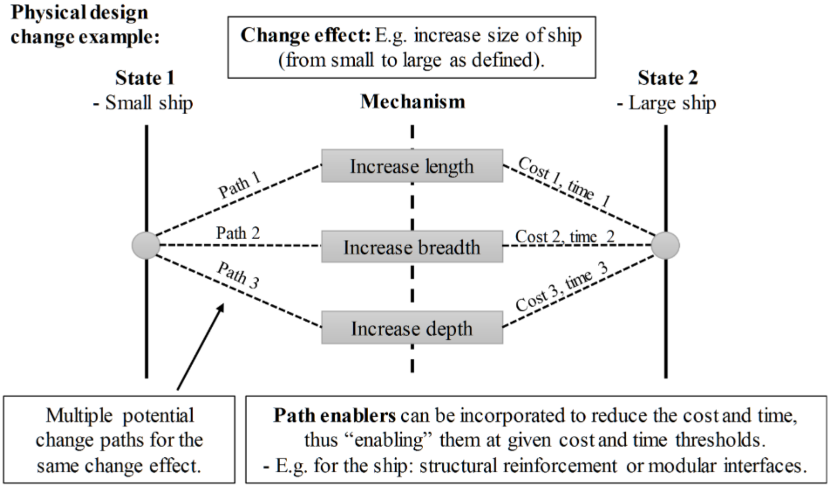


Figure 1: Changeability concepts and definitions, simple illustration of a physical design change from a small to a large ship by three potential change mechanisms (adapted from Ross et al. [2008]). This representation can alternatively be used for change between modes of operation.

The state change in Figure 1 is exemplified by change of physical design variables, but changes can also be determined by of the mode of operation. An operational state-change for a ship can be to move an offshore ship between two operational areas, e.g. from the North Sea to the East China Sea. This state change is without making any changes to the physical design itself. There are different routes one can take, such as through the Panama Canal, Suez Canal or through the Northeast Passage, each with an associated cost and time. An operational path enabler in this case may be to have ice reinforced hull to be able to sail in Northwest passage without help from other icebreaking assisting ships.

Operational changes are enabled by the design variables to some degree, i.e. what a design can do is a function of the design variables. In general, though, the space of possible operational modes is not limited by the specific physical design variables. Thus, there are two types of path enablers, even though one can argue that all are intended for the system to change operational mode as an overall objective. The difference is that some enable easier change of physical design variables (in order to change operation), while others enable easier operational change without considering change of physical design variables. An example of the former can be a modular interface to easily reconfigure the equipment on a ship. An example of the latter can be to have a multi-functional ship, which can take on a large set of different missions, without change of physical design. In the literature, this multi-functional property of systems is characterized as versatility [Chalupnik et al. 2013].

2.2. Two reference domains: Physical design and mode of operation

To describe the level of changeability of a system, we first need to address how to characterize a system. In general, system design can be described as a mapping from function to form [Coyne et al. 1990]. Consequently, one can represent a system either based on the physical form directly, or based on what it can do, i.e. which operations it can perform. We therefore separate between two main reference domains for quantification of changeability level for engineering systems: physical design and mode of operation. While the first is anchored in the physical object alone, the latter also concerns its interaction with the context. This is in line with the literature [Mekdeci et al., 2011; Fitzgerald, 2012; de Weck et al., 2012]. To help illustrate the need for these two different reference domains to describe the changeability level for a system, let us consider a simple example: a versatile offshore ship can be operationally changeable, without performing any physical changes in the design, as it can take on different types of contracts due to its level of inherent multi-functionality. However, the ship can also be physically modified to take on an even larger span of contracts. Hence, to some degree it possesses even more operational changeability – enabled by change of the physical design. This additional changeability would naturally need extra cost and time to be activated. Examples of physical design and modes of operation for a ship and an airplane are given in Table I. Here, we can see that individual physical design variables can be considered, such as the length of an airplane, or functional performances such as such as passenger capacity. One can also characterize an airplane design through its ability to function in different modes of operation, which for example can be characterized by the market segment (people vs. cargo) and route characteristics (short vs. long haul). For more detailed ways to classify concepts of operations (CONOPs) for system design applications see Mekdeci et al. [2011].

Table I: Physical design and modes of operation represent two reference domains for changeability. Examples from commercial aviation and shipping are used for illustration.

	Ship	**Airplane**
Physical design	Design variables: - Length, beam, depth. - Equipment: crane. Functional performance: - Capacity: deck area, deadweight. - Stability: initial metacentric height.	Design variables: - Length, wingspan, fuselage width. - Class configurations (econ/business). Functional performance: - Capacity (people, cargo). - Range in nautical miles.
Mode of operation	- Missions (Transportation, service type). - Areas (Atlantic, Pacific).	- Markets (people, cargo). - Routes (short-, medium-, long range).

2.3. DFC as a conceptual system design variable

Systems can be described both in terms of traditional design variables, intended to directly create value, and path enablers, intended to enhance changeability [Ross et al., 2008]. We adopt the term "Design for Changeability" (DFC) [Schulz and Fricke, 1999; Fricke and Schulz, 2005], and use it as a design variable that structures sets of path enablers. This approach is inspired by Fitzgerald and Ross [2012a, 2012b]. This way we operationalize the link between path enablers and design variables, and identify DFC as an overall system design variable, as illustrated in Figure 2 and exemplified in Table II. DFC thus lays the foundation for subsequent quantification of changeability level for design alternatives with different combinations of path enablers built in. Path enablers are case specific, and the DFC variable can therefore be constructed in multiple ways. We choose to represent DFC variable instances using numbers, with 0 as the baseline established for comparison purposes, but an alternative representation can be e.g. A, B, and C. It is also worth noting that path enablers may incur additional costs for a design alternative, both in terms of investment costs, and carry costs.

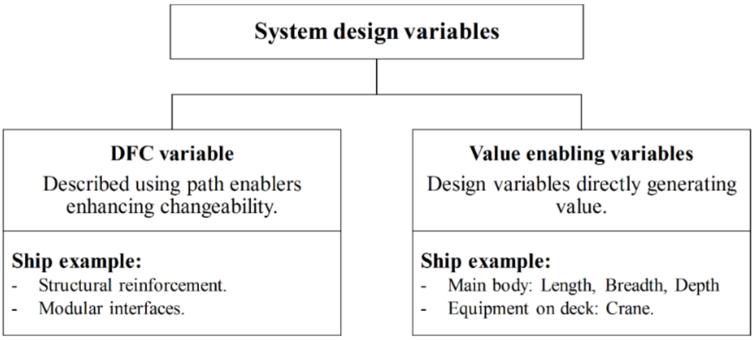


Figure 2: Design for changeability (DFC) variable materialized through different path enablers, where path enablers are system characteristics enhancing changeability.

Table II: The Design for changeability (DFC) variable defines and structures path enablers (system characteristics enhancing changeability), here exemplified for a ship.

DFC variable	Paths enablers
0	Baseline (none).
1	Structural reinforcement.
2	Structural reinforcement and modular interfaces.
3	Structural reinforcement, modular interfaces, and ice class capability.

2.4. Two main dimensions of changeability: cost and time

Fricke and Schulz [2005] mention that systems need to be able to change easily and rapidly. In the system generic agent-mechanism-effect framework by Ross et al. [2008], they talk about costs in terms of time and effort. For applications to engineering systems, we argue that quantification of changeability level for a given design alternative can be characterized by two main dimensions: monetary cost and time. It is important to differentiate between two aspects of cost, i.e. between carry cost and change cost. The cost we are interested in for means of changeability quantification is the exercise cost of the change. The time it takes to change reflects the ability of a system to change quickly, analogous to *agility* [Ross et al., 2008].

2.5. Two measures for changeability level quantification

We propose bottom-up and top-down as two approaches for quantifying the level of changeability for a given design alternative. This is to provide measures to quantify the level to which one design alternative is changeable, compared to another – as motivated by the airport example in the introduction of this paper. The design alternative of which we quantify the level of changeability for, is characterized both by an instance of the normal design variables (such as main dimensions and key equipment) and an instance of DFC representing the set of path enablers built into the design (such as modular slot interfaces and structural reinforcement). The bottom-up approach provides a simple means of approaching more specific terms of changeability, such as the details of changing one physical design variable, or between two modes of operation. This can for example be capacity expansion, or installation of a piece of equipment. The top-down approach is more comprehensive, investigating the space of change opportunities available at a given change cost and time.

- **Bottom-up:** Reduction in change cost or time: measured for each relevant change separately.
- **Top-down**: Number or fraction of states in the defined state space which can be changed into at given a cost and time.

These measures are based on a discretized state space representation of the overall system, as given by the X notation, comprising combinations of physical design states and modes of operation. Changing between two states in the set X gives us the possibility to measure changeability for three aspects of change: changes in physical design variables only, changes in modes of operation only, or changes in both physical design variables and modes of operation. The proposed quantification measures are limited as they are based on a discretized state space representation of the system, and thus not compatible with continuous variables.

Bottom-up:

The bottom-up measure relates to the expected reduced cost and time of performing a change for a given design alternative with a given DFC. This can be formalized with Equation (1) for costs and Equation (2) for time.

$$q_{COST}(x_{OLD}, x_{NEW}, DFC\ ) = \frac{C(x_{OLD}, x_{NEW}, DFC\ 0) - C(x_{OLD}, x_{NEW}, DFC)}{C(x_{OLD}, x_{NEW}, DFC\ 0)} \qquad (1)$$

q_{COST} represents the changeability metric for the normalized reduced cost from the given change represented by a change in the state space represented by the set X. *C* is the function for the cost of the change from x_{OLD} to x_{NEW} for a given DFC. The design with *DFC 0* is a baseline design chosen for comparative reasons, of which one can compare how much more changeable another design alternative is with additional path enablers built in.

$$q_{TIME}(x_{OLD}, x_{NEW}, DFC) = \frac{T(x_{OLD}, x_{NEW}, DFC\ 0) - T(x_{OLD}, x_{NEW}, DFC)}{T(x_{OLD}, x_{NEW}, DFC\ 0)} \tag{2}$$

Similarly, q_{TIME} represents the changeability metric for the normalized reduced time from the given change represented by a change in the state space X. *T* is the function for the duration of the change from x_{OLD} to x_{NEW} for a given DFC.

These two changeability level metrics are based on a predefined function for the estimation of cost and time for change, both for the baseline system (DFC 0), and for various DFCs representing different combinations and magnitudes of path enablers. Hence, q for a specific change takes a value between 0 and 1. $q = 0$ represents the baseline system, i.e. DFC 0 as defined. $q = 100\%$ represents the case where time or cost of a change is zero – i.e. there is a 100% reduction in change cost and time compared to the DFC 0.

Top-down:

The top-down approach for changeability quantification is determined by using the Filtered Outdegree (FOD) metric [Ross et al., 2008; Fitzgerald et al., 2012], which is based on a networked state space where nodes (states) are connected with arcs representing potential changes between states. There may exist multiple paths between two states, with different associated change duration and cost. Duration and cost of a path, and thus a state change, can be altered by implementing different path enablers in the design, as described using different DFCs. The original FOD metric is defined counting the number of paths, i.e. possible change mechanisms, from a state. However, for the current purposes, it is useful to count the number of end states. The $FOD_{End\ state}(x_j, \hat{C}, \hat{T})$ metric quantifies the number of feasible outgoing end state changes from state x_j, for a given DFC, under given cost $\hat{C}$ and time $\hat{T}$ thresholds, as defined by Equation (3).

$$FOD_{End\ state}(x_j, DFC, \hat{C}, \hat{T}) = \sum_{d \in X} H(C_{j,DFC,d,p}, T_{j,DFC,d,p}), \forall\ C_{j,d} < \hat{C}, T_{j,d} < \hat{T}, p \in P_{j,d} \tag{3}$$

Where, $C_{j,DFC,d,p}$ and $T_{j,DFC,d,p}$ are cost and time for changing from system state *j* to *d* at path *p*, for a given DFC, for *p* in the set of paths $P_{j,d}$ between *j* and *d*, and *H* is the Heaviside function taking 1 if both change cost and time are below the thresholds for at least one of the paths between *j* and *d*, and 0 else. As a change is represented solely by moving from one node to another, we only count one step, and not walks, in this network. Thus, double counting through e.g. cycles is eliminated.

This definition of FOD differs slightly from the one originally presented by Ross et al. [2008], as they originally base the FOD on the number of feasible paths, and not the feasible state transitions. These measures are not entirely similar, as there may be multiple paths between two states. However, Ross et al. [2008] introduce and discuss a generalized approach, in which either number of end states or number of change mechanisms can be counted in theory, based on the purpose of the analysis. In this paper, we focus on end states as this makes the measure less complex. For detailed single state change analyses, assessing the paths may be of more relevance. Moreover, Ross et al. [2008] discuss different degrees of changeability that can occur in a system and generalize to include countable vs. uncountable end states, and specified vs. open-ended change mechanisms. FOD is intended for cases with countable end states and specified change mechanisms.

