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Sigurd Solheim Pettersen

Resilience by Latent Capabilities in Marine Systems

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ISBN 978-82-326-3576-4 (printed version)
ISBN 978-82-326-3577-1 (electronic version)
ISSN 1503-8181

Doctoral theses at NTNU, 2018:394

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Thesis for the degree of Philosophiae Doctor

Trondheim, December 2018

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Printed by Skipnes Kommunikasjon as

Abstract

This thesis addresses the need for resilience, the ability of a system to recover from a disruption, in marine systems. It proposes to enhance resilience in the operational phase by taking advantage of latent capabilities, those capabilities that exist without neither being intended nor recognized during the design process. Marine systems like offshore support vessels are often complex, multi-functional assets, operating in a highly volatile environment. For these vessels to deliver value throughout an uncertain lifecycle, there is a need for addressing disruptions that occur during operations, and for enabling vessels to support emergency response. The topic of the thesis is motivated by the fact that not all negative events can be avoided, meaning something unforeseen will happen, and the fact that exposure to some uncertainty can be beneficial, implying opportunity rather than risk.

The research question addressed in this thesis concerns the relationship between the design characteristics of marine systems, and the ability of marine systems to recover from events that disrupt their operation or to respond to emergencies in the maritime environment. Providing additional structure to the problem situation, a set of five research objectives were formulated. These objectives are systematically met through four main articles, which document the analyses and results. Main Article 1 documents the ill-structured problem in early-stage ship design, starting from application of systems engineering methods for managing future uncertainty in design of offshore support vessels. Main Article 2 introduces the latent capabilities concept and connects it to resilience by using a function-form mapping model. Building on the case of Apollo 13, the article concludes in opposition to axiomatic design, seeing functional dependence as an enabler of resilience. Main Article 3 applies latent capabilities as an enabler of emergency response provided by advanced offshore support vessels. It uses the Deepwater Horizon case to argue for latent capabilities in the offshore industry and discusses key advantages and challenges to exploiting latent capabilities. Main Article 4 extends latent capabilities to the fleet level using fleet deployment to measure effectiveness, beyond what can be captured in ship design analyses.

The outcome of the research is an improved understanding of the relationship between design characteristics and the ability of marine systems to recover or to be recovered after unforeseen events. This is documented through five contributions: First, an industrial case study produced insights to design of advanced offshore vessels. Second, a conceptual framework for latent capabilities was developed. Third, models that relate latent capabilities to resilience were outlined. Fourth, a methodology was developed for assessment of latent capabilities in contingency planning, drawing on the modelling insights and a review of mission reports. Fifth, a deployment model captures the emergence of latent capabilities on the fleet level by measuring effectiveness beyond what is obtainable through single ship performance measures.

In conclusion, the research question is answered by adding to the overall knowledge about the relationship between latent capabilities and system resilience. Latent capabilities can contribute to enhanced resilience by enabling exploitation of functionality a system was not originally intended for. Hence, once new needs emerge, resources exist that can be used to resolve them. This requires that challenges for utilization of latent capabilities, including technical, operational, commercial and organizational factors, can be identified. While such factors have been identified in this work, further quantification of their relative importance is needed, before a methodology for assessment of latent capabilities is mature.

Preface

This thesis is submitted for partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD) in Marine Technology at the Norwegian University of Science and Technology (NTNU).

The work was carried out between August 2015 and August 2018, primarily at the Department of Marine Technology at NTNU in Trondheim. The research was supervised by Professor Bjørn Egil Asbjørnslett. My co-supervisors were Professor Stein Ove Erikstad and Professor Kjetil Fagerholt.

The research was funded by the Department of Marine Technology through several research projects funded by the Norwegian Research Council, and through additional funding to support teaching activities and research assistant tasks. In addition, Statoil and Anders Jahre's Grant funded my attendance at several conferences.

The target audience for this research is academics and practitioners with an interest in systems design and engineering, ship design, maritime logistics, operations management, risk assessment, and decision-making under uncertainty.

Acknowledgements

This thesis would not have been initiated, and could never have been finished without the guidance, support and inspiration of numerous people.

First, Professor Bjørn Egil Asbjørnslett has been my supervisor for the last three years. I am grateful he decided to fund my initial position as a research assistant, and for supervising my PhD work. Thank you for the great advice and all the thoughtful discussions along the way. Further, I would like to thank my co-supervisors Professor Stein Ove Erikstad and Professor Kjetil Fagerholt. Stein Ove supported my participation in the SIMOSYS case study. Stein Ove also supervised my MSc thesis three years ago and was the first to suggest that I do a PhD. Kjetil contributed with his knowledge of operations research applied to maritime problems and assisted with model development.

Carl Fredrik Rehn and Jose Jorge Garcia were my two close research collaborators. We worked together for the SIMOSYS project, co-wrote multiple papers, and became good friends. I thank you for sharing this great learning experience in Trondheim and at workshops in Ulsteinvik and Boston. Carl and I shared an office for three years, and ideas about research, technology, economics and so on, constantly bounced back and forth in that room. Jose works as a business analyst at Ulstein, and so he always helped out with data and industry insights when necessary.

From the industry side, I would like to thank Professor II and Ulstein International deputy managing director Per Olaf Brett. Per Olaf contributed with several decades of experience from the maritime industry, always took time to read and carefully comment on my paper drafts, and was never afraid to remind me not to get swamped in too-abstract theory. Ali Ebrahimi and Andre Keane at Ulstein International also deserve thanks for sharing their insights from marine business analytics.

At MIT, I would like to thank Donna Rhodes and Adam Ross for inviting and guiding us through the world of systems engineering at MIT. Thank you for including Carl, Jose, and myself in the SEAri community. Among SEAri students, Parker Vascik and Mike Curry deserve thanks for sharing their ideas on implementation and visualization of tradespace exploration results.

I would also like to thank the guys from the Marine Technology class of 2015 who stayed at Tyholt to do their PhDs: Emil Smilden, Pål Takle Bore, Henrik Schmidt, Øyvind Dalheim, Ole Alexander Eidsvik, John Martin Godø, Jan Vidar Ulveseter, and Jan-Tore Horn. Minjoo Choi, Martin Bergström, Endre Sandvik, and Hans Tobias Slette worked on related topics within optimization- and simulation-based design. I thank you for the interesting discussions.

Among the master students at the Department of Marine Technology, classes of 2017 and 2018, I want to thank Marius Buland, Ole-Johan Nekstad, Morten Strøm, Carsten Christensen, and Emil Høie for taking an interest in ship design subject to future uncertainty. Co-supervising your work was always a pleasure and I learnt a lot from that.

I would like to thank my family, mother Eli, father Thomas, and my brothers Øystein and Sverre, for their encouragement. Finally, I would like to thank Gunhild for her support, and for staying with me in Trondheim.

Table of contents

List of figures

List of tables

List of publications

Main articles

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, Vol. 34, No. 1, 2018, pp. 72-83.

Exploiting latent functional capabilities for resilience in design of engineering systems
Pettersen, S. S., Erikstad, S. O., & Asbjørnslett, B. E.
Research in Engineering Design, Vol. 29, No. 4, 2018, pp. 605-619.

Latent capabilities in support of maritime emergency response
Pettersen, S. S., Garcia, J. J., Rehn, C. F., Asbjørnslett, B. E., Brett, P. O., & Erikstad, S. O.
Submitted to Maritime Policy and Management.

Evaluating fleet effectiveness in tactical emergency response missions using a maximal covering formulation
Pettersen, S. S., Fagerholt, K., & Asbjørnslett, B. E.
Resubmitted after revision to the Naval Engineers Journal.

Supporting papers

Designing resilient fleets for maritime emergency response operations
Pettersen, S. S, & Asbjørnslett, B. E.
Proceedings of the 23rd EurOMA Conference, EurOMA 2016, Trondheim, Norway.

A design methodology for resilience in fleets for service operations
Pettersen, S. S, & Asbjørnslett, B. E.
Proceedings of the 13th International Symposium on PRActical Design of Ships and Other Floating Structures, PRADS 2016, Copenhagen, Denmark

Redefining the Service Vessel Fleet Size and Mix Problem Using Tradespace Methods
Pettersen, S. S, Buland, M. O., & Asbjørnslett, B. E.
Proceedings of the 29th Annual Nordic Logistics Research Network Conference, NOFOMA 2017, Lund, Sweden.

Design for resilience: Using latent capabilities to handle disruptions facing marine systems
Pettersen, S. S, Asbjørnslett, B. E., Erikstad, S. O., & Brett, P. O.
13th International Marine Design Conference, IMDC 2018, Helsinki, Finland, Trondheim, Norway.

Book chapters

Designing Resilience into Service Supply Chains: A Conceptual Methodology
Pettersen, S. S, Asbjørnslett, B. E., & Erikstad, S. O.
In Khojasteh, Y. (ed), 2018. Supply Chain Risk Management: Advanced Tools, Models, and Developments. Springer.

Assessing the vulnerability of supply chains: Advances from engineering systems
Pettersen, S. S., & Asbjørnslett, B. E.
In Zsidisin, G., & Henke, M. (ed), 2018. Revisiting Supply Chain Risk (forthcoming). Springer.

List of abbreviations

ABD	Accelerated Business Development
AHTS	Anchor Handling, Tug, Supply vessel
AIS	Automatic Identification System
CoG	Center of Gravity
C-K	Concept-Knowledge
DoD	United States Department of Defense
DSV	Diving Support Vessel
EEA	Epoch-Era Analysis
FBS	Function-Behaviour-Structure
FSA	Formal Safety Assessment
FVA	Formal Vulnerability Assessment
GoM	Gulf of Mexico
HRO	High Reliability Organization
IEEE	Institute of Electrical and Electronics Engineers
IJME	International Journal of Maritime Engineering
IMO	International Maritime Organization
IMDC	International Marine Design Conference
IMR	Inspection, Maintenance, and Repair
INCOSE	International Council of Systems Engineering
LWI	Light Well Intervention
OCV	Offshore Construction Vessel
OR	Operations Research
OSV	Offshore Support Vessel
MIT	Massachusetts Institute of Technology
NAT	Normal Accident Theory
NTNU	Norwegian University of Science and Technology
PSV	Platform Supply Vessel
RINA	Royal Institution of Naval Architects
RO	Research Objective
ROV	Remotely Operated Vehicle
RSC	Responsive Systems Comparison
SE	Systems Engineering
SEAri	Systems Engineering Advancement Research Initiative
SURF	Subsea, Umbilicals, Risers, and Flowlines

List of symbols

A	Design mapping matrix
B_e	Expected behavior
B_s	Evaluated behavior
CN	Customer needs
CN^L	Latent customer needs
CN^M	Manifest customer needs
C_R	Cost of recovery
DP	Design parameters
F	Failure profile
FR	Functional requirements
FR^L	Latent functional requirements
FR^M	Manifest functional requirements
I_{Total}	Information content of a system
R	Recovery profile
R_e	Resilience
Q_f	Performance at completely manifested disruption
Q_i	Performance pre-disruption
Q_r	Performance post-recovery
S	Structural description
T_e	Time at the end of the planning horizon
T_f	Time of completely manifested disruption
T_i	Time of disruptive event initiation
T_r	Time of completed recovery
ΔQ_r	Permanent performance degradation $(Q_i - Q_r)$
ΔT	Time between disruptive event initiation and completed recovery $(T_r - T_i)$
ΔT_f	Time between completed recovery and completely manifested disruption $(T_r - T_f)$
ΔT_r	Time between disruptive event and completely manifested disruption $(T_f - T_i)$

1. Introduction

The maritime industry is essential for the global economy (Stopford, 2009). Marine transportation is indispensable for the functioning of global trade. Marine natural resources constitute a large amount of our energy supply, including offshore oil and gas, and renewables. Additionally, the fisheries provide an incredibly important food source. The engineered marine systems that are essential for these industries, including ships and floating offshore structures, are capital-intensive systems that operate in a volatile environment characterized by disturbances with the potential for highly detrimental consequences. The ability of ships, floating structures, and higher-level marine systems like fleets to perform their function, are therefore greatly affected by uncertainty.

Uncertainties facing the maritime industry range from contextual factors that develop according to trends like the market state, technology, regulations, and the physical operating environment (Erikstad & Rehn, 2015; Thanopoulou & Strandenes, 2017), to sudden-onset disruptions of marine supply chains and other complex marine operations (Berle, Rice, & Asbjørnslett, 2011), including humanitarian crises, maritime warfare, and natural disasters. This thesis will mainly address the latter types of uncertainty; mostly concerning factors that have an adverse effect on value delivery. Doing this, we may enable recovery in marine systems after operational disruptions, and enable actors in the maritime industry to take advantage of business opportunities that arise from detrimental disturbances that affect the environment.

Sudden onset events that hurt the functioning of complex engineering systems or disrupt the environment have increasingly received attention over the years (Perrow, 1999; Sheffi, 2005; UN/ISDR, 2005). The failure of marine engineering systems, both due to accidental events, or intentional action by malevolent agents, have had immense consequences for humans and for the ocean environment. Further, most major cities are located close to the seafront, or along major rivers, making them exposed to natural disasters, like hurricanes, flooding, and tsunamis. With the current fear of changing climates, rising sea levels, and increasingly extreme weather, major population centres are becoming increasingly vulnerable. The sea then represents both a substantial hazard, something we need to protect, and an enabler of a maritime response to crises. Examples that illustrate the importance of considering such matters include the Deepwater Horizon accident and subsequent Macondo oil spill (Graham et al., 2011), and situations like the recent refugee crisis in the Mediterranean sea (Cusumano, 2017).

According to its most common definition, risk is a triplet of scenario, probability, and consequence (Kaplan & Garrick, 1981), often simplified to the product of probability and consequence (Rausand, 2011). The word "risk" itself has its roots in the maritime domain. In ancient Greece, *rhizikon* described "difficulty to avoid in the sea" (Skjong, 2005). Later, in Renaissance Italy, *risicare* took on the meaning "to dare" (Bernstein, 1998), reflecting the willingness of merchants to send ships into the unknown (Heckmann, Comes, & Nickel, 2015).

For engineering systems, the main objective of risk management is mitigation, meaning that the focus is on reducing the likelihood of accidents (Rausand, 2011). This remains the state-of-practice throughout maritime and land-based industries today. For example, Vinnem (2011) concludes for the offshore industry in the North Sea that preventive measures need to be prioritized over emergency response. Still, over the years, several theories have emerged within and outside of the engineering domain, to address certain limitations of this perspective on uncertainty. First, it is necessary to realize that not all negative events can be avoided and that some things not considered in our model of the world (unforeseen), will happen. Second, it is necessary to realize that exposure to some types of uncertainty, opportunities rather than risks, can be beneficial.

Regarding the first point, normal accident theory (Perrow, 1999) proposes that for highly complex, coupled systems, it will be impossible to successfully mitigate risks, due to our inability to understand how system elements interact. In turn, some accidental events will be "normal", meaning unavoidable. Wildavsky (1988) comes to a similar conclusion regarding the trade-off between investing in avoidance of events and investing in mechanisms for coping with the consequences of events. He argued for increased investment in capabilities that enable recovery, rather than investing in further efforts to mitigate risk beyond what is effective. In relation to risks in finance, Taleb (2007) calls events that escape risk models "black swans". These events are characterized by fat-tailed distributions; they occur very infrequently, escaping human recognition and historical records alike, but carry massive consequences. Similarly, Sheffi (2005) argues that a key competitive advantage in a complex and changing world is to become resilient, able to recover or bounce back from events that disrupt engineering systems. Regardless of risk management practice, something unexpected will occur. Hence, being positioned to better cope with the unexpected, may lead to improved business outcomes.

Instead of seeking only to avoid or to cope with every source of uncertainty, a shipping company may benefit from positioning itself to take advantage of uncertainty. In maritime economics, the benefits of servicing multiple markets using the same ship are addressed by measures like "lateral cargo mobility" defining the variety of cargoes a ship can transport (Stopford, 2009). The shipping literature also adopts financial real options analyses to quantify the value of adapting to new modes of operation when the market changes (Sødal, Koekebakker, & Ådland, 2008). In systems engineering, similar insights have led to considerable attention being given to the "ilities", properties that enable sustained value delivery through the system lifecycle (de Weck, Roos, & Magee, 2011; McManus & Hastings, 2006). While "ilities" like reliability have been considered for a long time, and are very well-defined (Rausand & Høyland, 2004; Saleh & Marais, 2006), recent focus has been on "ilities" improving the exposure to upsides, rather than protect against downside risks. These include aspects with design implications, like changeability (Fricke & Schulz, 2005), and attempts to quantify (Ross, Rhodes, & Hastings, 2008) or value flexibility (de Neufville & Scholtes, 2011). While modularity and flexibility have had a significant impact on systems design, the sudden onset disruptions we will focus on in this thesis often demand an immediate response, meaning that a search for ways to reconfigure the system physically become ineffective. The key then becomes to exploit opportunities in the operational phase, by using existing physical resources.

In practice, the question for system managers facing functional failures, accidents, and other situations that require rapid response, will be: "What resources do we have available that can be useful for recovering functionality from this disrupted state?" or "What functional resources do we have available that can be useful to provide a response to this emergent need?" Hence, the purpose here is *not* to suggest how the "ilities" can be addressed in the design phase, for example by designing ships to be flexible or modular. Rather, the purpose is to understand how marine engineering systems can rise to the occasion and provide support during disturbances, and enable recovery from a disrupted state by utilizing the designed system in a new way. The "ility" that best describes this is "resilience" (Asbjørnslett & Rausand, 1999; Weick & Sutcliffe, 2007; Woods, 2015). Hence, the use of that word in the title. Resilience implies that we enable the system to respond to and recover from disruptive events (Sheffi, 2005), and requires an approach where stakeholders monitor operations and adapt system functionality as required as the system state and environment changes (Woods, 2015). Creating resilience can hence become a question of continually designing better operations by utilizing the existing system form, rather than designing a new system. This "operational design" to achieve system resilience is design only in the broad sense described by Simon (1996) as turning the current state into an improved state. To clarify, in this thesis we will limit the use of "design" to describing what is done (in the design phase) to synthesize a physical form that meets a set of functional requirements and customer needs (Hubka & Eder, 1988; Pahl & Beitz, 1996).

History provides numerous examples where fleets of vessels have entered modes of operation beyond the preconceived intent and recognition of their designers. Common to these situations is that the critical question becomes not "what to design to meet the emerging need?" but rather "what resources do we have available?" Some examples from military logistics, humanitarian relief, and emergency response are presented and put into a historical context below:

- **Second World War (1940 – 1945):**
  During the Second World War, the Norwegian government in exile managed to requisition large parts of the Norwegian merchant fleet. The fleet was put under the management of a governmental organization known as Nortraship (Rosendahl, 2015).
- **Falklands War (1982):**
  During the Falklands War, the United Kingdom military logistics effort was supported by "Ships Taken Up From Trade", which ensured the sufficient capacity to transport weaponry, ammunition, vehicles, and personnel ("Logistic Support for Operation Corporate," 1982).
- **Persian Gulf War (1990 – 1992):**
  During Operation Desert Storm, the United States Military relied on maritime transportation services from US- and foreign-flagged carriers that were chartered in, due to a huge demand for capacity, and difficulties activating the US Ready Reserve Fleet (Wilkinson, 1993).
- **Haiti Earthquake (2010):**
  In the aftermath of the Haiti Earthquake, humanitarian aid was supplied on commercial carriers contracting for example with the US military. The support of roll-on, roll-off carriers was important due to the failure of unloading equipment in port (Berle, Spens, & Asbjørnslett, 2012).
- **Deepwater Horizon accident (2010):**
  The Deepwater Horizon accident and subsequent oil spill from the Macondo well, lead to a response in which vessels collaborated towards performing operations related to oil recovery and well containment (British Petroleum, 2010).
- **Operation Triton (2014 – 2016):**
  During the Mediterranean refugee crisis, commercial vessels have been redeployed to engage in rescue services through Operation Triton, including platform supply vessels (Cusumano, 2017).