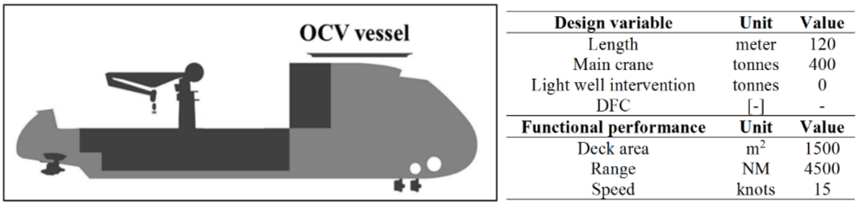
With no cost and time filters applied, the end state FOD simply becomes the end state Outdegree (OD), which represents the number of nodes considered in the analysis, minus one. This is if you count end states, but if you focus on paths it can be much higher. The end state FOD metric can thus either be measured on an absolute term, or on a relative basis measuring the fraction of the total states which can be reached at a given cost and time. The end state Relative Filtered Outdegree (RFOD) is given by Equation (4).

$$RFOD_{End\ state}\left(x_j, DFC, \hat{C}, \hat{T}\right) = \frac{FOD_{End\ state}\left(x_j, DFC, \hat{C}, \hat{T}\right)}{OD_{End\ state}\left(x_j, DFC\right)} \tag{4}$$

A subscript “*end state*” is added in Equation (3) and (4) to specify which arcs the metric is counting, however in the following illustrative case this specification is left out.

3. Case study: Offshore ship

A case study from the concept design of a commercial offshore ship is presented. Offshore ships, in contrast to traditional cargo ships, provide various services typically related to the offshore oil and gas industry, and comprise a wide group of vessels such as offshore construction vessels (OCV) and light well intervention (LWI) vessels. These ships are typically multi-functional, complex, and costly to design, build and operate. Changeability analysis for conceptual offshore ship design is particularly relevant, due to the uncertain and heterogeneous requirements in these markets, coupled with high investment costs. There are multiple examples of expensive retrofits made to offshore ships recently, as results of changing market needs. One example from 2015 was the conversion of a platform supply vessel to a wind farm service vessel, which in addition to changing equipment on deck involved changing the dimensions of the main body, significantly driving retrofit costs [Rehn et al., 2016]. Important characteristics determining the reconfigurability of a ship, such as stability and maximum weight capacity, are determined by the main dimensions [Rehn et al., 2018]. Dimensions of the main body are determined at the early stages of the design process, and changing them later often require significant rework, driving costs and potentially resulting in compromised solutions. This example supports our claim that changeability analysis should be performed already at this early stage of the design process, as it can significantly influence the choice of design concept. In this case study, we will quantify the level of changeability for a baseline offshore ship, as specified in Figure 3. The case study is based on an actual case from the industry, in collaboration with Ulstein International, a major Norwegian ship design and ship building company, for more details see [Pettersen et al., 2017].



Design variable	Unit	Value
Length	meter	120
Main crane	tonnes	400
Light well intervention	tonnes	0
DFC	[-]	-
Functional performance	**Unit**	**Value**
Deck area	m^2	1500
Range	NM	4500
Speed	knots	15

Figure 3: Offshore construction vessel (OCV) baseline details.

3.1. Discretizing the design and operational spaces

A parameterization of the physical design space is presented in Table III. In this case, DFC is conceptualized as a discrete design variable from 0 to 4. In the following, we will elaborate on what that means. The design space enumerates to eight combinations, excluding DFC, as illustrated in Figure 4 (left).

Table III: Parametrization of OCV case design space.

Design variable	Abbr.	Units	Values
Length	L	m	120, 140
Main crane capacity	MC	tonnes	400, 800
Light well intervention tower	LWIT	tonnes	0, 500
Design for changeability	DFC	[-]	0, 1, 2, 3, 4

The operational space comprises missions and geographical areas of operation. Each of the mission types have technical requirements, as specified in Table IV. In addition to the technical details of a mission, it can also be in different geographical areas, which for this case is represented by three areas: Gulf of Mexico, Brazil, and North Sea. Thus, the complete operational space enumerates to nine different states, as illustrated in Figure 4 (right). The distance between North-Sea (NS) and Gulf of Mexico (GoM) is 4200 nautical miles, and between NS and Brazil it is 5100 nautical miles.

Table IV: Operational mission type descriptions, with technical requirements to the ship.

#	Mission	Abbr.	Technical requirements (minimum)		
			Main crane	LWI tower	Deck area
1	Subsea installation and construction	OSC	300 tonnes	0	1400 m^2
2	Light well intervention	LWI	200 tonnes	400 tonnes	1000 m^2
3	Subsea decommission	ODS	500 tonnes	200 tonnes	1000 m^2

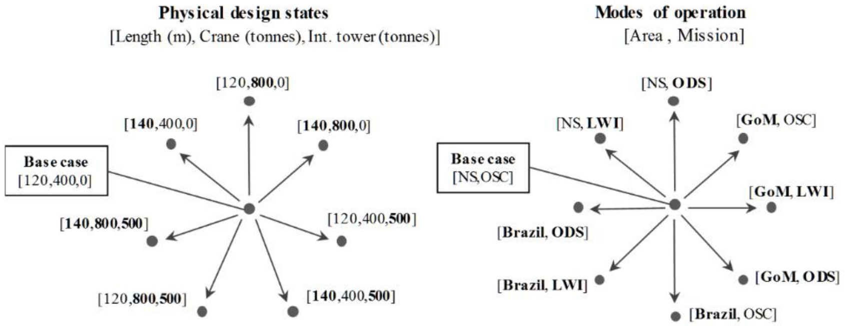


Figure 4: Eight physical design states, and nine modes of operation considered, represented relative to the baseline for potential changes (arrows). The changed variables are highlighted in bold. NS= North Sea, GoM = Gulf of Mexico, OSC = Subsea installation and construction, LWI = Light well intervention, ODS = Subsea decommission.

3.2. DFC variable description

The DFC variable structures sets of path enabling variables. For the offshore ship, physical design related path enabling variables enable easier change of design variables, such as structural reinforcement for equipment retrofit. Operational non-retrofit path enablers enable easier change of operational state, without change of physical design variables. This includes increased speed and range to change between missions in different geographical areas more easily. Figure 5 illustrates the changeability space for the offshore ship.

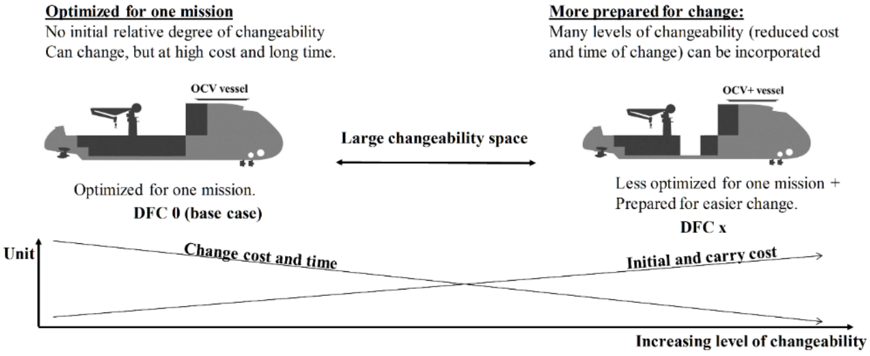


Figure 5: Illustration of the space of changeability level for the offshore ship case study. The ship on the right has a moonpool, which is an opening in the ship, to enable easier retrofit of a light well intervention tower.

For the case, the specific path enabling variables are described in Table V. Four are considered in this case study for simplicity, although a high number of potential path enablers can be explored and included. As all path enablers enhance operational changeability, we separate between those that do, or do not, involve change of physical design variables. Moonpool (an opening in the ship to provide access to the water) and structural reinforcement enable easier retrofit of equipment, and thus relate to change in form. However, a larger engine for extra power, and a larger fuel tank are characteristics of the design that enhance the operational agility of the vessel, i.e. the speed and range of which it can move. Other examples from retrofit-enabling path enablers in the maritime literature are given by Buxton, and Stephenson [2001] and Knight, and Singer [2012]. To provide design alternatives with different levels of changeability for further analyses, we combine and structure these path enablers. Table VI structures and describes four DFC examples, in addition to the baseline defined as DFC 0. Table VI includes the added investment costs associated with the chosen DFC. These numbers are based on historical data from earlier ship design and retrofit projects. For example, the costs of structurally reinforcing the hull is roughly 20 000 USD, based on a need for 40 metric tons extra steel and a price of 500 USD per metric ton for steel. The cost of reinforcing the hull when the ship originally is built does not involve any significant extra labor costs. Structurally reinforcing the hull enables easier retrofits of equipment on deck, and easier elongation, since it provides margins ensuring structural integrity. The requirements to the structural properties of the ships are governed by classification societies, following strict rules ensuring hull integrity and safety.

Table V: Declaration of path enabling variables. A separation is made between path enablers affecting change of physical design and modes of operation – all can affect operation, but not all enable physical design change.

Path enabling variable	Change mechanism	Physical Des. path enabler	Op. path enabler	Description
Moonpool	Add LWIT	Yes	Yes	A moonpool is an opening through the deck to access the water, enabling easier light well intervention tower (LWIT) retrofit.
Structural reinforcement	Length, Crane /LWIT	Yes	Yes	Enables easier elongation of hull, in addition to crane and LWIT retrofits.
10% extra power	Speed	No	Yes	Enables quicker geographical repositioning due to the option to sail with higher speed.
Extra fuel tank	Range	No	Yes	Enables larger span of geographical areas.

Table VI: Design for changeability (DFC) descriptions for the offshore case, with associated investment costs.

DFC	Paths enablers added to the baseline design	Inv. Cost
0	Baseline (none)	-
1	Moonpool	\$1.00 m
2	Moonpool, structural reinforcement	\$1.02 m
3	Moonpool, structural reinforcement, extra power.	\$1.82 m
4	Moonpool, structural reinforcement, extra power, and extra fuel tank.	\$1.92 m

3.3. Bottom-up changeability level quantification

Physical design space related quantification of changeability:

Table VII describes the reduction in cost and time enabled by the different sets of path enablers included in the design described through the DFC variable. Equations (1) and (2) are used, and the specific change is given per variable alone based on the change in the predefined state space clarified in Table III, and illustrated in Figure 4. For this simple example, the change in length is from 120 to 140 meters, in crane capacity from 400 to 800 tonnes, and in intervention tower it is from 0 to 500 tonnes. This table provides information both about the absolute cost and time of change, in addition to the relative reduction of cost and time – which is the bottom-up measure. For example, in Table VII, we can see that when increasing from DFC 1 to 2, the cost of increasing the length of the ship from 120 to 140 meters is reduced by 4%, from 10.1 to 9.7 million USD, due to the structural reinforcement. Further, Table VII shows that the savings in terms of cost and time from installing the well intervention tower on a vessel with moonpool, compared to a vessel that did not include the moonpool initially, are substantial. The estimates in Table VII are based on data from previous ship design and retrofit projects. In the event of a tower installation, the cost savings from having moonpool and steel reinforcements amount to approximately 9 million USD. The reason for this is that the well intervention tower accesses the sea, working through the moonpool. Besides the large investment the intervention tower requires itself, the installation of a moonpool in the vessel after it has been built requires large amounts of rework. The largest contributors to the costs associated with a moonpool retrofit are; i) replacing the section of the ship where the moonpool is located, ii) adding a new, structurally strengthened section including the moonpool, and iii) re-arranging existing ship systems, including pipes, electrical systems, and tanks. The cost estimates for these elements are estimated to be i) 4 mill. USD, ii) 2 mill. USD, and iii) 3 mill. USD.

Table VII: Design variable bottom-up changeability level quantification, including both absolute values and relative reduction (q) for both time and cost domains, for the three design variables: length, crane, and intervention tower.

DFC	**Cost**						**Time**					
	Length		**Crane**		**Int. tower**		**Length**		**Crane**		**Int. tower**	
	$ mill	q_{cost}	$ mill	q_{cost}	$ mill	q_{cost}	Days	q_{time}	Days	q_{time}	Days	q_{time}
0	10.1	-	23.2	-	82.2	-	90	-	20	-	150	-
1	10.1	-	23.2	-	72.5	12%	90	-	20	-	40	73%
2	9.7	4%	22.8	2%	72.1	12%	85	6%	10	50%	40	73%
3	9.7	4%	22.8	2%	72.1	12%	85	6%	10	50%	40	73%
4	9.7	4%	22.8	2%	72.1	12%	85	6%	10	50%	40	73%

Table VII describes physical design variable changeability. DFC 1 and 2 are the only alternatives that introduce path enablers for change of physical design variables – recall from Table V. The extra path enablers included in DFC 3 and 4 relate to improved operational changeability without change in physical design, as described in Table VI. Thus, there are no changes to the values in Table VII for from DFC 2 to DFC 3 and 4.