Similar to these motivating examples, the recent industry report “Think Ocean” produced by the Norwegian Shipowners’ Association (2018) highlights the importance of leveraging existing maritime capabilities, particularly those of the Norwegian fleet, for emergency preparedness. Their recommendations are especially applicable to the development of the offshore industry in the Arctic, where very little emergency infrastructure exists. The following observation is made in the report (Norwegian Shipowners’ Association, 2018):

> *“Due to its global presence and the number of ships, the fleet represents a formidable emergency preparedness resource for the Norwegian authorities and their allies. In order to contribute to global maritime security, and Norway’s ability to exploit the fleet as an emergency preparedness asset, improved contingency plans and a comprehensive strategy are needed.”*

This communicates the importance of leveraging vessels for purposes outside their intended modes of operation. After Merton's (1968) concept of “latent functions”, we adopt the term “latent capability” to address the fact that maritime engineering systems can contribute to a wide range of services without these being representative of the “intended or recognized” functioning of the marine engineering system at the design stage. “Latent capabilities” then constitutes a counterpoint to “manifest capabilities”, those capabilities that the system was explicitly designed for.

The existence of latent capabilities signify that it is possible to effectively respond to, and recover from disruptions by reliance on some latent function, a function that exists without being intended nor recognized by the designers. Latent capabilities may exist in systems at several levels of analysis, justifying investigations through the hierarchy of technical systems (Hubka & Eder, 1987), from the fleet perspective taken in the examples above, and down through the ship level to the subsystems that exist on a vessel. The role of a system may change depending on the configuration of a fleet as a whole, as a result of failures disrupting its intended functioning, or as a result of changes in the operating environment. This may then spur changes in what behaviours the stakeholders see as desirable, and what functions the system performs (Crilly, 2015).

To incorporate the managerial and social aspects that enable an organization to effectively exploit latent capabilities, the thesis will take an engineering systems perspective. An excellent introduction to engineering systems is presented by de Weck et al. (2011). A key change this perspective represents is that an engineering system should be seen as an adaptive and evolving system, rather than as a product of a design process alone (Park, Seager, Rao, Convertino, & Linkov, 2013). This mindset breaks with much of the engineering design discipline but fits very well with key attributes associated with system resilience, such as the importance of organizational sensemaking and operational improvisation in the face of the unknown (Grøtan, 2014; Woods, 2015).

The remainder of the introductory chapter outlines the research problem in further detail, gives a presentation of the main articles with corresponding contributions, limits the scope of the study, and presents a structure for the remainder of the thesis.

1.1. Research problem

Building on the background presented, an underlying goal of this thesis is to understand *what* enables marine engineering systems to recover *after* a disturbance, and to build knowledge about how this can be accomplished. Hence, the overall research question for this thesis is:

> *"What is the relationship between characteristics designed into marine systems, the ability to recover from operational disruptions, and the ability to respond to swiftly emerging demands?"*

This formulation focuses on the *relation* between the *characteristics* of a marine system and the *ability* to address sudden-onset demands from both *inside* and *outside* the system boundaries. First; by *characteristics,* we refer to the fundamental means we use to describe and interpret a marine system; "what needs does the vessel serve?", "what functionality does the vessel rely on to fulfil the need?", and "what are the physical parameters that describe the ship?". Note that the investigations in this thesis will encompass systems at several levels of analysis, ranging from subsystems, via systems, to systems-of-systems. Second; by the ability to *recover from disruptions of operation*, we address *what* will be needed to recover from the loss of intended functionality. Third; by the ability to *respond to swiftly emerging demands*, we address the connection between what will be the demands given a rapidly changing system environment, and the *characteristics* above. In a sense, this clarification highlights two major courses for the research: We will answer the research question by addressing both i) *system-internal disruptions* and ii) *system-external, sudden-onset emergencies*. Figure 1 captures these high-level concepts and the relationships that represent the overall research question.

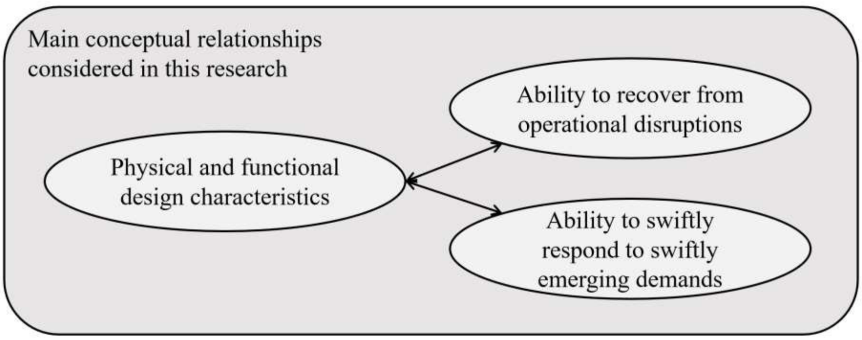

Figure 1: Main conceptual relationships addressed in this thesis.

The research scope is defined further by a set of research objectives, which are specifically addressed through the analyses and results that are found in the main articles. The following research objectives (ROs) address the research question:

RO 1 Explore challenges in the ship design problem that arise due to *future uncertainty* and differing *stakeholder expectations*.

RO 2 Develop a *conceptual* framework for characterizing latent capabilities enabling enhanced system resilience.

RO 3 Investigate the *relationship* between *latent capabilities*, and *axiomatic design* theory.

RO 4 Investigate the design *characteristics* that enable complex service vessels to generate value in unconventional emergency response missions.

RO 5 Develop a *deployment* model that effectively captures fleet performances relating to *emergency response* not captured during ship design.

1.2. Contributions

The following contributions of the PhD thesis represent the outcome of the work after meeting the research question and the research objectives. The five contributions of the thesis are shortly presented here:

C 1 An industrial *case study* from the design of advanced *offshore support vessels* with *multiple stakeholders under uncertainty*.

C 2 A *definition* and *characterization* of latent functions and *latent functional capabilities* for engineering systems.

C 3 *Models* that demonstrate how *latent functional capabilities* can enhance *system resilience*.

C 4 A *methodology* for identification, assessment, and contingency planning for *latent functional capabilities*.

C 5 A new *measure of fleet effectiveness* that captures emergence of *latent functional capabilities* on the system-of-systems level.

1.3. Overview of main articles

The main articles of this PhD project are summarized in a series of papers, as shown in Table 1. Each of the main articles bridges the gap between research objectives and contributions. Besides the main articles, which are published in, or submitted to journals, several supporting papers have been presented at conferences. Detailed discussions of every research objective and contribution are added in Chapter 4 of the thesis.

Table 1: Overview of the main articles.

Paper ID	Paper title	Publication
Main Article 1	Ill-structured commercial ship design problems: The Responsive Systems Comparison Method on an Offshore Case	*Journal of Ship Production and Design*
Main Article 2	Exploiting latent capabilities for resilience in engineering systems	*Research in Engineering Design*
Main Article 3	Latent capabilities in support of maritime emergency response	Submitted to *Maritime Policy and Management*
Main Article 4	Evaluating fleet effectiveness in tactical emergency response missions using a maximal covering formulation	Resubmitted after revision to the *Naval Engineers Journal*

Main Article 1 explores challenges of future uncertainty and different stakeholder expectations (RO 1), and develops a case study that documents the actual design process for offshore support vessel design (C 1), as well as triggering RO 2 and RO 3 by the proposition that development of decision support models is a design problem by itself. The case study that was used in Main Article 1 is documented in further detail in Appendix C.

Main Article 2 develops the conceptual framework for latent capabilities in relation to resilience (RO 2) and investigates the relationship between latent capabilities and the design axioms (RO 3). The article contributes with definitions and characterizations of latent functions and latent capabilities (C 2), it presents the latent function concept in a function-form mapping model (C 3) and proposes the first steps towards a methodology for latent capabilities assessment (C 4).

Main Article 3 adds to the conceptual framework for latent capabilities characterization (RO 2), by revisiting the system architecture of offshore support vessels and illustrating how the characteristics of these vessels make them particularly fit to contribute in emergency response missions (RO 4). The article contributes further towards the same contributions as Main Article 2 (C 2 – C 4). As Main Article 3 is not constrained by the focus on axiomatic design, the contribution towards a methodology for latent capabilities assessment (C 4) is improved.

Main Article 4 presents a deployment model that seeks to optimize how well given fleet alternatives cover a given area, meeting RO 5. Hence, it enables measurement of fleet effectiveness going beyond what can be considered at the single ship level. The deployment model presented can be used for decision support, but also shows how interaction effects that emerge on the fleet level can add value beyond what is perceived during design. Hence, Main Article 4 contributes to C 3 and to C5.

1.4. Limitations

In order to meet the research objectives, the following delimitations are made: First, as this research is concerned with theoretical and conceptual constructs, it provides a limited level of detail with respect to the modelling of specific phenomena, compared to much other engineering research. Second, in terms of a typical engineering system lifecycle, we consider only the design stage and the operations stage. Implications for production and disposal are not considered. Third, we will limit the research to considering what is often referred to as special vessels, which as opposed to vessels that transport goods, "go to sea to do something" (Andrews, 2018). Still, some motivating examples from transportation will be used. Special vessels that "go to sea to do something" include offshore support vessels (OSVs), and naval vessels. The main case for much of the research process has been offshore support vessels, as seen from Main Article 1 and Main Article 3 in particular. Fourth, the scope is largely limited to cases from emergency response. This was chosen as emergency response represents a complicated set of operations, with rapidly evolving needs. Even though the research considers disruption risks and emergencies, the treatment of reliability engineering and engineering risk analysis is very limited, due to the focus on how we can plan and adapt for what to do *after* events occur. Still, reference is given to several major contributions in the risk literature that consider the need for response and recovery. Fifth, the relationship between the current research and human factors research remains largely unexplored, beyond some high-level discussions about the role of humans and organizations in enabling latent capabilities.

1.5. Structure of the thesis

The remainder of this thesis is structured as follows: **Chapter 2** presents a review of the relevant literature. The literature review spans engineering design generally, marine systems design specifically, the literature on function modelling and latent functionality, the literature on resilience in engineering systems, and the literature on maritime contingency planning. **Chapter 3** presents the research design, positioning this thesis with respect to research methodology and research methods, and outlines the research process. **Chapter 4** revisits the research objectives, presents the results and contributions of the research. The main articles are presented and mapped to the research objectives and the contributions. **Chapter 5** discusses the results and contributions. Key implications for academics and practitioners interested in engineering systems are discussed. **Chapter 6** concludes and presents recommendations for future work.

A glossary is presented in Appendix A, documenting key concepts and definitions used in the thesis. **The main articles** that constitute the primary documentation of the results are provided in Appendix B. **A case study** on advanced offshore support vessel design that elucidated much of the early thesis work, particularly in Main Article 1, is presented in Appendix C.

2. Literature review

This chapter reviews the literature that influenced and informed the development of this thesis. A wide literature has been consulted, spanning from engineering design and marine systems design and operations to fields like systems engineering, operations management, and operations research. The review moves through the two lifecycle phases considered in the thesis; the design phase and the operational phase. Section 2.1. and Section 2.2. treats design, whereas Section 2.4. and Section 2.5. treats operations, with an emphasis on handling disruptive events. Section 2.3. connects concepts from design and operations by studying the existing literature on concepts similar to latent capabilities, as well as giving a base of examples of that concept.

2.1. Foundations of systems design

Design is a fundamental, purposeful human activity that aims to improve existing conditions, turning them into preferred ones (Simon, 1996). Humans have designed since pre-historic times, and marine design dates back to the first dugout canoes at least 40 000 years ago. Still, from a scientific point of view, the discipline of *design* is often seen as immature when compared to engineering *analysis* (Eekels & Roozenburg, 1991; Simon, 1996; Suh, 1990). Engineering *analysis* is closely linked to natural *science*. Where *science* attempts to find out "what is", *design* answers "what ought to be" (Simon, 1996). As design depends heavily on preference, Asimow (1962) makes the preliminary conclusion that there cannot really exist objective criteria for evaluating concepts. Similarly, Archer (1979) positions design relative to both science and the humanities. Designing holds both the creative freedom associated with the arts, while constrained by the laws of nature, economics and stakeholder requirements. Compared to the opening statement of this paragraph we limit *design* to concern situational improvements in which the final product is a description of a physical system. In accordance with Hubka & Eder (1987) we define *engineering design* in the following manner:

> *"Engineering design is a process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that this technical system meets the requirements of mankind."*

The definition above requires that we define what a technical system is. We define a technical system, following Hubka & Eder (1988), as an artefact resulting from a production process, and as the physical form by which humans achieve needs. Technical systems are hence limited in scope to a narrow view of function and form, on which we concentrate in this chapter. Adding to the technical, we will in this thesis discuss engineering systems, which are defined to incorporate additional social and managerial aspects (de Weck et al., 2011). In the engineering systems domain, systems evolve through their lifecycle, experiencing changes in their mission, function and form. Hence, concepts like the "ilities", resilience and latent capabilities become important when taking an engineering systems perspective. Still, to ground the concepts in systems design, we limit the scope in this section to technical systems, with minor reflections on the implications of lifecycle changes. Table 2 presents a taxonomy of technical systems according to their complexity, extending the generic taxonomy for technical systems proposed by Hubka & Eder (1988) to account for examples of marine systems.

Table 2: System characterization according to degree of complexity (based on Hubka & Eder (1988)).

Level of complexity	**Technical system**	**Characteristics**	**Marine examples**
I (simplest)	Component	Elementary parts whose manufacturing does not include assembly.	
II	Mechanism, sub-assembly	Parts consisting of a number of components, contributing to simple functions.	
III	Machine, equipment	Systems that perform a closed function.	Propulsion system, marine machinery, topside equipment (cranes, winches, etc).
IV	System	System that encapsulates different machines, equipment, and sub-systems, each fulfilling a function towards a common "functional and spatial unity" (Magee & de Weck, 2004).	Ship, marine structures, subsea systems, etc.
V	Super-system, system-of-systems	Higher-order systems, due to the existence of common functional unity across several Level IV systems, possibly with operational and managerial independence (Maier, 1998).	Fleet, marine transport system, offshore oil and gas infrastructure, etc.

This thesis will revolve around the three highest level of this hierarchy, ranging from that of machines, equipment, and subsystems, to the system or ship level, and on to the super-system, system-of-systems or fleet level. The subsystem level is commonly addressed in mechanical design, and often approached via the methods outlined in this section. The system level, at which ships are examples, incorporates additional complexities that has lead to a significant literature which is reviewed in the next section. The system-of-systems level, at which our marine equivalent is that of a fleet of vessels, is characterized by additional emergence, and by a functional, but not physical unity. Literature concerning the fleet level includes the fleet size and mix problem and some of the emergency response literature in operations research, fleet effectiveness analyses in naval ship design, and systems-of-systems engineering. We will return to systems-of-systems in several later sections in the review.

2.1.1. Systems design as a mapping process

Systems design is a process of mapping between design domains (Coyne, Rosenman, Radford, Balachandran, & Gero, 1990; Pahl & Beitz, 1996; Suh, 1990). Starting from the "ends", or needs, the role of the designer of a technical system like a ship is to identify the "means" that produce the behaviours that provide the needs (Hubka & Eder, 1988). In marine systems design, the "means" will constitute a ship or other marine system. Figure 2 introduces the design task as a mapping between three design domains. The design process closes once we have produced a description of form and function that satisfy the needs.

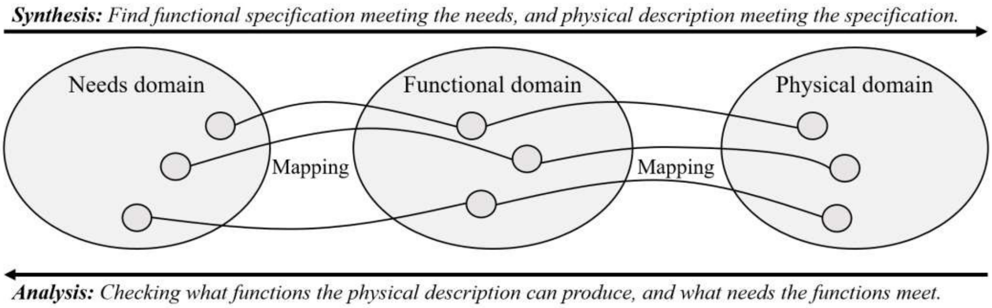

Figure 2: The design process as a mapping between domains.

The design domains are briefly explained below:

1. **The needs domain** accounts for stakeholder needs. This encompasses the objectives and goals that the system is to achieve or the "ends". These needs relate strongly to the business opportunities in current and future markets.
2. **The functional domain** includes the performances or behaviours that are instrumental to meet what was determined in the needs domain. Functions can both be defined as what the system does, or what the system should do (Eckert, 2013). In a design process, we are obviously interested in defining what the system should do. The functions of the system are often stated in terms of processes and operands, which are the objects the process works on (de Weck et al., 2011). Generic processes include transformation, transportation, and storage. Generic operands include matter, energy, and signals (Pahl & Beitz, 1996). Hence, a function will often be presented as a combination of a verb and a noun (Hirtz, Stone, McAdams, Szykman, & Wood, 2002; Pahl & Beitz, 1996). Figure 3 shows a simple example of a functional structure with operands and relations between subfunctions.
3. **The physical domain** refers to descriptions of the form that shall perform the functions. The outcome of the design process is a description of some technical artefact or collection of artefacts that can produce the desired behaviours.

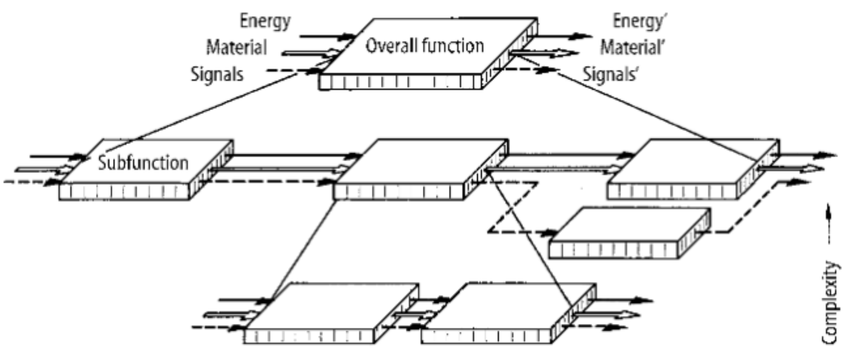

Figure 3: Functional structure of a system with basic operands (Pahl & Beitz, 1996).