For some purposes, it may be more relevant to investigate how different levels of changeability affect functional performance, such as the capacity in terms of deck area or payload. For the considered case, structural reinforcement enables easier change of the deck area, to take one example. This is due to easier elongation, and consequently deck area changeability properties are equivalent to change of length, as illustrated in Table VII. That is, by going from DFC 1 to 2, we have an expected 4% cost and 6% time reduction for the option of increasing the deck area from 1500 m2 (baseline) to 2100 m2. As functional performance mapping not necessarily is one-to-one with form, it means that multiple mechanisms can be utilized for the same change effect. Thus, one needs to be consistent in terms of which change mechanism one intends to use for the change effect. In general, to enhance changeability, we are interested in the change mechanism that reduces the cost and time of the intended change. For deck area expansion, elongation is the mechanism with the lowest cost and time in this case. Thus, the information about deck area changeability is one-to-one with increasing the length.

Operational related quantification of changeability:

For simplification, we define the initial baseline operational state for the ship as on a mission doing subsea installation and construction work (OSC) in the North-Sea. Multiple domains of changes may be analyzed, but for simplicity only two are considered in this case: Table VIII presents mission related changeability level quantification within the same geographical locations, while Table IX presents geographical area related changeability level quantification for a constant mission type.

Table VIII: Bottom-up operational changeability quantification for missions (constant area: North-Sea) q_{cost} and q_{time} represent the relative reduction in change cost and time, abbreviation for missions are: OSC = subsea installation and construction, ODS = subsea decommission and LWI = light well intervention.

DFC	**Cost**				**Time**			
	OSC to LWI		**OSC to ODS**		**OSC to LWI**		**OSC to ODS**	
	$ mill	q_{cost}	$ mill	q_{cost}	Days	q_{time}	Days	q_{time}
0	82.2	-	94.9	-	155	-	165	-
1	72.5	12%	86.1	9%	45	71%	55	67%
2	72.1	12%	85.4	10%	45	71%	50	70%
3	72.1	12%	85.4	10%	43	72%	48	71%
4	72.1	12%	85.4	10%	43	72%	48	71%

Since changing between missions may involve change of physical design variables, the cost and time reduction values in Table VIII show similar trends as in Table VII. However, they are not the same as a change of mission is more generalized, which can involve other aspects of change, such as time of transportation to and from the assumed yard used.

The baseline design ($DFC\ 0$) does not have enough range to make it from North-Sea to Brazil without refueling underway, which is assumed to add extra 2 days to the transport time. This renders durations for the initial ship at max speed of 15 knots to 12 days from North-Sea (NS) to Gulf of Mexico (GoM) and 16 days from North-Sea to Brazil. This explains the information provided in Table IX. Extra (non-retrofit) operational path enablers are added for DFC 3 and 4, which are intended to increase operational agility. More specifically, the speed increases from 15 to 17 knots with the extra engine power, and the range increases from 4500 to 6500 nautical miles with the extra fuel tank. Added engine power increases the speed and thus reduces the time to change between operational areas. The time reduction for geographical changeability from North-Sea (NS) to Brazil from DFC 3 to 4 is further reduced due to no need for refueling underway.

Table IX: Bottom-up operational changeability quantification for areas from North-Sea (NS) (constant mission: OSV), disregarding costs.

DFC	Cost				Time			
	NS to Gulf of Mexico		NS to Brazil		NS to Gulf of Mexico		NS to Brazil	
	$ mill	q_{cost}	$ mill	q_{cost}	Days	q_{time}	Days	q_{time}
0	-	-	-	-	12	-	16	-
1	-	-	-	-	12	-	16	-
2	-	-	-	-	12	-	16	-
3	-	-	-	-	10	12%	14	10%
4	-	-	-	-	10	12%	12	22%

3.4. Top-down changeability level quantification

End state filtered outdegree (FOD), or end state Relative FOD (RFOD), can be used to quantify changeability between all states or various sets of states, for example related to the design or operational space alone, which are illustrated in Table X and Table XI respectively. In the tables, both FOD and RFOD are included. FOD represents the number of alternative states that can be changed into at the given threshold cost and time, while RFOD similarly represents the fraction of total alternatives i.e. FOD divided by the maximum FOD.

Table X: Top-down changeability level quantification for design space only using Filtered Outdegree (FOD) and Relative Filtered Outdegree (RFOD) for different cost and time thresholds, reference (x_j) ship is the initial design.

DFC	Threshold ($10m, 14days)		Threshold ($100m, 14days)		Threshold ($10m, 140days)		Threshold ($100m, 140days)	
	FOD	**RFOD**	**FOD**	**RFOD**	**FOD**	**RFOD**	**FOD**	**RFOD**
0	0	0%	0	0%	0	0%	3	43%
1	0	0%	0	0%	0	0%	7	100%
2	0	0%	1	14%	1	14%	7	100%
3	0	0%	1	14%	1	14%	7	100%
4	0	0%	1	14%	1	14%	7	100%

The RFOD levels presented in Table X are defined for the design space alone, which spans eight total states as defined in Table III and illustrated in Figure 4 (left). From Table X, we can get an overview of the scale of cost and time of making changes to the design variables of the ship. At the thresholds of $10 million and 14 days, no design changes are feasible, and a significant portion of changes are not made feasible before the threshold is set to $100 million and 140 days. At this threshold level, DFC 2 is needed for “full physical design changeability”.

Table XI: Top-down changeability level quantification for operations space only using Filtered Outdegree (FOD) and Relative Filtered Outdegree (RFOD) for different cost and time thresholds, reference (x_j) ship is the initial design.

DFC	Threshold ($10m, 14days)		Threshold ($100m, 14days)		Threshold ($10m, 140days)		Threshold ($100m, 140days)	
	FOD	**RFOD**	**FOD**	**RFOD**	**FOD**	**RFOD**	**FOD**	**RFOD**
0	1	13%	1	13%	2	25%	2	25%
1	1	13%	1	13%	2	25%	8	100%
2	1	13%	1	13%	2	25%	8	100%
3	2	25%	2	25%	2	25%	8	100%
4	2	25%	2	25%	2	25%	8	100%

For the case considering only operational changeability, as presented in Table XI, the total space spans nine states as defined in Table IV and illustrated in Figure 4 (right). RFOD is 100% at FOD 8, and not 9, since the start baseline occupies one state. In Table XI, we can gain insight of the overall scale of cost and time of making operational changes. We can see that the impact of DFC on RFOD is relatively low for the various cost and time thresholds, and that costs and time in the order of $100 million and 140 days respectively are needed to achieve 100% RFOD. The results in Table X and Table XI are relatively similar, indicating that the retrofit changes are the most dominant for the overall changeability for the system.

3.5. Comparing the bottom-up and top-down measures

The top-down and bottom-up measures quantify changeability level for the same system. The difference between them is the way they are structured, and the information and insights one can extract from them. The bottom-up measure is particularly useful for investigating specific changes, such as adding a piece of equipment, or switching to a new market. For the case study, we can see that the different DFCs affect the change time and cost differently for the various design variables. For example, the moonpool path enabler included at DFC 1 reduces the cost of adding an intervention tower by 12%, while the structural reinforcement in the hull introduced at DFC 2 affects both the length and crane retrofit changeability, though differently. The bottom-up approach is good for capturing detailed information for each type of change. In the case study, the bottom-up approach allows us to investigate the expected enhanced operational agility of the system, and we can see that by adding extra engine power and fuel tank reduces the time it takes to move the ship between specified geographical areas. This can be valuable e.g. if there are high-paid contracts that only are available at the short-term notice. Moving on to determine which design is better would incur valuation, which is outside the scope of this paper. However, this is the natural next step in the conceptual design analysis.

The bottom-up measure is appropriate for answering questions such as:

- How much can we reduce the cost of adding a crane to the ship by pre-reinforcing the hull?
- How much more operationally agile would the ship be by adding 10% extra engine power?

The top-down measure is more holistic, characterizing the changes possible at given cost and time thresholds. For example, from the case study, when applying the FOD on the operational space, we can see that only 25% of the possible missions can be entered at a change cost and time of $10 million and 140 days, for all DFCs. These two state changes are reallocation to Gulf of Mexico or Brazil, from the North-Sea, without change of mission type. Thus, no retrofit is needed. These results illustrate that none of the alternative changeable designs seems to be the significantly different, and that much of the change costs comes from acquiring the equipment from external sources. What may be particularly useful with the top-down approach is that by varying the cost and time thresholds, one can explore the FOD for various design alternatives. In this paper, we used tabular illustrations for various cost and time thresholds, and found that even at significant thresholds of $100 million and 140 days, at least DFC 1 (moonpool path enabler included) was needed to have full operational changeability. For more high-resolution exploration here, graphical representations of FOD and RFOD as functions of thresholds values could provide more insights.

The top-down measure is appropriate for answering questions such as:

- How versatile is the ship, i.e. how many missions in the market can be served without reconfiguration of the ship itself?
- How large fraction of possible equipment retrofits can be made on the ship within one week?

4. Discussion

Two aspects of changeability quantification are discussed, the first being how to structure changeability through the Design for Changeability (DFC) construct as a conceptual design variable, and second how the level of changeability for various design alternatives can be quantified based on the expected reduced change cost and time. We separate between bottom-up and top-down approaches, applied to either the design or operational domains, or both. In general, we do not argue that one approach is better than another, only that the different approaches may be relevant depending on the purpose of the analysis.

We argue for a clear differentiation between quantification of changeability level, and changeability valuation. The proposed metrics for changeability level quantification are based on expected reduced time and cost of making changes, which obviously have some connection to value – otherwise, there would be no meaning incorporating changeability in a design. Per definition, going from quantification to valuation involves some sort of transformation that describes the subjective interpretation of value from the cost and time savings. This process adds a layer of complexity to the problem, and is likely based on the system of interest, its stakeholders, and details of the expected future context. The differentiation between quantification and valuation becomes clear in traditional real options analyses, where the purpose is to determine the value of a well-defined option. Traditional options are well-defined, but with the application of options terminology on physical systems through real options analysis, one must investigate *how* real options even can be included in a system and what this means. However, for certain systems and application areas, the differentiation between quantification and valuation may not be that meaningful. For example, for non-commercial systems, assessing implications of changeability in the functional performance space may be directly related to perceived value for the stakeholders [Fitzgerald, 2012]. We acknowledge that for certain applications, the proposed metrics and reference domains may not be applicable.

The proposed metrics for changeability level quantification, both bottom-up and top-down, rely on estimations of cost and time of state changes. This is in general difficult, as they are uncertain at the initial stage, which can be of exogenous or endogenous types. Exogenous uncertainties may arise from potential time delays, cost slips, and questions related to equipment and facility availability. For example, for the offshore illustrative case, will retrofit equipment be available at the yard when needed, or will there be lead time? Endogenous uncertainty may result from system complexity, as design subsystems may have a high degree of interconnectivity. Changes in a design can propagate between elements that are not directly connected and influence each other in ways difficult to predict [Clarkson, Simons, and Eckert, 2004]. The point, however, with building changeable systems is to handle and reduce this potential interconnectivity – to enable change with less effort. In addition to technical aspects for the offshore ship, there may be issues with the crew and their expertise, or with laws and regulations, which may be significant for estimating change time and costs. Moreover, a clear separation between cost and time may not be purposeful for certain considerations. For example, there may be lost opportunity costs (cost of time), as there is a lost income from taking an asset out of operation. This relates more to aspects of changeability valuation, and we therefore argue that the clear separation between cost and time still makes sense for quantifying the level of changeability for engineering systems in an attempted objective manner.

The offshore case presented is for illustrative purposes, and in practice, there are multiple other types path enablers, and design variables that can be considered. For example, one can theoretically explore the DFC space the same way one can explore the traditional design space. A more thorough exploration of different combinations of path enablers in a design can help decision makers see tradeoffs and gain insights, to make better conceptual design decisions. In addition to the resolution and span of design variables, it is important to be careful defining the system boundaries. For example, for the offshore ship case, increased operational changeability can alternatively be achieved through use of external transportation means. This is the case for several low-speed offshore drilling units today, which can only sail a couple of knots themselves. When these offshore units need faster transportation, a large semi-submersible transportation vessel can be used to transport them on deck at higher speeds. The semi-submersible then serves as a system-external operational path enabler. A similar example from aviation may be aerial refueling for range extension. Increased level of changeability for a design comes at a cost, which comprises both investment cost and carry cost. When describing the levels of changeability in the case study, carry costs were neglected. Carry costs may be hard to quantify, as they include aspects such as various degrees of reduced capacity and increased water resistance. For example, the moonpool, which is an opening through the hull of the ship to access the water, serves as a path enabler for easier retrofit of a light well intervention tower, but also reduces the deck area and increases the water resistance.