In relation to Figure 2, the design process is initialized in the needs domain. The design process progresses with defining the functions and describing the physical form that is to achieve the functions. This process is called synthesis. Synthesis builds upon existing knowledge by combining units of information (e.g. subsystems that can deliver subfunctions) in a new way and seeks to provide the overall desired functionality by creating more complex structures from simpler ones (Simon, 1996). In its simplest representation, a systematic design process can then be defined to consist of the following four phases (Pahl & Beitz, 1996):

1. **Task clarification** elicits the needs the system should meet, including the definition of the tasks it should perform. This serves to inform the selection of requirements, and identification of constraints. The outcome of this step is a specification.
2. **Conceptual design** defines a principle solution by identifying essential problems in the design, establishes functional structures, searches for solution principles, combines into concept variants, and performs a preliminary evaluation.
3. **Embodiment design** develops a layout in the physical domain, based on the outcome of the conceptual design phase. The designer further optimizes the design description, while checking against technical and economic considerations.
4. **Detail design** refers to the process where final considerations are made. This stage mainly documents the description, so that production can commence.

This model follows the synthesis of the mapping model from Figure 2 closely. Task clarification primarily considers how stakeholder needs can be translated into a high-level functional specification. Conceptual design develops the high-level functional specification and maps from the functional structure into a physical system description. In the conceptual design phase, Pahl & Beitz (1996) recommends the use of design catalogues that document the cumulative knowledge about the mapping from function to form, from the physical sciences and previously proven concept solutions to specific functions.

2.1.2. Synthesis and analysis in design

There are naturally numerous loops between the tasks of the process defined by Pahl & Beitz (1996), partially due to the incomplete knowledge base at the beginning of a design process, the need for balancing system options, or the need for correcting erroneous decisions (Wynn & Eckert, 2017). Knowledge in a design context can be defined as a statement about the mapping between facts (Coyne et al., 1990), embedded for example in design catalogues or mathematical expressions relating function to form.

Opposite to the prescriptive Pahl & Beitz' model of design described above, descriptive design models comment on the deviation between intended and actual performances (Finger & Dixon, 1989). The deviation between intended and actual performance makes design a process that needs to iterate between the tasks of analysis, synthesis, and evaluation (Asimow, 1962). Central descriptive design models address the need for iteration as a means for knowledge generation. Examples include the Function-Behavior-Structure (FBS) model (Gero, 1990; Gero & Kannengiesser, 2004), Formal Design Theory (Braha & Reich, 2003), and Concept-Knowledge (C-K) theory (Hatchuel & Weil, 2009). The FBS model (Gero, 1990) differentiates between the intended and observed behaviours by introducing two transformations. First, the physical structure S will produce a set of behaviors B_s, that can be found by analysis, hence the transformation $S \rightarrow B_s$. Second, the expected behaviors B_e that should produce the desired functions F are found by the transformation $F \rightarrow B_e$. Evaluation is needed to verify that a proposed description S produces behaviors B_s that are sufficiently close to B_e. The processes of analysis, synthesis and evaluation in design are illustrated in Figure 4.

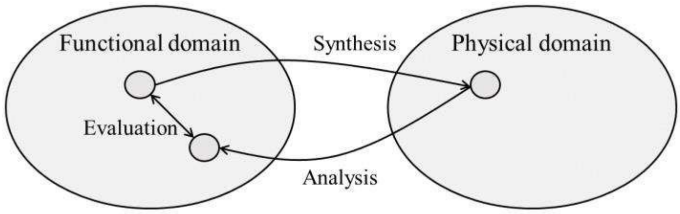

Figure 4: Analysis, synthesis, and evaluation in the function-form mapping.

Formal design theory and C-K theory focus on the need for an expandable knowledge base in design. Formal design theory (Braha & Reich, 2003) is a mathematical framework for the refinement of functional specifications and physical solutions. Braha & Reich (2003) present a generic design model, and use topological structures to model synthesis and analysis in the design process, addressing the complex interplay between function and form, given limited knowledge about resulting performances. C-K theory (Hatchuel & Weil, 2009) iterates between a knowledge space that expands from an initial knowledge basis, as a design concept is developed in the concept space. The starting point is an incomplete design brief in the concept space and an expandable knowledge base in the knowledge space. Hatchuel & Weil (2009) describe design as a process that generates increasingly more well-defined solutions and an expanding knowledge base.

Coyne et al. (1990) address analysis and synthesis in relation to fundamental modes of reasoning. All problem solving, either using existing knowledge, or for deriving new knowledge, is based on the application of one of three inference processes; deduction, induction, and abduction. A taxonomy of these reasoning modes is presented in Table 3.

Table 3: Deduction, induction, and abduction in engineering design.

Reasoning process	**Input**	**Output**	**Example of problem statement**
Deduction	Case (Fact) Rule (Knowledge)	Result (Inferred fact)	"Calculate the metacentric height of the given ship form".
Induction	Case (Fact) Result (Inferred fact)	Rule (Knowledge)	"Determine the underlying relationship between ship form and resistance".
Abduction	Rule (Knowledge) Result (Inferred fact)	Case (Fact)	"Create a ship form with the desired stability and resistance".

Deduction underlies analysis and evaluation in design. Consider the case of a ship form whose stability we wish to evaluate. If we know the parameters that describe the ship form, we can apply the rules of hydrostatics to calculate the ship metacentric height, which we then compare to a design criterion for the desired metacentric height. Induction takes a "case" and a "result" to derive a "rule". Therefore, inductive reasoning is the basis of an empirical study to develop the relationship between a design description and its behaviours.

A fundamental problem in design is that it employs a mapping from one functional specification to a large number of good physical descriptions that could meet that functional specification. Synthesis applies abductive reasoning when making the one-to-many mapping from function to form (Coyne et al., 1990). To create a ship description that meets its desired behaviours in terms of speed, operability and functional capabilities, is an abductive reasoning process. Through this process, a set of rules, derived from deductive and inductive reasoning, are utilized. These rules constitute a knowledge base for design, encompassing relations between function and form.

2.1.3. Axiomatic design

Axiomatic design was presented as a means to develop a more scientific design discipline in "The Principles of Design" (Suh, 1990). It was extended towards other applications later, including production and manufacturing, organizations, and design of large-scale systems (Farid & Suh, 2016; Suh, 2001).

Axiomatic design suggests that good design practice is founded on two axioms that dictate how designers should map between the design domains. Suh (1990) uses the terms "functional requirement", and "design parameter" to distinguish the functional and physical domains, respectively. He outlines two design axioms, the independence axiom, and the information axiom:

1. **The independence axiom:** The functional requirements of the design should be independent.
2. **The information axiom:** The information content of the design should be minimized.

Equation 1 is a generic design matrix mapping between functional requirements (FR) and design parameters (DP), where A describes the relationship between the FRs and DPs. The shape of the mapping matrix $\boldsymbol{A}$ determines whether the independence axiom is met. When A takes on the form of the identity matrix, the independence axiom is met. If this is the case, an adjustment of a DP will affect only its corresponding FR.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ 0 & A_{22} & 0 \\ 0 & 0 & A_{33} \end{bmatrix} \cdot \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{1}$$

In the case that no uncoupled design can be devised, designers should seek a decoupled design. That is one in which adjustment of one DP affects multiple FRs, but the unintended impact of adjusting the DP on an FR can be offset by subsequently adjusting another DP. The decoupled design is shown in Equation 2.

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & 0 & 0 \\ A_{21} & A_{22} & 0 \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \cdot \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{2}$$

All design matrices that do not follow the structure of either Equation (1) or Equation (2) are coupled. In a coupled design, the sequence of adjustments of DPs does not matter, as the interactions will interfere with a number of FRs regardless of how the DPs are tweaked. If a proposed design for a system initially is coupled, the system should be redesigned into a decoupled system. A coupled design matrix is provided in Equation (3).

$$\begin{bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \cdot \begin{bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{bmatrix} \tag{3}$$

Similar thoughts regarding functional independence are also found in the application of design structure matrices to facilitate clustering of tasks in project management, or clustering of components contributing to the same function within the same module in a system architecture (Eppinger & Browning, 2012). Evidence supporting structural and functional independence is offered by empirical studies that apply design structure matrices to analyse change propagation due to design changes (Clarkson, Simons, & Eckert, 2004).

The second design axiom should be sought after functional independence has been secured. According to the second axiom, minimization of information content should be used as the criteria to select among a set of alternatives. The information content in design is a common measure of complexity used in engineering design, as proposed by Kolmogorov (1983). The reason is that a simpler design is more likely to meet all functional requirements. The total information content of a design is calculated according to Equation (4). Here, I_{Total} is the total information content, p_n is the probability of meeting functional requirement n.

$$I_{Total} = \sum_{n=1}^{3} \log_2 \left(\frac{1}{p_n} \right) \tag{4}$$

Equation (4) implies that the probability of meeting functional requirements decreases with increasing information content. The basic idea of Equation (4) is that the more information we need to describe a system, the harder it will be to understand, and hence to design. This notion is also found in other theoretical work on design complexity. For example, Braha & Maimon (1998) make the distinction between structural complexity and functional complexity. They define structural complexity as the information describing the number of parts and interactions between them. They define functional complexity similar to Equation (4). There is also a close connection to Taguchi's robust design, as illustrated by Bras & Mistree (1995), who combine Suh's design axioms with measures of design robustness and tolerances. The relationship to robust design is also commented on by Suh (2001) in the interpretation of the probability of meeting functional requirements.

Axiomatic design exemplifies a larger literature that attempts to address problems with system complexity in engineering design. According to Perrow, (1999), the general argument for designing complex systems is simply that a complex system can produce outcomes that cannot be achieved by simpler means. Similar to the second axiom, many authors point to design complexity as problematic, as it makes deviations between intended and actual performance more likely (Braha & Bar-Yam, 2007; Braha & Maimon, 1998; Gero, 1990). Recent efforts to understand complexity goes further in the direction of situating systems according to their operating context and the stakeholder preferences (Gaspar, Rhodes, Ross, & Erikstad, 2012; Magee & de Weck, 2004; Rhodes & Ross, 2010), or the complexities of the design and development process (Braha & Bar-Yam, 2007; Eppinger & Browning, 2012; Gero & Kannengiesser, 2004).

An axiomatic perspective on the challenges of meeting the design axioms given changing contexts and needs is provided by Suh (1999). An extended overview of theorems resulting from the axioms is presented in Suh (2001), including propositions for large-scale, flexible systems that will need to meet changing FRs. Some of these propositions have positive implications for flexible systems. For example, it is commonly accepted that functional independence leads to flexibility (Clarkson et al., 2004; Eppinger & Browning, 2012; Fricke & Schulz, 2005). Furthermore, such flexible systems need not be "infinitely" flexible, if there is a bounded number of sets of FRs to meet. By implication, if the number of sets of FRs is unknown, situations may occur in which the chosen design no longer meets the design axioms (Suh, 2001).

2.1.4. Decision-making models in systems design

The one-to-many mapping employed in design demands that evaluative procedures are employed, not only to verify that we reach the desired performances but also to verify that the chosen alternative is among the better alternatives (Hazelrigg, 1998; Papalambros & Wilde, 2000). The latter can be achieved through the use of decision analysis and optimization, as proposed as early as the 1960's (Asimow, 1962; Simon, 1996). For design problems, the decision makers often care about a multitude of design characteristics, making these *multi-attribute* decision problems (Ross, Hastings, Warmkessel, & Diller, 2004; Thurston, 1991). Multi-attribute utility functions are especially attractive if economic measures of merit like net present value are difficult to reliably define for the problem at hand; as in the case of non-commercial decisions like those faced by governmental organizations (for example in the design of naval vessels). For guidelines on how to structure a hierarchy of system objectives, see the following five characteristics of such a hierarchy (Keeney & Raiffa, 1993):

- **Completeness**, representative of all important aspects
- **Operational**, possible to measure
- **Decomposable**, meaning that it can be broken down and analyzed as a hierarchy
- **Non-redundant**, suggesting that attribute should not be counted twice
- **Minimal**, meaning that the number of attributes should be kept small.

The use of decision-making models we will cover can further be parsed into two main categories; design optimization, and concept exploration. These categories respectively reflect what has been referred to as *selection* problems, and *compromise* problems (Mistree, Smith, Bras, Allen, & Muster, 1990). According to Coyne et al. (1990), the formulation of an optimization problem *reduces* the abductive one-to-many mapping problem of design, by interpreting design performances in terms of a design specification, developing a model. This is similar to arguments made by Rittel & Webber (1973) in their definition of the *wicked problem,* Ackoff's (1979) distinction between a *problem*, which can be *solved* e.g. by mathematical programming, and a *mess*, which can never be *solved* but only repeatedly *resolved*, and by Simon (1973) in his definition of the *ill-structured problem*. Providing such problems with a well-defined structure implies a reduction of their complexity, by defining stopping rules in the search for solutions, and by prioritizing among stakeholder interests (Goel & Pirolli, 1989). Furthermore, Arrow's Impossibility Theorem proves that groups of more than three individuals exhibit *intransitive preferences*[1], meaning that it is impossible to guarantee an

[1] Intransitive preferences are exhibited when the following condition is observed: $A \succ B \succ C$, but $C \succ A$, where $\succ$ implies "preferred to". For an individual, this preference structure is considered irrational according to utility theory (Hazelrigg, 1998). For a group, intransitive preferences can result even though each individual has transitive preferences.

optimal solution to a design problem where members of a group share decision-making power (Hazelrigg, 1998). Papalambros & Wilde (2000) outline four steps that constitute design optimization:

1. Select a set of design variables describing the alternatives, in the *physical domain*.
2. Select objectives to minimize or maximize in the *needs domain*, expressed by causal relations with the design variables.
3. Determine constraints on combinations of design variables, delimiting a *physical* design space.
4. Finding the optimal values of the design variables.

While design optimization aims to solve the selection problem, tradespace or concept exploration constitutes an alternative means to provide insight. The exploration process is similar to the design of experiments, applied in statistics and system simulation for the evaluation of alternative parameter configurations (Box & Liu, 1999). Exploration methods aim to increase our understanding of compromises arising in design, by evaluating and visualizing the design space in a scatter plot with different objectives along the axes and identifying Pareto optimal alternatives (Ross et al., 2004). The exploration process mitigates early fixation on single design alternatives and contributes to delayed decisions to later stages in the design process when more knowledge is available (Erikstad, 1996).

Tradespace exploration has been taken into a complete system development methodology that takes future uncertainty regarding context and stakeholder needs into account, by Ross, McManus, Rhodes, Hastings, & Long (2009). Their method is called Responsive Systems Comparison and combines concept exploration with epoch-era analysis (Ross & Rhodes, 2008). Epoch-era analysis combines performance assessment in static, short-run scenarios based on the parametrization of possible contexts, *epochs*, and dynamic, long-run scenarios, *eras,* constituting sequences of *epochs*. In principle, the approach to planning for the uncertain future offered by epoch-era analysis is more akin to scenario planning, than a probabilistic approach (for example Monte Carlo simulation or stochastic programming), even though the epoch-era framework easily extends to considering probabilities and path-dependencies between design decisions and options for changes of functionality later in the lifecycle.

2.1.5. Summary of design theory

Engineering design is a mapping process from stakeholder needs, to functions, to a description of the system. The output of the design process is the physical system and a plan for how the system should be operated according to its function. Due to system complexity, there will often be deviations between the desired and the actual performances delivered by the system. There are limitations to the degree to which design methods consider what systems actually end up doing in the operational phase.

The systems design literature supports the elucidation of the relationship between Research Objective 1 and Contribution 1 by grounding the case study from offshore ship design in design theory. For this, decision-based design perspectives are particularly influential. Axiomatic design is addressed specifically by Research Objective 3 and supports modelling for Contribution 2 and 3. A partial refutation of the design axioms results in Contribution 2. The function-form mapping model introduced in axiomatic design is used as a basis for modelling the relationship between resilience and latent capabilities in Contribution 3.

2.2. A review of marine systems design

The main unit of analysis in this PhD project is the marine system, both as an integral structure; the ship, and as a collection of constituent ships; the fleet. Hence, we review the literature that addresses ship design, and fleet size and mix. While the general design literature provides insights that are applicable in marine systems design, there is a substantial literature documenting domain-specific challenges for ship design.

2.2.1. Ship design methodology

The Evans-Buxton-Andrews design spiral is the common starting point for reviews of the ship design literature. In its original conceptualization (Evans, 1959), the design spiral starts from the general arrangement as given by ship owner, reducing the role of the naval architect, or ship designer, to analyzing and balancing weights, volumes, powering, ship lines, and so on. It puts little emphasis on synthesis, and the mapping from needs, via functions, to ship form. Rather, the original conceptualization of the design spiral is more focused on the analyses that go into balancing the subsystems of the ship and calculating the performances. Several later sources also present visualizations of the design spiral. The version presented by Andrews (1981) is shown in Figure 5.

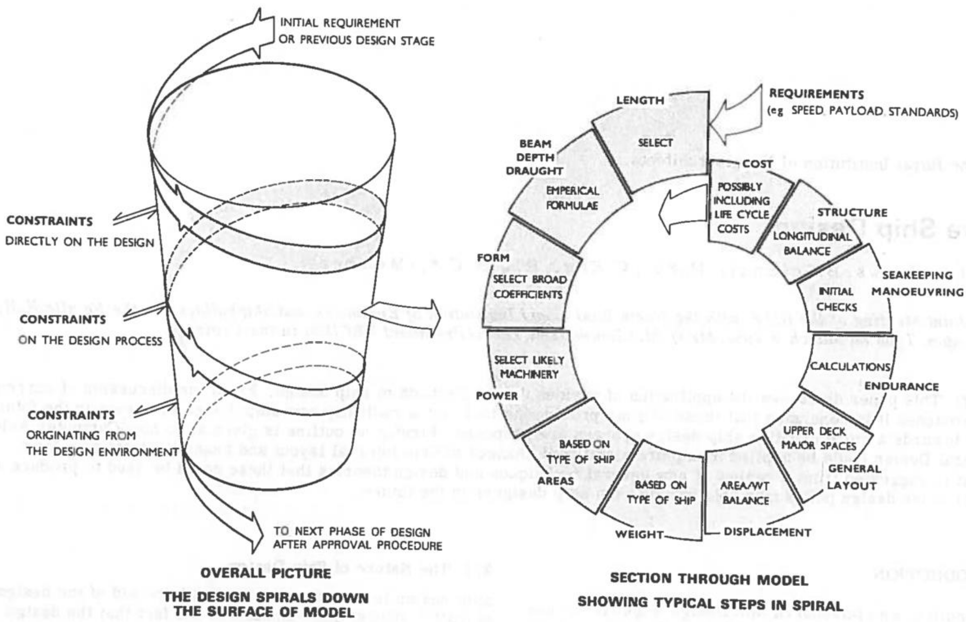

Figure 5: The Evans-Buxton-Andrews ship design spiral (Andrews, 1981).

The original spiral published by Evans (1959) has been criticized for its lack of considerations beyond structural engineering, and for its swift convergence to one solution, which is then refined and detailed. Later iterations of the design spiral put a larger emphasis on design synthesis and creativity (Andrews, 1981), and the establishment of ship dimensions on basis of transport needs and engineering economics (Benford, 1967; Buxton, 1972). Several articles written in the 1960's and 1970's on ship design methodology reflect changes in the type of decisions ship designers were involved in (Lamb, 1969; Mandel & Chryssostomidis, 1972;

Watson & Gilfillan, 1976). Among key themes were the role of updated vessel statistics, and the increased computing power, for both synthesis, optimization and concept exploration. For early perspectives on the opportunities and risks associated with computer-based ship design, see Andrews (1981, 1986). For a review of the advances from the first 50 years of computer-aided ship design, see Nowacki (2010). He presents an alternative instantiation of the processes in ship design, as shown in Figure 6. This process overview illustrates key tasks related to the generation of alternatives, use of various existing ship data, and a final evaluation.