The driving factor behind changeability for such commercial systems is changes in market needs and hence also the operating context. For offshore shipping, the market is heterogeneous, with tenders of various length, functional requirements and in different operational areas. The shipping industry is capital intensive, coupled with an uncertain market, therefore it should be expected to see retrofits and redesigns of existing vessels. It has been demonstrated in the marine industry that a design for changeability (DFC) approach exist today, mainly through the implementation of different types of “readiness”. Readiness simply means ready for change, or that some measures are taken to make the change quicker and cheaper. For example, there exist class notations for flexibility such as “Gas Ready” by the classification society DNV GL [DNV GL, 2015]. This represents a set of predefined measures (path enablers) that enable a ship to more easily change fuel source from diesel to dual-fuel, i.e. from “diesel” to “diesel or natural gas”. Other measures of readiness are also used, for example for equipment retrofit. In terms of further research, it could be of significant value to define some common classes of DFC for various types of segments, particularly for the notion of communication between decision makers.

5. Conclusion

This paper outlines and discusses the suitability of a generic method for quantifying changeability level, to support better decision making in conceptual system design. We argue that the two aspects that are important when it comes to changeability quantification for engineering systems are cost and time. Two approaches for quantifying changeability level are proposed: bottom-up, measuring at the relative cost and time reduction enabled for each relevant variable changed, and top-down, measuring the span of change opportunities at a given time and cost using Filtered Outdegree (FOD). By following the method outlined in this paper, system designers can more easily structure their conceptual explorative analyses for implementing changeability in systems, and thus provide the fundamentals to be able to understand what level of changeability is preferable. Further, using this method can particularly help define and communicate changeability in system design between people involved in design problems, from low-level to high-level decision makers. Overall, this can result in design of better, more value robust, systems.

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Article 4

Versatility vs. retrofittability tradeoff in design of non-transport vessels

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Versatility vs. retrofittability tradeoff in design of non-transport vessels

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Abstract:
In this paper, we study the relationship between economic performance and flexibility for non-transport vessels. More specifically, we investigate the difference between two means of achieving flexibility: retrofittability and versatility, i.e., the ability of a vessel to satisfy diverse needs *with* or *without* change of physical form, respectively. A model is presented to study this relationship, where we first generate design alternatives with relevant, flexible properties before we subsequently evaluate the design alternatives based on their expected discounted economic lifecycle performance. The evaluation model is based on a two-level decomposition of the planning horizon to handle temporal complexity, using scenario planning and Epoch-Era analysis (EEA) for long-term strategic considerations, and Monte Carlo simulation and optimization for medium-term tactical ship deployment. The proposed model is applied to an offshore construction ship design case. Findings indicate that retrofittability significantly can increase economic performance for non-transport vessels operating in an uncertain heterogeneous context.

Keywords: Ship design, Retrofittability, Versatility, Flexibility, Uncertainty

1. Introduction

Determination of the design-specifications of a new ship is a complex strategic problem every shipowner needs to solve as part of a fleet renewal or expansion program. Due to long time horizons and a high degree of contextual uncertainty in the maritime markets (Alizadeh and Nomikos, 2009; Erikstad and Rehn, 2015), this problem is complex and strategic in nature (Christiansen et al., 2007). The ship design problem is different for transport and non-transport vessels. Non-transport vessels serve various service-related needs in the maritime industry, such as offshore construction and anchor handling. This contrasts with traditional ships designed for transportation purposes, such as oil tankers and bulk ships. The revenues for non-transport ships come from contracts with various technical requirements and durations. The ship designer thus needs to determine whether the ship should be designed only for the short-term contract specifications or to be *versatile* and have additional capabilities to handle a broader set of missions after the first contract has ended. However, adding extra equipment increases the initial investment costs. Alternatively, the ship can be optimized for the initial contract, but be *retrofittable* and prepared to be easily retrofitted later. The retrofit decisions can then be made after future uncertainty has been resolved. Following, the degree to which a ship is designed to be flexible is thus a decision to be made at the conceptual design stage, as it will significantly influence the choice of design-concept. This motivates the following research question: What is the relationship between economic performance and flexibility for non-transport vessels? By economic performance, we mean aspects of investment cost, retrofit costs, and revenue potential.

In ship design, one needs to understand the operational phase of the lifecycle to evaluate and compare the performance of different design alternatives. In traditional design literature, this is often reduced to the process of requirements elicitation, or elucidation (Andrews, 2011). However, to study the link between contextual uncertainty and the ability of a system to change form, function, and operation, we need to explicitly consider temporal and contextual complexities of the operational part of the lifecycle (Rhodes and Ross, 2010). Operations research, therefore, becomes an integrated part of this extended design problem. Operations research is a well-established field, with extensive contributions for maritime transportation applications. An excellent review of transportation ship routing and scheduling is presented by Christiansen et al. (2013). However, operations research for non-transport shipping cases is less covered in the literature. A case for operational planning of offshore ships is presented by Fagerholt and Lindstad (2000), where optimal policies for supply in the Norwegian Sea are determined with the objective to reduce operational costs. Gundegjerde et al. (2015) present a case study of a *fleet size and mix problem* for maintenance operations at offshore wind farms using a stochastic optimization model. Christiansen et al. (2007) discuss strategic, tactical, and operational planning in the context of maritime transportation. Even though their perspective is from maritime operations research, they clearly relate strategic decisions to ship design, such as *fleet renewal* and *fleet size and mix*. They thus classify ship design as a long-term strategic decision problem.

Erikstad, Fagerholt, and Solem (2011) present the ship design and deployment problem (SDDP), which is applied to the design of non-transport vessels. This problem involves the determination of the best specification for a non-transport vessel facing a set of available contracts with different start-up periods, durations, and capability requirements. The authors propose a binary integer programming model to select the optimal design and its deployment specifications. Therefore, the SDDP explicitly considers the deployment of the vessel in the operational phase of the lifecycle, with the purpose of improving the initial design specifications. Building on SDDP, Gaspar, Erikstad, and Ross (2012) discuss aspects of handling temporal complexity in design using Epoch-Era Analysis (EEA). However, SDDP, as presented by these collective authors, does not consider the possibility of changing a ship's capabilities after it is built, which we explicitly address in this paper.

The ability of a system to change form, function, or operation, generally called *changeability* (de Weck et al., 2012), is extensively covered in the systems engineering literature. Changeability is a collective term for change-related system properties such as flexibility, adaptability, versatility, and agility. Fricke and Schulz (2005) introduce the term Design for

Changeability (DFC) and discuss principles enabling changeability in design. Ross, Rhodes, and Hastings (2008) present a design-neutral framework for defining changeability and explicitly connecting it to change-related ilities, including adaptability and flexibility. Traditional methods for evaluation of changeable design alternatives have roots in the financial derivatives literature, with real options applied to physical systems (Trigeorgis, 1996). However, traditional option pricing methods rely on various assumptions that do not necessarily hold for applications of systems design (Wang and de Neufville, 2005). To separate between traditional, well-defined real options on assets and more ill-structured real options in systems design, Wang and de Neufville (2005) introduce real options "on" and "in" projects respectively. Real options "in" projects do not treat technology as a "black box," in contrast to traditional real options "on" projects. A good reference for flexibility in engineering design, including practical applications and examples, is de Neufville and Scholtes (2011).

The literature on design of non-transport vessels under uncertainty has increasingly focused on aspects of changeability to handle operational uncertainty. Choi, Rehn, and Erikstad (2017) present a module configuration model for adaptable ship design. They use a rolling horizon optimization approach for tactical decision-making in the operational phase of the lifecycle and use that to evaluate and compare two initial main body design alternatives. They conclude that flexibility enabled by modularity can mitigate risks and increase performance. Changeability in ship design is also covered by Niese and Singer (2014), using Markov decision processes for changeability evaluation studying a case from ballast water treatment.

While most contributions on changeability in ship design provide insights into the *evaluation* of one changeable design alternative, they typically do not explicitly study *different changeable design alternatives.* That is, little or no focus is on the characterization and exploration of alternative design solutions with different types and levels of changeability built in. This especially accounts for design characteristics that enable retrofits. Versatility, or multi-functionality by design, is to some degree addressed in the literature, e.g., by Stopford (2009), who introduces *lateral cargo mobility* (LCM) measuring the number of different types of cargo a vessel can carry. Rehn et al. (2018) differentiate between two main aspects of changeability in systems engineering practices: quantification of changeability level for a design alternative, and valuation of a given level of changeability for a design alternative. They further present a case from offshore shipping to illustrate how different levels of changeability in design can be quantified. A more practical perspective on ship design and retrofit is presented by Ullereng (2016), who studies how offshore shipping companies can reutilize platform supply vessels (PSVs) in poor offshore markets. Ullereng focuses both on classical operational real options such as sell, layup, or scrapping, in addition to exploring retrofit options. He mentions that offshore shipping companies have discarded potential ship conversions due to too high conversion costs. This supports the research topic explored in this paper, as we investigate how retrofittability, enabling reduced conversion costs and times, can be of importance for the next generation offshore ships.

2. Flexibility in non-transport shipping

2.1. Concepts and definitions

Changeability represents the ability of a system to change form, function, or operation (de Weck et al., 2012), and is a collective term for change-related ilities such as flexibility, adaptability, versatility, and agility. In this paper, we generally use the term flexibility, as it assumed best suitable for the targeted ship design audience. Changeability and flexibility are thus used interchangeably. We are interested in studying two nuances of flexibility, which relate to the ability to satisfy a diverse set of needs *with or without* change of form. Change of form represents physical change of an engineering system, which can be collectively called retrofits. Change of form can result in a change of function, but change of function do not necessarily require change of form. For example, a multi-functional offshore ship can handle different types of missions, without the need for any retrofits. This built-in multi-functionality is characterized as *versatility* (Chalupnik et al., 2013). This example illustrates the two different aspects of flexibility in design:

- ➢ **Versatility:** the ability of a system to satisfy diverse needs, *without* change of form.
- ➢ **Retrofittability:** the ability of a system to satisfy diverse needs, *by* change of form.

We define *retrofittability* as a general change-related ility involving change of form, for lack of a better word. Other, more specific ilities in the literature relating to change of form are reconfigurability, modifiability, scalability, and extensibility. de Weck et al. (2012) define these as: reconfigurability – ability to change component arrangement and links reversibly; modifiability – ability to change the current set of specified system parameters; scalability - ability to change the current level of a specified system parameter; and extensibility – ability to accommodate new features after design. Retrofittability thus represents a superset encapsulating these four change-related ilities, explicitly contrasting versatility. One relevant application of the phrase *retrofittable* in the literature is by Baker et al. (2016), who study requirements engineering for retrofittable subsea equipment.

2.2. Examples from the industry

Market changes are the driving factors for flexibility in commercial maritime systems. The needs-specifications from the industry are operationalized through tenders. For offshore shipping, the market is heterogeneous, with tenders of various length, technical requirements and at different operational areas. The shipping industry is capital intensive, coupled with an uncertain heterogeneous market, therefore is it natural to see retrofit and redesign of vessels. Table 1 provides some recent examples from retrofits in the maritime industry.

Table 1: Vessel retrofit examples with approximate cost estimates (Rehn and Garcia, 2018), PSV= platform supply vessel, OCV = offshore construction vessel.

Vessel name	**Type**	**Year of**		**Cost $ millions**		**Retrofit description**
		Build	**Retrofit**	**Built**	**Retrofit**	
Belle Carnell	PSV	2004	2013	25	40	Accommodation, equipment
Aker Wayfarer	OCV	2010	2016	220	90	Equipment
Vestland Cygnus	PSV	2015	2015	38	18	Beam, equipment
Enchantment of Seas	Cruise	1997	2005	300	60	22 m. elongation
MSC Lirica (+3 sis.)	Cruise	2003	2014	250	65	24 m. elongation

It has been demonstrated in the marine industry that several ships are prepared for retrofits at the design stage. For non-transport vessels, examples typically involve being prepared for equipment retrofits. In the classification societies, there exist class notations for flexibility such as *Gas Ready* (DNV GL, 2015). This class notation represents a set of predefined characteristics that enable a ship to easily change from diesel to dual-fuel, i.e., to diesel and natural gas, for propulsion. Table 2 presents examples from the industry with vessels prepared for retrofits.

Table 2: Examples of retrofittable ships in the industry (Rehn and Garcia, 2018), PSV = platform supply vessel, AHTS = anchor handling tug supply, MSV = multiservice vessel.

Vessel name	Type	Built	Retrofittability, prepared for:
Olympic Intervention IV	MSV	2008	Light well intervention tower
Olympic Zeus	AHTS	2009	250 tonnes crane
Go Matilda / Mundara	PSV	2016	Crane, remotely operated vehicle
Dina Polaris	MSV	2017	150 tonnes crane, helideck

Contrasting retrofittability, several ships are also built versatile of which there are multiple examples, as presented in Table 3. The cases presented in Table 1, 2 and 3 demonstrate the need for explicitly considering flexibility in design of non-transport vessels.