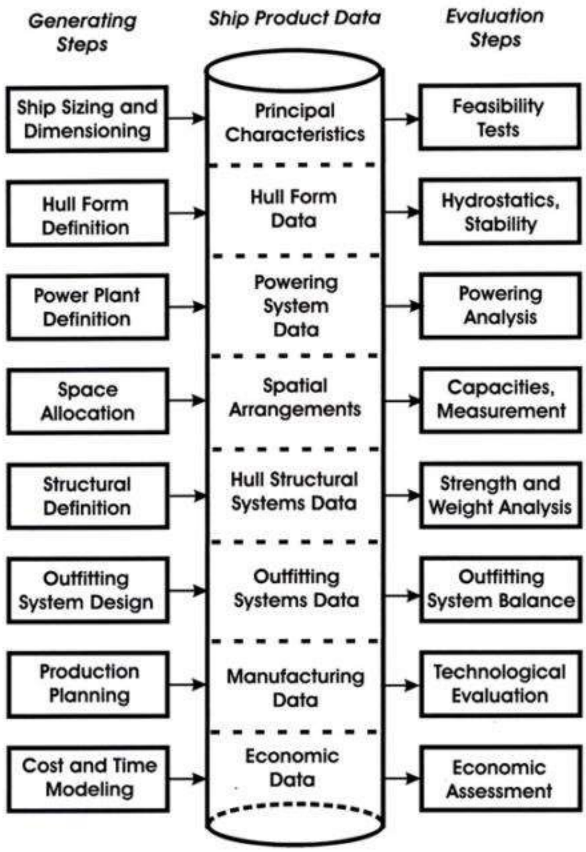

Figure 6: Key steps in a ship design process (Nowacki, 2010).

System-based ship design (Erikstad & Levander, 2012; Levander, 2012) have adopted the philosophy of systematic design as presented by Pahl & Beitz (1996). The system-based design makes use of design catalogues that document costs, volumes and weight required for specific ship functions. Synthesis is then achieved by combining these volume blocks within the ship form. The ship main dimensions are found by use of statistics collected from vessel databases. The early-stage design is hence contingent on balancing the internal required volumes and weights, within the constraints set by hull form. In system-based ship design, the design spiral commences once a ship concept is available. The layout for the system-based ship design methodology is shown in Figure 7. A notional functional breakdown from an application of system-based ship design to offshore support vessels is shown in Figure 8.

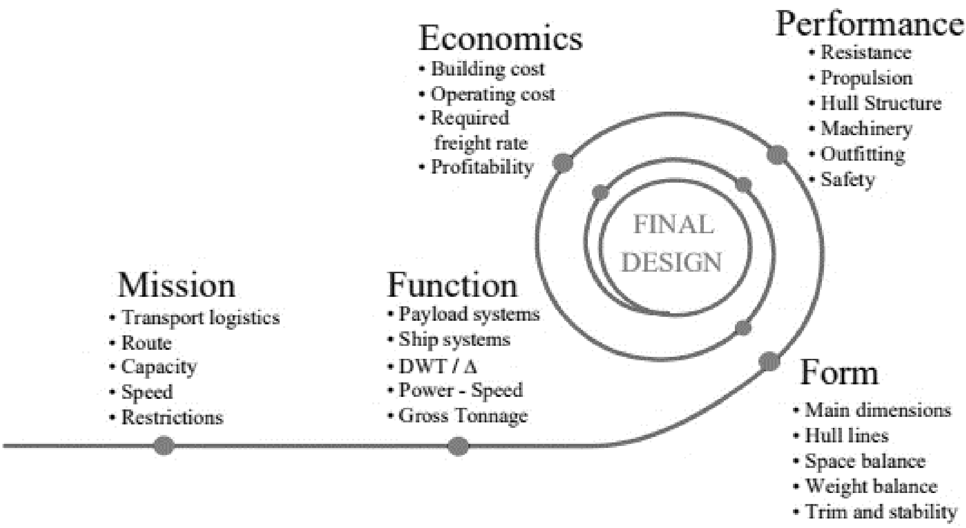

Figure 7: The system-based ship design process (Levander, 2012).

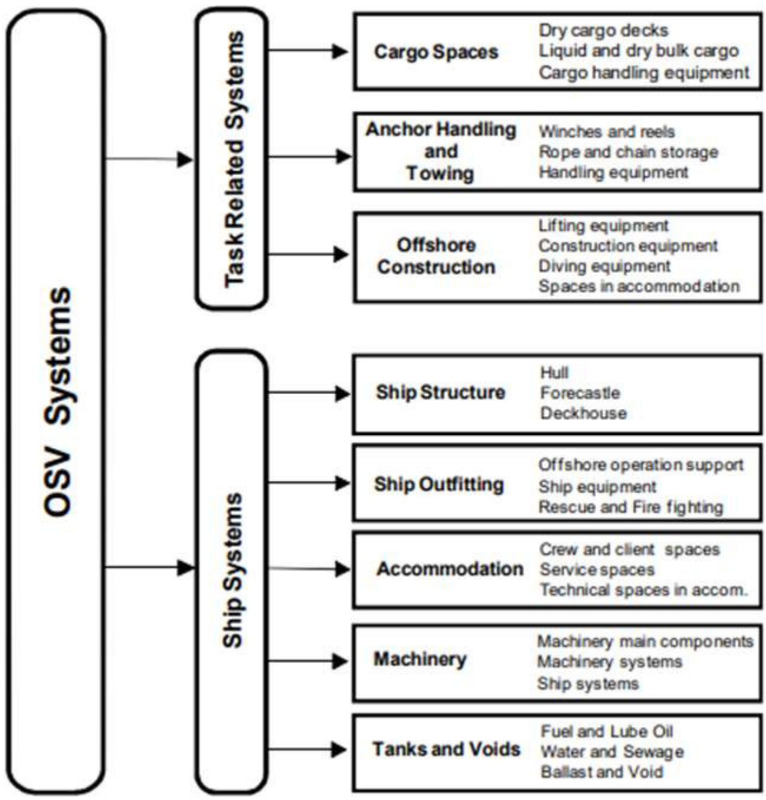

Figure 8: Functional breakdown of offshore vessels in system-based ship design (Levander, 2012).

The design building block methodology (Andrews, 1998, 2012) addresses the inherent difficulty of solving the “wicked problem” of ship design, after Rittel & Webber's (1973) work on planning, and emphasizes that ship design is considerably more complex than many engineering design problems. Andrews (1998) points out that marine systems design in some respects is more like architecture, reflected by the term “naval architecture”, as ships also act as human habitats. Further, ships are subject to more complex procurement processes, where many ships are one-off designs, and seldom are replicated. The building block approach, like system-based ship design, makes use of functional building blocks that are attached to possible volumes, for synthesis. The task of balancing functional building blocks within the ship hull becomes very difficult as specific configuration changes may lead to changes in vessel performance. This makes it particularly hard to match the desired performance with actual performance.

Addressing this, Andrews (2011) counters the idea that a “physically large and complex system” like a ship, could be developed through application of “requirements engineering”, where functional requirements are defined in an abstract manner. “Requirements engineering” has been proposed within systems engineering, and had some impact on naval ship design. Instead of that approach, Andrews (2011) favours “requirements elucidation”, in which a more pragmatic approach to functional requirements is taken. Rather than fixing functional requirements, and then developing the ship, requirements will be subject to change as the layout of the vessel is determined. This is a difficulty for design methods that attempt to develop requirements independent of form, including the V-model in systems engineering and to an extent the Pahl & Beitz (1996) method. For an analogy to task complexity in product development more generally, see Braha & Bar-Yam (2007). Some of the tasks in the concept design phase according to the building block approach, are provided in Figure 9.

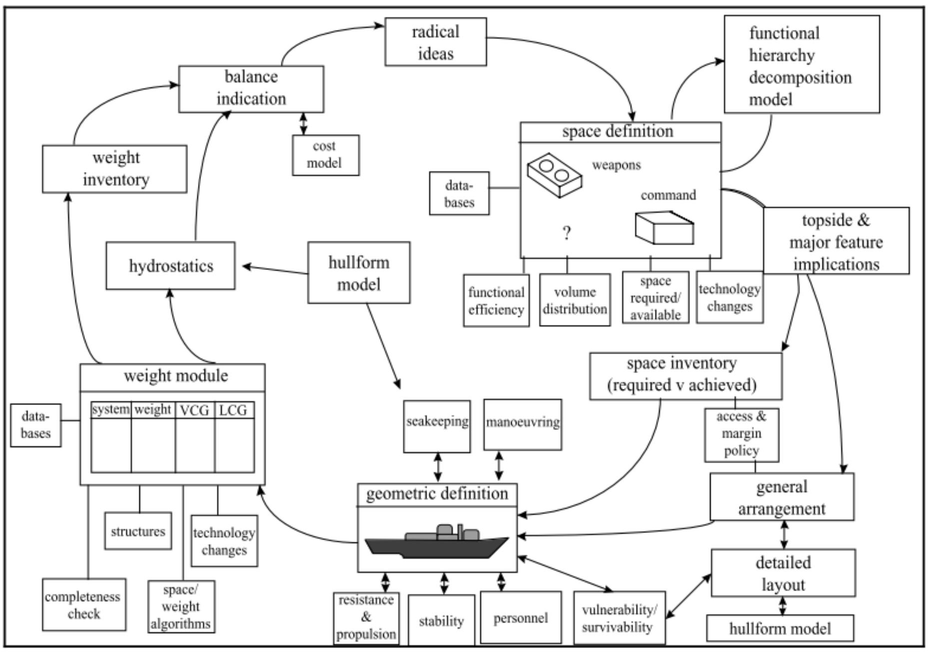

Figure 9: Ship design considerations in the design building block methodology (Andrews, 2006).