Table 3: Examples of versatile ships (Rehn and Garcia, 2018).

Vessel name	Type	Built	Versatility description
Front Striver	Oil bulk ore	1992	Can carry either dry or wet bulk
AKOFS Seafarer	Well Intervention Unit	2010	Multi-purpose offshore ship
Wes Amelie	Container ship	2011	Dual fuel engine: diesel/natural gas

3. Methodology

3.1. Overall stepwise methodology

A stepwise methodology illustrated in Figure 1 is used to investigate the relationship between flexibility and economic performance. Two main aspects of the design process are outlined: 1) generating flexible design alternatives and 2) evaluating flexible design alternatives. This is in line with the short two-stage definition of systems design by Hazelrigg (1998). The procedure in terms of searching for solutions and identifying candidate flexibilities can be described as patterned search using a simple bottom-up screening model (de Neufville and Scholtes, 2011). That means that a low-fidelity model of the system is utilized and explored with guidance from conceptual models familiar for the design team.

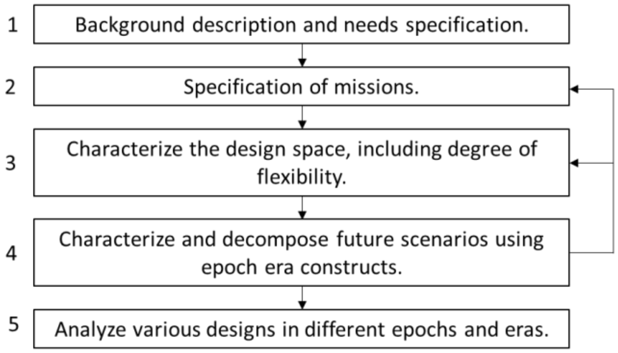

Figure 1: Proposed stepwise methodology.

3.2. Generation of flexible design alternatives

The procedure used to generate design alternatives is based on the technical requirements from the possible missions in the market. As motivated in the introduction of the paper, we are interested in investigating the design of non-transport vessels that can provide capabilities beyond the specifications of the first contract. Three cases are considered:

- **(i)** *Base case:* the vessel is optimized for the first contract.
- **(ii)** *Retrofittable:* the ship is primarily optimized for the first contract but is prepared to be retrofitted later.
- **(iii)** *Versatile:* additional multi-functionality is included in the design from the beginning.

Moreover, there are multiple nuanced design alternatives that can be retrofittable, versatile, or combinations of both. We, therefore, need a smart way to structure flexible design alternatives and measure the degree to which one alternative design is flexible compared to another.

Characterizing flexible design alternatives

A system-change can be represented by a transition between two functional states, e.g., the ship before and after a retrofit. Let us, for example, consider the case of an offshore construction vessel (OCV) with a crane, which is to be retrofitted with a large well intervention tower (LWI), as illustrated in Figure 2. Here, alternatives (i) and (ii) are retrofitted into alternative (iii). The retrofittable alternative (ii) has a moonpool (path-enabler), which makes the transition cheaper. Alternative (ii) is thus more retrofittable. A moonpool is an opening through the hull of a ship to access the water, which is required capability of the ship platform for the retrofit of well installation tower equipment. Additional path-enablers can be included, such as a pre-reinforced deck. Further, sufficient margins on the stability and deadweight of the vessel are also crucial for reducing change costs, analogous to having a *flexible base platform* (Rehn et al., 2018a). Combinations of path-enablers built into a design alternative can be explored to investigate various aspects of flexibility for an otherwise similar design solution.

Quantifying the level of flexibility for a design alternative

Quantifying the level of flexibility for a design alternative involves measuring the impact on change cost, and or change time, from the inclusion of a set of path-enablers in a design. An example of a path-enabler that reduces the cost of the retrofit installation of a light well intervention (LWI) tower on an offshore construction vessel is a moonpool. A moonpool is expensive to retrofit on an existing vessel, and a preinstalled moonpool can save about $9 million in retrofit costs, on a total cost of about $90 million (Rehn et al., 2018b). The cost of this potential retrofit can therefore be reduced by about 10%, this is however at the up-front moonpool pre-installation expense of about $1 million. This example is illustrated in Figure 2. Different aspects of quantification of flexibility level is discussed by Ross et al. (2008b) and Rehn et al. (2018b).

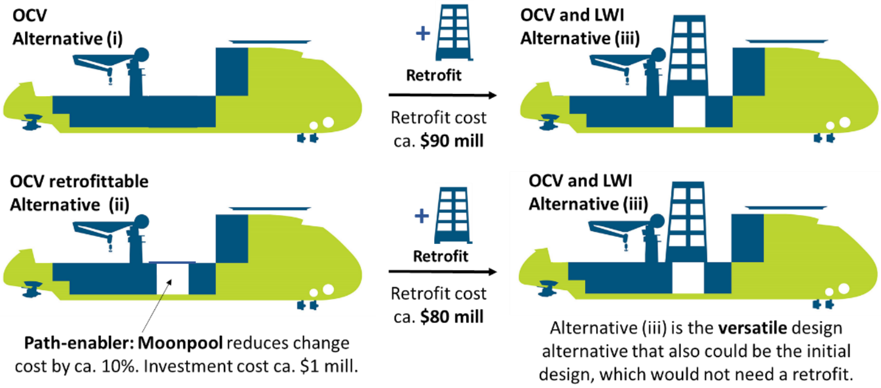

Figure 2: Flexible design alternatives, change cost illustration, OCV = offshore construction vessel, LWI = light well intervention, 500 tonnes tower installation (models provided by Ulstein International AS).

3.3. Evaluation of flexible design alternatives

3.3.1. Evaluation approach

Evaluation of flexibility is generally done using real options theory. However, traditional option pricing methods rely on several assumptions that do not necessarily hold for systems design applications. These include constructing a replicating portfolio that can be traded in an arbitrage-free market (Wang and de Neufville, 2005). When these conditions do not hold, instead of using risk-neutral "probabilities" and risk-neutral discounting, we perform "actual valuation" using *actual probabilities* and *risk-adjusted discount rates*.

3.3.2. Temporal decomposition of the planning problem

The design alternative evaluation method is decomposed mainly into two segments based on the length of the planning horizon: tactical and strategic. Strategic, tactical, and operational planning are three terms used to characterize managerial planning horizons. Strategic planning refers to decisions with long-term implications, typically from five years to multiple decades. Tactical planning refers to decisions with medium-term implications, typically from months to five years. Operational planning refers to decisions with short-term implications, typically day-to-day to months, such as a specific lifting operation. In this paper, we use scenario planning and Epoch-Era Analysis (EEA) at the long-term strategic level, and Monte Carlo simulation and optimization at the tactical level. Operational aspects are not explicitly considered in this paper. The two-level decomposition is illustrated in Figure 3. This approach is inspired by Gaspar, Erikstad, and Ross (2012). A similar decomposition is presented by Kaut et al. (2014) who call it a multi-horizon approach. Schoemaker (1991) also presents a decoupled method, using scenario planning for strategic issues, and Monte Carlo simulation at the operational level.

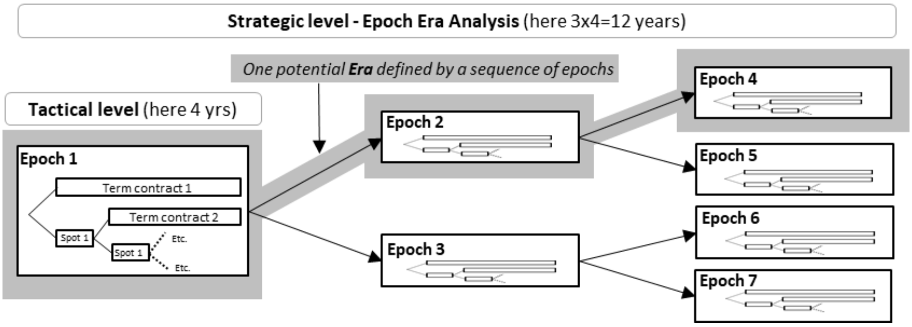

Figure 3: Planning horizon decomposition for the operational part of the lifecycle of a non-transport vessel. The long-term strategic analysis is conducted using Epoch-Era Analysis (EEA). Within an epoch, tactical planning of which contract to assign a ship to is determined, where the ship either can take "term" contracts (4 years duration) or "spot" contracts (3 months duration).

Strategic level: Epoch-Era Analysis

Epoch-Era Analysis (EEA) is used to handle the long-term contextual and temporal complexities of the operational part of the lifecycle (Ross et al., 2008a). This includes both the structuring and generating long-term futures through use of short-term epochs as building blocks for long-term eras and subsequently performing strategic analyses based on these constructs. A short-term *epoch* is a period with fixed *context and needs*, for a given level of abstraction, described by well-defined epoch variables. Long-term eras emerge when sequences of short-term epochs are assembled in time, representing the lifecycle-scenario of a system, as illustrated in Figure 3. Two main steps are thus needed to generate short-term epochs and long-term eras:

1) *Short-term epoch characterization*

   The goal of this step is to identify and parameterize uncertainties in the context and stakeholder needs. We are mainly interested in the uncertain contextual factors that can potentially affect the system success. Essential uncertainties usually originate in domains such as market, technology, and regulations. Identification of epoch variables may involve methods like brainstorming and consultation with subject matter experts. This step results in a well-defined epoch vector comprising the epoch variables, and a combination of the epoch variables will thus define an epoch.

2) *Long-term era construction*

   Long-term eras represent the operationalization of futures through the sequencing of short-term epochs, as illustrated in Figure 3 (one Era is highlighted in grey, comprising the sequence of epochs 1, 2 and 4). Eras can be developed using multiple approaches, for example using expert judgment which accounts for possible narratives, or one can use more quantitative methods. For cases with a high degree of uncertainty and complexity, narrative scenario generation in line with *scenario planning* is a recommended approach (Schoemaker, 1991). Scenario planning is a process for exploring alternative futures, where we seek to answer *"What can conceivably happen?*", and "*What would happen if…?"* (Lingren and Bandhold, 2003).

Tactical level within short-term epochs: Monte Carlo simulation and optimization

At the tactical level, within a well-defined, short-term epoch with constant contextual parameters, we quantify the economic performance of different design alternatives. To do this, we find the optimal deployment and retrofit decisions for each design alternative. That is, given the set of available contracts sampled, with specified technical requirements, we identify the most valuable decision path for a given design alternative. Since the economic performance of a design alternative may vary significantly based on the specific contract scenario sampled within an epoch, we sample multiple contract-scenarios and take the average. The tactical model is based on two main parts:

1) *Mission generation within a short-term epoch*

   Within an epoch of four years, mission scenarios are generated with a resolution of one quarter of a year. In each time step, there is a set of available contracts in the market. The contracts, each with technical requirements, market rates and durations, are sampled for each time step. This sampling is dependent on the epoch variable instance. A Monte Carlo simulation of the multiple tactical scenarios within an epoch is performed.

2) *Optimal deployment for a given contract scenario within a short-term epoch:*

   For a given contract scenario within an epoch, an optimal deployment model is solved. Deciding which contract to take, and potentially which retrofit to make is determined by a complete enumeration of the decision alternatives, of which the one with the highest net present value is chosen. Alternative strategies of operation are tested, regarding whether the ship is to be operated on spot or term contracts.

4. Case study

4.1. Step 1: Background description

The business case emerges from an expected strong demand for energy in the future, materialized through continued demand for offshore oil and gas over the next couple of decades despite recent oil price volatility. This business opportunity is targeted by a shipowner, contracting a ship first for a given four-year contract and thereafter on speculation. After the first contract ends, several missions are identified as described in Table 4. The goal of the shipowner is profitability.

First contract (M1): The first contract is an inspection, maintenance, and repair (IMR) mission, with a low technical requirement level and a duration of 4 years. The technical requirements of this contract are given in Table 4 (M1), including accommodation capacity for 50 people, remotely operated vehicles (ROV) and a deck area of 700 m^2. The first contract rate is $85 000 per day.

4.2. Step 2: Mission specification

Five mission types, each with two technical requirement levels, are identified to generate ten possible missions, as described in Table 4.

Table 4: Mission details, including technical requirements. Acc. = accommodation (ppl.), ROV = remotely operated underwater vehicles.

Mission description			**Technical mission requirements**					
Type	Number	Req. level	Tower [tonnes]	Crane [tonnes]	Acc. [ppl.]	ROV [y/n]	Deck area [m2]	Gangway [y/n]
Inspection maintenance and repair (IMR)	M1	Low	0	0	50	1	700	0
	M2	High	0	150	100	1	1000	0
Subsea installation and construction (OSC)	M3	Low	0	200	50	1	1000	0
	M4	High	0	400	100	1	1500	0
Light well intervention (LWI)	M5	Low	200	100	130	1	1000	0
	M6	High	600	300	180	1	1000	0
Field decommissioning support (ODS)	M7	Low	0	300	100	1	600	0
	M8	High	600	600	200	1	1400	0
Offshore wind support (SOV)	M9	Low	0	0	100	0	250	1
	M10	High	0	50	150	1	500	1

4.3. Step 3: Characterization of design alternatives

Three main types of design alternatives are investigated: (i) baseline, (ii) retrofittable, and (iii) versatile. The general vessel details are given in Figure 4. An overview of technical details of the nine design alternatives is given in Table 5. To ensure technical feasibility of the design alternatives, stability and structural integrity of the hull were tested. For more technical details see (Rehn et al., 2018a).

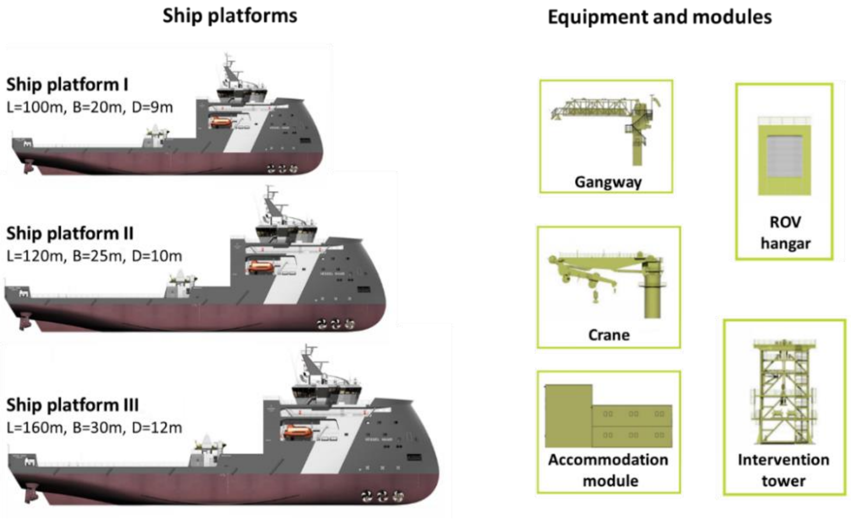

Figure 4: General ship details, decomposed into the ship platform and value-enabling equipment and modules to be placed on the ship platform which together constitute a design alternative (models provided by Ulstein International AS).

Table 5: Overview of the nine design alternatives analyzed, LOA = length overall, B = beam, D = depth, Dwt = deadweight, POB = persons on board (accommodation), LWI = light well intervention tower.

#	Name	Plat-form	LOA [m]	B [m]	D [m]	Moon pool [y/n]	Deck reinf. [y/n]	SPS code [y/n]	Dwt [ton]	Deck area [m2]	Crane [ton]	POB [ppl]	LWI [ton]	ROV [no.]	Gang-way [y/n]	Cost [m$]
A	Baseline	I	100	20	9	0	0	0	3000	1400	0	50	0	2	0	50.40
B	Retrofittable 1	I	100	20	9	0	1	0	2950	1400	0	50	0	2	0	50.42
C	Retrofittable 2	I	100	20	9	0	1	1	2950	1400	0	50	0	2	0	50.52
D	Retrofittable 3	II	120	25	10	0	1	1	4650	2450	0	50	0	2	0	64.92
E	Retrofittable 4	II	120	25	10	1	1	1	4200	2350	0	50	0	2	0	65.92
F	Retrofittable 5	III	160	30	12	1	1	1	10100	4100	0	50	0	2	0	110.6
G	Versatile 1	II	120	25	10	0	0	1	3500	2000	400	100	0	2	0	99.80
H	Versatile 2	II	120	25	10	1	1	1	3150	1650	400	200	200	2	0	137.00
I	Versatile 3	III	160	30	12	1	1	1	7050	3050	600	200	600	2	1	254.00

Alternative (i) – Baseline design

The design alternative that is optimized for the first contract (Mission M1 in Table 4) is characterized as the *baseline*. This design alternative has remotely operated underwater vehicles (ROV) and accommodation for 50 persons, but no gangway, crane, or light well intervention tower. Furthermore, it has the smallest of the three platforms outlined in Figure 4. This is because platform I can carry the equipment needed for mission M1 at the lowest investment cost. However, the small platform provides lower margins on stability and deadweight to support for retrofits for other missions later in the lifecycle.

Alternative (ii) – Retrofittable design

The retrofittable design alternatives considered are based on the baseline design in terms of immediate technical capability level (can only take contract M1) but are prepared for retrofits to satisfy a broader span of missions. The space of potential missions is defined in Table 4. What is of interest, is thus to investigate which system-characteristics (path-enablers) that can be included in the baseline design to make the future retrofits cheaper. The common denominator is that the system-characteristics collectively reduce the change cost in the event of a retrofit, at an up-front investment cost. An overview of the four identified system-characteristics enhancing retrofittability for this case study is given below.

- Deck reinforcement: Additional strength in the main deck reduces the need for additional steelwork when retrofitting equipment and, therefore, also reduces the overall retrofitting cost. The largest cost saving comes from the reduced need of labor and engineering work for the retrofit operation, as the reinforcement can be done with little additional effort during the initial design process.
- Special Purpose Ships (SPS) Code: The SPS code is required for vessels carrying more than 12 special-personnel onboard. The special-personnel can for example be crane operators, offshore technicians, and ROV drivers. In order to fulfill the SPS code, the vessel is required to comply with stricter stability and subdivision requirements. To satisfy these requirements after the initial construction of the vessel, in most cases it is necessary to add additional bulkheads and watertight doors, which can significantly increase the cost and complexity of a retrofit.
- Moonpool: A moonpool is an opening through the hull to access the water and is required (in most cases) for the installation of a light well intervention tower. A pre-installed moonpool significantly reduces the tower retrofit costs, as the retrofit of a moonpool has a high impact on the integrity of the main ship platform.
- Ship platform: The ship platform carries the value-enabling equipment and is in this case defined by the main dimensions: length overall (LOA), breadth (B) and depth (D). For a ship to be feasible, there are multiple criteria that must be satisfied, such as regarding stability and sufficient deck area and deadweight, where the platform plays a vital role.

The four characteristics described above can be included in baseline design in multiple combinations. The Design for Changeability (DFC) variable is used to structure sets of characteristics included in the design. Five alternative retrofittable designs are considered, as described in Table 6.

Table 6: Design for changeability (DFC) descriptions for the offshore case, with associated investment costs.

DFC	**DFC description**		**Total cost**	**Extra cost**
	Platform	Extra characteristics		
0	I	Baseline (none)	$50.40m	-
1	I	Deck reinforcement	$50.42m	$0.02m
2	I	Deck reinforcement and SPS code	$50.52m	$0.12m
3	II	Deck reinforcement and SPS code	$64.92m	$14.52m
4	II	Deck reinforcement, SPS code, and moonpool	$65.92m	$15.52m
5	III	Deck reinforcement, SPS code, and moonpool	$110.62m	$60.22m

To understand how much more retrofittable the combinations of characteristics make the ship, we investigate their impact on the retrofit costs. The costs for each potential equipment retrofit is given in Table 7, as a function of DFC. That is the costs of adding a piece of equipment to the baseline design (which already has accommodation for 50 people and ROV hangar). For simplicity, we assume that the main platform remains the same during the lifecycle of the ship. In Table 7, we can see that the larger platforms are needed to be able to take on the larger equipment. These numbers are estimated based on historical ship design and retrofit data.

Table 7: The retrofit cost *for the design alternatives with different design for changeability (DFC) levels, retrofit costs are based on retrofit from the baseline design, numbers in million USD.*

DFC	**Crane (from 0)**		**Tower (from 0)**		**Acc. (from 50)**		**Gangway (from 0)**
	200t	400t	200t	600t	100ppl	200ppl	Yes
0	7.50	-	-	-	2.70	5.70	4.40
1	7.30	-	-	-	2.50	5.40	4.20
2	7.30	-	-	-	1.50	4.40	4.20
3	7.30	10.40	24.60	-	1.50	4.40	4.20
4	7.30	10.40	21.60	-	1.50	4.40	4.20
5	7.30	10.40	21.60	72.20	1.50	4.40	4.20

Alternative (iii) – Versatile design

The versatility of a vessel is relatively easy to conceptualize, compared to retrofittability, as it is a static measure of the set of needs a ship can satisfy without performing any retrofits. The degree to which one design alternative is versatile can, for example, be measured by the span of possible missions that can be served. The maximum number of possible missions to serve is ten – covering all potential missions in Table 4. The baseline design alternative (i) can only serve one mission (M1). Three alternative versatile designs are considered, as described in Table 5. The span of missions that can be served for design alternative "versatile 1, 2, and 3" is five, six and ten (max) respectively.

4.4. Step 4: Characterization and breakdown of future scenarios

4.4.1. Short-term epoch construction and ship-contract allocation

Short-term epochs variables are elicited in Table 8. The complete epoch space spanned by these variables comprise 24 epochs. We assume that one epoch is of length 4 years. The first epoch, where the first term contract (M1) is manifested, is called Epoch 1 and is described in Table 8.

Table 8: Short-term epoch characterization at the strategic level.

Epoch variable	**Unit**	**Values**	**Epoch 1**
Oil price	USD/barrel	30, 80, 130	80
Competition	[-]	Low, high	High
Renewable focus	[-]	Low, high	Low
Decommission focus	[-]	Low, high	Low

Within a short-term epoch, we perform a Monte Carlo simulation to estimate the expected performance of each ship design alternative. The organization of the simulation comprises two main parts: 1) sampling multiple contract scenarios based on the overall orientation of the epoch, and 2) simulation of the managerial operation (contract-allocation) to estimate the expected economic performances of each design alternative in each epoch. The parametric details of the simulation model are calibrated based on discussions with subject matter experts. Having a realistic and well-calibrated model is obviously essential for the correct estimation of performance. However, the estimated absolute values from the model are in fact not that important for us, as we are most interested in studying the *differences between* the performances of design alternatives.

1) Contract sampling within a short-term epoch

Multiple potential contracts may exist in the market in a given time step, of which one is to be selected. A contract is a mission with an associated market rate and duration. Ten different missions are considered in this analysis, as described in Table 4. The market rate for a given contract is sampled on a scale between 10 000 USD/day and 250 000 USD/day, which is dependent on the epoch details and technical difficulty of the mission. The contract duration is either *spot* or *term*, with durations of 3 months or 4 years respectively. That means, given an epoch state described by the epoch variables, e.g., Epoch 1 in Table 8, a set of contracts for a given time-period is generated.

2) Ship-contract allocation model

A model is developed that determines the allocated contract for each time-step the ship is idle. A short-term epoch is assumed to be four years, and we use a time step of three months to be able to capture the temporal dynamics of the spot market within an epoch. We assume that the functionality requested for a mission in the spot market must be provided immediately, such that retrofits are only considered for term contracts. Unless a ship already is assigned to a term contract, the shipowner must decide in each time step whether to allocate the ship to a term contract, or a spot contract – for a given contract availability. If a spot contract is assigned, a similar decision must be made next quarter – after the spot contract is finished. Two operational strategies that dictate the market preferences of the shipowner are explored. This is done to untangle managerial complexity.

- **S1 – Term market priority:** The most profitable spot market contract is chosen.
- **S2 – Spot market priority:** The most profitable term market contract is chosen, but if there are no profitable term contracts available, the ship is offered in the spot market until a possible term contract emerges.

If there is a contract yielding a positive contribution margin, the ship will be in operation. If not, the ship will be temporarily put into layup. The contribution margin is estimated as the dayrate of the contract, minus the cost of the crew which is assumed to be $650 per day per person. We assume a discount rate of 15% in this case study, which is in line with similar industries (Kaiser, 2014). However, we note that for real applications, the choice of discount rate is highly case- and stakeholder-specific, and should be carefully estimated as the results can be highly dependent on this assumption.

4.4.2. Long-term era construction

The length of an era is assumed to be 12 years, as illustrated in Figure 3, of which the first four years are determined by Epoch 1. Thus, the different eras are described only by two subsequent epochs. Two market segments are considered for era construction: the traditional oil and gas (O&G) market, and emerging markets. Five narrative scenarios are developed, as described in Table 9. O&G is the targeted marked, of which we assume three main scenarios: (1) Petroleum upswing, (2) Business as usual and (3) Oil crisis. Two additional scenarios, describing the emerging markets are (4) Renewable revolution and (5) Decommission boom.

Table 9: Overall description of the five long-term eras considered in the analysis, and details of the two short-term epochs characterizing the era after the Epoch 1, from time period 4-8 years and time period 8-12 years.

#	**Era name**	**Description**	**Short-term Epochs (after Epoch 1)** *[oil price, competition., renew., decom.]* **4-8 years**	**8-12 years**
1	Petroleum upswing	Strong O&G market: Oil price increasing and staying high, good market conditions.	[130, low, low, no]	[130, high, low, no]
2	Business as usual	Medium O&G market: Oil price relatively stable at medium levels, medium market conditions.	[80, high, low, no]	[30, low, low, no]
3	Oil crisis	Pool O&G market: Oil price decreasing and stays low, poor market conditions.	[30, high, low, no]	[30, high, low, no]
4	Renewable revolution	Wind market emerges after five years, O&G market medium.	[80, low, high, no]	[80, low, high, no]
5	Decom. boom	Decommission market emerges after five years, O&G market poor.	[30, low, high, yes]	[30, low, high, yes]

4.5. Step 5: Design alternative evaluation analysis

The net present values (NPVs) from the first contract alone for the nine design alternatives are presented in Table 10. In the model, we assume for simplicity that the cost of the vessel occurs instantaneously at t=0. That is, the owner does not have to pay for the ship until the it is delivered and the first 4-year contract starts. The market rate for the first contract is $85 000 per day, and the crew costs for the 50 people crew is ca. $29 000 per day. The aggregated contract contribution margin from the first contract is $72.1 million, which is discounted to $51.5 million. We can see from Table 10 that design alternative A has the highest NPV from the first contract. This is as expected, as this is the ship which can satisfy the technical requirements of the first contract at the lowest investment costs. What we are more interested in, however, is what happens after the first contract has ended.

Table 10: Economic performances of the design alternatives, NPV= net present value, numbers in million USD, for the first contract with length of four years.

	Design alternative	Invest. cost	Present value of contribution margin	NPV first contract
A	Baseline	50.4	51.5	1.1
B	Retrofittable 1	50.4	51.5	1.0
C	Retrofittable 2	50.5	51.5	0.9
D	Retrofittable 3	64.9	51.5	-13.5
E	Retrofittable 4	65.9	51.5	-14.5
F	Retrofittable 5	110.6	51.5	-59.2
G	Versatile 1	99.8	51.5	-48.3
H	Versatile 2	137.0	51.5	-85.5
I	Versatile 3	254.0	51.5	-202.5

An overall representation of the economic performance of the nine design alternatives is presented in Table 11 for the term contract priority, and in Table 12 for the spot contract priority. In these tables, the present value of the contribution margins (PVCM) over the lifecycle for each era is presented, in addition to the expected present value of the contribution margin (EPVCM) over all eras, assuming equal probability for each era for simplicity. Subtracting the investment costs gives us the expected net present values (ENPVs). We also estimate the lower ten-percentile of the ENPV, which is called Value at Risk (VaR).

Table 11: Term strategy: Economic performances of the design alternatives, numbers in million USD, including the first contract., PVCM = present value of contribution margin (net revenue), EPVCM = expected net present value of contribution margin, ENPV = expected net present value, VaR = Value at Risk.

		Inv.	**Era 1**	**Era 2**	**Era 3**	**Era 4**	**Era 5**		**Total performance**	
	Design alt.	**cost**	$PVCM_1$	$PVCM_2$	$PVCM_3$	$PVCM_4$	$PVCM_5$	EPVCM	**ENPV**	10% VaR
A	Baseline	50.4	207.2	82.5	55.9	88.5	87.0	104.2	**53.8**	16.1
B	Retrofittable 1	50.4	207.2	82.6	55.9	88.6	87.1	104.3	**53.9**	16.2
C	Retrofittable 2	50.5	207.3	82.8	56.0	89.1	87.4	104.5	**54.0**	16.2
D	Retrofittable 3	64.9	410.1	122.8	61.2	113.7	113.6	164.3	**99.4**	17.3
E	Retrofittable 4	65.9	402.7	116.4	61.4	111.4	110.8	160.5	**94.6**	15.2
F	Retrofittable 5	110.6	409.8	112.1	61.5	109.3	110.7	160.6	**50.0**	-30.0
G	Versatile 1	99.8	426.7	130.4	62.4	117.7	116.1	170.7	**70.9**	-16.0
H	Versatile 2	137.0	420.0	126.9	62.9	116.0	115.3	168.2	**31.2**	-53.1
I	Versatile 3	254.0	435.4	138.0	63.3	122.2	120.8	175.9	**-78.1**	-167.7

From Table 11, presenting the results with term contract strategy, we can see is that the retrofittable design alternatives have superior expected performance, and lower downside, compared to the versatile design alternatives. The versatile design alternatives do however have higher expected income potential (measured by EPVCM), but the high up-front cost of versatility reduces their overall performance. We can also see the significant difference in income potential for the design alternatives with different platform sizes.

Table 12: Spot strategy: Economic performances of the design alternatives, numbers in million USD, including the first contract., PVCM = present value of contribution margin (net revenue), EPVCM = expected net present value of contribution margin, ENPV = expected net present value, VaR = Value at Risk.

	Design alt.	**Invest.**	**Era 1**	**Era 2**	**Era 3**	**Era 4**	**Era 5**		**Total performance**	
		cost	PVCM$_1$	PVCM$_2$	PVCM$_3$	PVCM$_4$	PVCM$_5$	EPVCM	**ENPV**	10% VaR
A	Baseline	50.4	96.0	56.4	51.7	56.2	54.5	62.9	**12.5**	2.4
B	Retrofittable 1	50.4	96.0	56.4	51.7	56.2	54.5	62.9	**12.5**	2.4
C	Retrofittable 2	50.5	96.0	56.4	51.7	56.2	54.5	62.9	**12.4**	2.3
D	Retrofittable 3	64.9	96.0	56.4	51.7	56.2	54.5	62.9	**-2.0**	-12.1
E	Retrofittable 4	65.9	96.0	56.4	51.7	56.2	54.5	62.9	**-3.0**	-13.1
F	Retrofittable 5	110.6	96.0	56.4	51.7	56.2	54.5	62.9	**-47.7**	-57.8
G	Versatile 1	99.8	333.3	98.5	53.3	87.7	70.1	128.6	**28.8**	-39.8
H	Versatile 2	137.0	357.5	106.3	53.5	93.6	73.5	136.9	**-0.1**	-75.5
I	Versatile 3	254.0	401.4	142.1	53.8	143.6	127.9	173.8	**-80.2**	-170.6

From Table 12, presenting the results with spot contract strategy, we can see that the retrofittable design alternatives do not have the same economic superiority as with the term strategy. One of the reasons for this is the agility that versatility provides, i.e., the swiftness to which a ship can change contracts. In the spot market, which is characterized by being short-term, retrofits may take too long and are thus not allowed in this mode. This explains why the income potentials (PVCM) are identical for ships with the same capabilities.

5. Discussion

The results presented in Table 11 and Table 12 indicate that retrofittability can be of significant value in design of non-transport vessels. The reason for this is the increased upside it enables as a relatively low up-front investment cost. These insights account explicitly for the multi-year (term) contracts. In the spot market, it is less obvious which type of flexibility that is better. This illustrates the operational complexity of the non-transport ship design problem, and that specific preferences of the stakeholders dictating contract preferences, e.g. risk attitude, can have significant impact on the overall economic performance. When operating in the spot market, the ship is more exposed to both downside risks and upside opportunities, and the overall performance of the design alternative is dependent on whether the ship hits a “jackpot contract,” or the market surges when the ship is idle.

In contrast to traditional transportation shipping, non-transport shipping is characterized by a heterogeneous market. That is, the contracts span a wide range of technical requirements, which make the design problem more ill-structured. As essentially no contract is similar, we encounter issues with market modeling. This is one of the reasons why we chose to decompose the scenario model and utilize narrative scenario planning on the overall strategic level. This approach increases transparency and makes it easier to understand under which conditions one design alternative performs better compared to another. Furthermore, as there exist little long-term market data, especially for the emerging markets, pure quantitative scenario modeling relying on historical data naturally becomes difficult. The proposed scenario planning model provides especially useful as it allows for exploration of extreme scenarios, and in a straightforward manner can facilitate communication between analysts and decision makers. In the expected value calculations, we assumed for simplicity that each era has the same probability of occurring. This assumption is made to help drawing clear and straightforward conclusions. For real-life considerations, a more rigorous analysis of scenario probabilities is central for making proper design decisions. Furthermore, the expected net present value (ENPV) criteria may not even be appropriate, and other measures of merit, such as payback-time, can be considered.

Regarding the method utilized to structure flexible design alternatives, we need to estimate the costs of future retrofits. However, for multiple reasons, the actual retrofit costs are uncertain. For example, the costs of occupying a shipyard to perform a retrofit can fluctuate with the general market, which is not considered in this model. Furthermore, we assume that the change cost is linearly additive for combined equipment retrofits, which is a significant simplification as there would be synergy effects of changing multiple pieces of equipment at the same time. The estimation of retrofit cost and duration may also in itself be difficult, as system-changes can propagate and have unforeseen consequences (Eckert et al., 2004). To make the change costs as accurate as possible in this case study, they are estimated based on historical ship retrofit data from Ulstein ship design company.

6. Conclusion

This paper studies the relationship between economic performance and flexibility for non-transport vessels. We focus on two aspects of flexibility: retrofittability and versatility, i.e., the ability of a vessel to satisfy diverse needs *with* or *without* change of physical form, respectively. A model is presented to study this relationship, which first generates design alternatives, before subsequently evaluating them based on their discounted economic lifecycle performance. Albeit being case specific, we conclude that retrofittability can be of significant value in design of non-transport vessels. Versatility provides income potential, but at a higher up-front cost. Retrofittability is of particular value due to the increased upside potential enabled at a relatively low up-front cost. An interesting area of research for future work could be the identification of retrofittable ship design alternatives.

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Appendix C: Previous PhD theses

Previous PhD theses published at the Departement 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-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)
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MTA-94-99	Passano, Elizabeth, MK	Efficient Analysis of Nonlinear Slender Marine Structures. (Dr.Ing. Thesis)
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MTA-95-106	Ulstein, Tore, MH	Nonlinear Effects of a Flexible Stern Seal Bag on Cobblestone Oscillations of an SES. (Dr.Ing. Thesis)
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MTA-96-110	Bratland, Anne K., MH	Wave-Current Interaction Effects on Large-Volume Bodies in Water of Finite Depth. (Dr.Ing. Thesis)
MTA-96-111	Herfjord, Kjell, MH	A Study of Two-dimensional Separated Flow by a Combination of the Finite Element Method and Navier-Stokes Equations. (Dr.Ing. Thesis)
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MTA-98-124	Hansen, Edmond, MH	A Discrete Element Model to Study Marginal Ice Zone Dynamics and the Behaviour of Vessels Moored in Broken Ice. (Dr.Ing. Thesis)
MTA-98-125	Videiro, Paulo M., MK	Reliability Based Design of Marine Structures. (Dr.Ing. Thesis)
MTA-99-126	Mainçon, Philippe, MK	Fatigue Reliability of Long Welds Application to Titanium Risers. (Dr.Ing. Thesis)
MTA-99-127	Haugen, Elin M., MH	Hydroelastic Analysis of Slamming on Stiffened Plates with Application to Catamaran Wetdecks. (Dr.Ing. Thesis)
MTA-99-128	Langhelle, Nina K., MK	Experimental Validation and Calibration of Nonlinear Finite Element Models for Use in Design of Aluminium Structures Exposed to Fire. (Dr.Ing. Thesis)
MTA-99-129	Berstad, Are J., MK	Calculation of Fatigue Damage in Ship Structures. (Dr.Ing. Thesis)
MTA-99-130	Andersen, Trond M., MM	Short Term Maintenance Planning. (Dr.Ing. Thesis)
MTA-99-131	Tveiten, Bård Wathne, MK	Fatigue Assessment of Welded Aluminium Ship Details. (Dr.Ing. Thesis)
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MTA-99-133	Tønnessen, Rune, MH	A Finite Element Method Applied to Unsteady Viscous Flow Around 2D Blunt Bodies With Sharp Corners. (Dr.Ing. Thesis)
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MTA-2000-137	Storteig, Eskild, MM	Dynamic characteristics and leakage performance of liquid annular seals in centrifugal pumps. (Dr.Ing. Thesis)
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MTA-2000-139	Tronstad, Harald, MK	Nonlinear analysis and design of cable net structures like fishing gear based on the finite element method. (Dr.Ing. Thesis)
MTA-2000-140	Kroneberg, André, MP	Innovation in shipping by using scenarios. (Dr.Ing. Thesis)
MTA-2000-141	Haslum, Herbjørn Alf, MH	Simplified methods applied to nonlinear motion of spar platforms. (Dr.Ing. Thesis)
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MTA-2001-143	Baarholm, Rolf Jarle, MH	Theoretical and experimental studies of wave impact underneath decks of offshore platforms. (Dr.Ing. Thesis)
MTA-2001-144	Wang, Lihua, MK	Probabilistic Analysis of Nonlinear Wave-induced Loads on Ships. (Dr.Ing. Thesis)
MTA-2001-145	Kristensen, Odd H. Holt, MK	Ultimate Capacity of Aluminium Plates under Multiple Loads, Considering HAZ Properties. (Dr.Ing. Thesis)
MTA-2001-146	Greco, Marilena, MH	A Two-Dimensional Study of Green-Water Loading. (Dr.Ing. Thesis)
MTA-2001-147	Heggelund, Svein E., MK	Calculation of Global Design Loads and Load Effects in Large High Speed Catamarans. (Dr.Ing. Thesis)
MTA-2001-148	Babalola, Olusegun T., MK	Fatigue Strength of Titanium Risers – Defect Sensitivity. (Dr.Ing. Thesis)
MTA-2001-149	Mohammed, Abuu K., MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
MTA-2002-150	Holmedal, Lars E., MH	Wave-current interactions in the vicinity of the sea bed. (Dr.Ing. Thesis)
MTA-2002-151	Rognebakke, Olav F., MH	Sloshing in rectangular tanks and interaction with ship motions. (Dr.Ing. Thesis)

MTA-2002-152	Lader, Pål Furset, MH	Geometry and Kinematics of Breaking Waves. (Dr.Ing. Thesis)
MTA-2002-153	Yang, Qinzheng, MH	Wash and wave resistance of ships in finite water depth. (Dr.Ing. Thesis)
MTA-2002-154	Melhus, Øyvin, MM	Utilization of VOC in Diesel Engines. Ignition and combustion of VOC released by crude oil tankers. (Dr.Ing. Thesis)
MTA-2002-155	Ronæss, Marit, MH	Wave Induced Motions of Two Ships Advancing on Parallel Course. (Dr.Ing. Thesis)
MTA-2002-156	Økland, Ole D., MK	Numerical and experimental investigation of whipping in twin hull vessels exposed to severe wet deck slamming. (Dr.Ing. Thesis)
MTA-2002-157	Ge, Chunhua, MK	Global Hydroelastic Response of Catamarans due to Wet Deck Slamming. (Dr.Ing. Thesis)
MTA-2002-158	Byklum, Eirik, MK	Nonlinear Shell Finite Elements for Ultimate Strength and Collapse Analysis of Ship Structures. (Dr.Ing. Thesis)
IMT-2003-1	Chen, Haibo, MK	Probabilistic Evaluation of FPSO-Tanker Collision in Tandem Offloading Operation. (Dr.Ing. Thesis)
IMT-2003-2	Skaugset, Kjetil Bjørn, MK	On the Suppression of Vortex Induced Vibrations of Circular Cylinders by Radial Water Jets. (Dr.Ing. Thesis)
IMT-2003-3	Chezhian, Muthu	Three-Dimensional Analysis of Slamming. (Dr.Ing. Thesis)
IMT-2003-4	Buhaug, Øyvind	Deposit Formation on Cylinder Liner Surfaces in Medium Speed Engines. (Dr.Ing. Thesis)
IMT-2003-5	Tregde, Vidar	Aspects of Ship Design: Optimization of Aft Hull with Inverse Geometry Design. (Dr.Ing. Thesis)
IMT-2003-6	Wist, Hanne Therese	Statistical Properties of Successive Ocean Wave Parameters. (Dr.Ing. Thesis)
IMT-2004-7	Ransau, Samuel	Numerical Methods for Flows with Evolving Interfaces. (Dr.Ing. Thesis)

IMT-2004-8	Soma, Torkel	Blue-Chip or Sub-Standard. A data interrogation approach of identity safety characteristics of shipping organization. (Dr.Ing. Thesis)
IMT-2004-9	Ersdal, Svein	An experimental study of hydrodynamic forces on cylinders and cables in near axial flow. (Dr.Ing. Thesis)
IMT-2005-10	Brodtkorb, Per Andreas	The Probability of Occurrence of Dangerous Wave Situations at Sea. (Dr.Ing. Thesis)
IMT-2005-11	Yttervik, Rune	Ocean current variability in relation to offshore engineering. (Dr.Ing. Thesis)
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IMT-2005-13	Heggernes, Kjetil	Flow around marine structures. (Dr.Ing. Thesis
IMT-2005-14	Fouques, Sebastien	Lagrangian Modelling of Ocean Surface Waves and Synthetic Aperture Radar Wave Measurements. (Dr.Ing. Thesis)
IMT-2006-15	Holm, Håvard	Numerical calculation of viscous free surface flow around marine structures. (Dr.Ing. Thesis)
IMT-2006-16	Bjørheim, Lars G.	Failure Assessment of Long Through Thickness Fatigue Cracks in Ship Hulls. (Dr.Ing. Thesis)
IMT-2006-17	Hansson, Lisbeth	Safety Management for Prevention of Occupational Accidents. (Dr.Ing. Thesis)
IMT-2006-18	Zhu, Xinying	Application of the CIP Method to Strongly Nonlinear Wave-Body Interaction Problems. (Dr.Ing. Thesis)
IMT-2006-19	Reite, Karl Johan	Modelling and Control of Trawl Systems. (Dr.Ing. Thesis)
IMT-2006-20	Smogeli, Øyvind Notland	Control of Marine Propellers. From Normal to Extreme Conditions. (Dr.Ing. Thesis)
IMT-2007-21	Storhaug, Gaute	Experimental Investigation of Wave Induced Vibrations and Their Effect on the Fatigue Loading of Ships. (Dr.Ing. Thesis)
IMT-2007-22	Sun, Hui	A Boundary Element Method Applied to Strongly Nonlinear Wave-Body Interaction Problems. (PhD Thesis, CeSOS)

IMT-2007-23	Rustad, Anne Marthine	Modelling and Control of Top Tensioned Risers. (PhD Thesis, CeSOS)
IMT-2007-24	Johansen, Vegar	Modelling flexible slender system for real-time simulations and control applications
IMT-2007-25	Wroldsen, Anders Sunde	Modelling and control of tensegrity structures. (PhD Thesis, CeSOS)
IMT-2007-26	Aronsen, Kristoffer Høye	An experimental investigation of in-line and combined inline and cross flow vortex induced vibrations. (Dr. avhandling, IMT)
IMT-2007-27	Gao, Zhen	Stochastic Response Analysis of Mooring Systems with Emphasis on Frequency-domain Analysis of Fatigue due to Wide-band Response Processes (PhD Thesis, CeSOS)
IMT-2007-28	Thorstensen, Tom Anders	Lifetime Profit Modelling of Ageing Systems Utilizing Information about Technical Condition. (Dr.ing. thesis, IMT)
IMT-2008-29	Refsnes, Jon Erling Gorset	Nonlinear Model-Based Control of Slender Body AUVs (PhD Thesis, IMT)
IMT-2008-30	Berntsen, Per Ivar B.	Structural Reliability Based Position Mooring. (PhD-Thesis, IMT)
IMT-2008-31	Ye, Naiquan	Fatigue Assessment of Aluminium Welded Box-stiffener Joints in Ships (Dr.ing. thesis, IMT)
IMT-2008-32	Radan, Damir	Integrated Control of Marine Electrical Power Systems. (PhD-Thesis, IMT)
IMT-2008-33	Thomassen, Paul	Methods for Dynamic Response Analysis and Fatigue Life Estimation of Floating Fish Cages. (Dr.ing. thesis, IMT)
IMT-2008-34	Pákozdi, Csaba	A Smoothed Particle Hydrodynamics Study of Two-dimensional Nonlinear Sloshing in Rectangular Tanks. (Dr.ing.thesis, IMT/ CeSOS)
IMT-2007-35	Grytøyr, Guttorm	A Higher-Order Boundary Element Method and Applications to Marine Hydrodynamics. (Dr.ing.thesis, IMT)
IMT-2008-36	Drummen, Ingo	Experimental and Numerical Investigation of Nonlinear Wave-Induced Load Effects in Containerships considering Hydroelasticity. (PhD thesis, CeSOS)

IMT-2008-37	Skejic, Renato	Maneuvering and Seakeeping of a Singel Ship and of Two Ships in Interaction. (PhD-Thesis, CeSOS)
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IMT-2008-39	Alsos, Hagbart S.	Ship Grounding. Analysis of Ductile Fracture, Bottom Damage and Hull Girder Response. (PhD-thesis, IMT)
IMT-2008-40	Graczyk, Mateusz	Experimental Investigation of Sloshing Loading and Load Effects in Membrane LNG Tanks Subjected to Random Excitation. (PhD-thesis, CeSOS)
IMT-2008-41	Taghipour, Reza	Efficient Prediction of Dynamic Response for Flexible amd Multi-body Marine Structures. (PhD-thesis, CeSOS)
IMT-2008-42	Ruth, Eivind	Propulsion control and thrust allocation on marine vessels. (PhD thesis, CeSOS)
IMT-2008-43	Nystad, Bent Helge	Technical Condition Indexes and Remaining Useful Life of Aggregated Systems. PhD thesis, IMT
IMT-2008-44	Soni, Prashant Kumar	Hydrodynamic Coefficients for Vortex Induced Vibrations of Flexible Beams, PhD thesis, CeSOS
IMT-2009-45	Amlashi, Hadi K.K.	Ultimate Strength and Reliability-based Design of Ship Hulls with Emphasis on Combined Global and Local Loads. PhD Thesis, IMT
IMT-2009-46	Pedersen, Tom Arne	Bond Graph Modelling of Marine Power Systems. PhD Thesis, IMT
IMT-2009-47	Kristiansen, Trygve	Two-Dimensional Numerical and Experimental Studies of Piston-Mode Resonance. PhD-Thesis, CeSOS
IMT-2009-48	Ong, Muk Chen	Applications of a Standard High Reynolds Number Model and a Stochastic Scour Prediction Model for Marine Structures. PhD-thesis, IMT
IMT-2009-49	Hong, Lin	Simplified Analysis and Design of Ships subjected to Collision and Grounding. PhD-thesis, IMT
IMT-2009-50	Koushan, Kamran	Vortex Induced Vibrations of Free Span Pipelines, PhD thesis, IMT

IMT-2009-51	Korsvik, Jarl Eirik	Heuristic Methods for Ship Routing and Scheduling. PhD-thesis, IMT
IMT-2009-52	Lee, Jihoon	Experimental Investigation and Numerical in Analyzing the Ocean Current Displacement of Longlines. Ph.d.-Thesis, IMT.
IMT-2009-53	Vestbøstad, Tone Gran	A Numerical Study of Wave-in-Deck Impact usin a Two-Dimensional Constrained Interpolation Profile Method, Ph.d.thesis, CeSOS.
IMT-2009-54	Bruun, Kristine	Bond Graph Modelling of Fuel Cells for Marine Power Plants. Ph.d.-thesis, IMT
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IMT 2009-57	Kong, Xiangjun	A Numerical Study of a Damaged Ship in Beam Sea Waves. Ph.d.-thesis, IMT/CeSOS.
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IMT 2010-60	Hals, Jørgen	Modelling and Phase Control of Wave-Energy Converters. Ph.d.thesis, CeSOS.
IMT 2010- 61	Shu, Zhi	Uncertainty Assessment of Wave Loads and Ultimate Strength of Tankers and Bulk Carriers in a Reliability Framework. Ph.d. Thesis, IMT/ CeSOS
IMT 2010-62	Shao, Yanlin	Numerical Potential-Flow Studies on Weakly-Nonlinear Wave-Body Interactions with/without Small Forward Speed, Ph.d.thesis,CeSOS.
IMT 2010-63	Califano, Andrea	Dynamic Loads on Marine Propellers due to Intermittent Ventilation. Ph.d.thesis, IMT.
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IMT 2010-65	Seim, Knut Sponheim	Mixing Process in Dense Overflows with Emphasis on the Faroe Bank Channel Overflow. Ph.d.thesis, IMT
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IMT 2010-67	Jiao, Linlin	Wave-Induced Effects on a Pontoon-type Very Large Floating Structures (VLFS). Ph.D.-thesis, CeSOS.
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IMT-2012-88	Dong, Wenbin	Time-domain fatigue response and reliability analysis of offshore wind turbines with emphasis on welded tubular joints and gear components, CeSOS
IMT-2012-89	Zhu, Suji	Investigation of Wave-Induced Nonlinear Load Effects in Open Ships considering Hull Girder Vibrations in Bending and Torsion, CeSOS
IMT-2012-90	Zhou, Li	Numerical and Experimental Investigation of Station-keeping in Level Ice, CeSOS
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IMT-2013-2	Kurniawan, Adi	Modelling and geometry optimisation of wave energy converters, CeSOS
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IMT-17-2013	Gaspar, Henrique	Handling Aspects of Complexity in Conceptual Ship Design, IMT
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IMT-6-2018	Bård Stovner	Aided Intertial Navigation of Underwater Vehicles
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IMT-8-2018	Børge Rokseth	Safety and Verification of Advanced Maritime Vessels
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