An important part of the conceptual ship design phase is concept exploration, which is applied before more focused concept studies and synthesis are instigated (Andrews, 1998). Concept exploration becomes a means for ship designers to acquire more knowledge before making committed decisions (Erikstad, 1996; Singer, Doerry, & Buckley, 2009). As seen from Figure 9, understanding of complex trade-offs in early-stage ship design is essential to properly balance ship capabilities. Concept exploration was proposed by Mandel & Chryssostomidis (1972), as a means to identify the most interesting alternatives. Concept exploration is somewhat related to the set-based design methodology proposed by Singer et al. (2009). Set-based design proposes the concurrent development of multiple ship concepts. Singer et al. (2009) argue that this leads to reduced development costs as design decisions can be delayed until their implications are more fully understood. As highlighted in Section 2.1. exploration can improve the understanding of *compromise* problems, and the trade-offs between vessel characteristics, before applying optimization to the *selection* of an alternative. Methods for the consequent multi-objective optimization applied to ship design is discussed in detail by Papanikolaou (2010).

Among relatively recent examples of concept exploration applications are studies of the trade-off between costs faced during production, operation, and due to ship resistance (Temple & Collette, 2017), characteristics of internal ship layout (van Oers, 2011), and the impact of context and needs changes on ship value (Gaspar, Rhodes, et al., 2012). The packing approach proposed by van Oers (2011) bridges the gap between concept exploration and the building block approach through the use of genetic algorithms. Contextual factors and future uncertainty has been thoroughly studied by combining exploration with the epoch-era framework by Gaspar (2013). The relation between ship design and future uncertainty in system environment will be considered next.

These examples represent some highlights, albeit far from exhaustive, of the literature on ship design methodology. Extensive reviews are periodically published by the International Marine Design Conference (IMDC), see for example Andrews & Erikstad (2015) or Andrews, Papanikolaou, Erichsen, & Vasudevan (2009). We now present some core topics of importance for this thesis; the extension of system boundaries for ship design, and problems in fleet design.

2.2.2. Extension of system boundaries in ship design

Recent years have seen a growing interest in environmental aspects, the impact of regulations, and the importance of considering the market status and an extended set of stakeholder preferences during early-stage design (Hagen & Grimstad, 2010). While the need for setting ship size based on economics and logistics has been argued for several decades (Benford, 1967; Buxton, 1972; Erichsen, 1989; Stopford, 2009), these factors have become increasingly central in ship design (Brett et al., 2006; Ulstein & Brett, 2012). Gaspar, Hagen, & Erikstad (2016) frame the extension of boundaries as a question of matching the right vessel for the right mission within the right context. The need to extend system boundaries is also discussed as part of the wicked problem in ship design (Andrews, 2011, 2012). A recent review (Andrews, 2018) documents the difficulty of addressing the wicked problem arising in early-stage ship design, particularly for special vessels where valid measures of merit are hard to define. Other authors (Kaiser, 2015; Stopford, 2009) comment on a lack of homogenous markets for certain types of special vessels, like offshore construction vessels, as a source of this problem. Addressing these issues, a varied literature focused on complexity and uncertainty in ship design has emerged.

Uncertainty and complexity in ship design

Change of contextual factors beyond the current market situation is important to consider. The main reason is that changing markets or non-compliance with new regulation can render a vessel unprofitable (Erikstad & Rehn, 2015). Gaspar, Erikstad, & Ross (2012) account for exogenous uncertainty faced in the ship design and deployment problem by using epoch-era analysis. The ship design and deployment problem is defined as a deterministic, mathematical program by Erikstad, Fagerholt, & Solem (2011), in which decisions about design and lifecycle ship deployment to missions are done simultaneously. Stochastic programming (Balland, Erikstad, Fagerholt, & Wallace, 2013) and Markov decision processes (Niese & Singer, 2014) are also used for guiding ship design and deployment under uncertainty. Kana, Shields, & Singer (2016) draw on the need for requirements elucidation, as well as models from psychology to address the complexity of naval ship design, which takes place in a highly politicized design environment.

A generalized framework for complexity in ship design is applied by Gaspar, Rhodes, et al. (2012), in combination with the Responsive Systems Comparison method (Ross et al., 2009), to show how *contextual*, *temporal*, and *perceptual* aspects of complexity (Rhodes & Ross, 2010) affect special vessels. The latter framework is visualized in Figure 10.

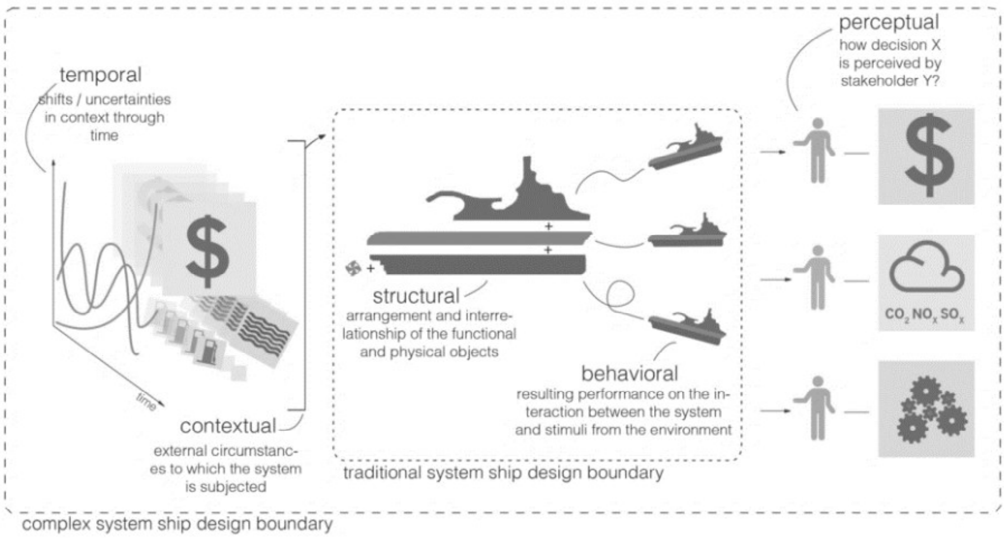

Figure 10: Five aspects of complexity in ship design (Gaspar, Rhodes, et al., 2012).

The perspectives in the research reviewed above are representative of a trend to system thinking being introduced into ship design in the industry. Ulstein & Brett (2012) argue that ship designers and ship owners should move towards considering commercial and operational aspects, in addition to technical details. This is indicative of the engineering design approach that starts with considering what provides value and proceeding to considerations of system solutions later. Ulstein & Brett (2015) contribute to the perceptual aspect of ship design by considering multiple perspectives to the question of *what makes a better ship?*

The realization that what constitutes a good ship will change over time, either by a change in the context or the stakeholder needs, has been influential in recent research. The focus of this research has both been to develop more flexible, modular ships, and to introduce methods to support decisions regarding how flexible ships should be (Choi & Erikstad, 2017; Niese & Singer, 2014; Rehn, Pettersen, Garcia, et al., 2018). Flexibility can then be introduced by application of general principles for design, for example by keeping functional requirements independent, to the extent it is possible to achieve this in a complex system like a ship.

Figure 10 summarizes difficulties in adapting a ship to the changing operating conditions. A ship is both *structurally* and *behaviorally* complex, as shown by the functional breakdown in Figure 8, and by the balancing act outlined in the building block methodology in Figure 9. Furthermore, advanced offshore vessels can enter into many different *contexts*, meeting *temporally* alternating mission requirements. A breakdown of possible missions for advanced offshore vessels, with related requirements, is shown in Figure 11.

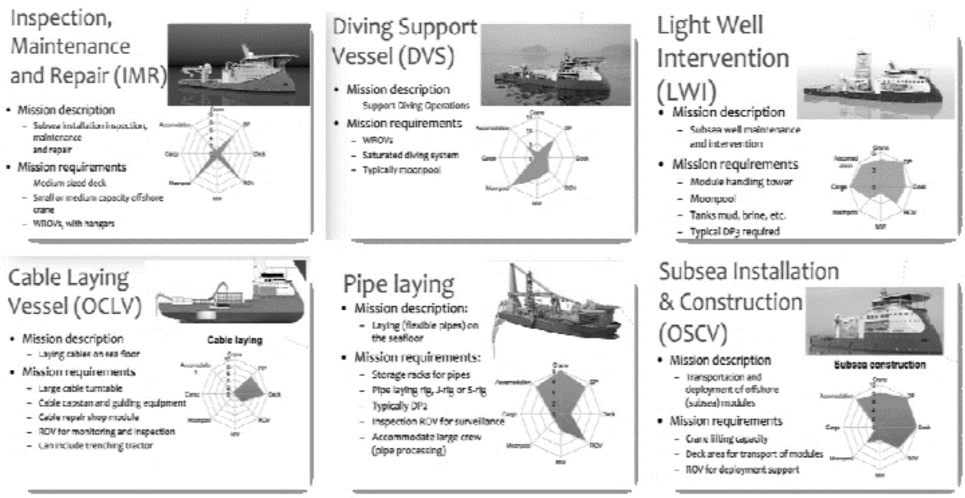

Figure 11: Notional mission breakdown for offshore ships with a description of mission requirements (Ulstein & Brett, 2015).

Risk-based ship design

The development of risk-based methods also deserves a mention in relation to the extended boundaries of ship design. Risk-based design attempts to ensure safe ship design by facilitating a move from descriptive to prescriptive rules, and towards goal-based standards (Papanikolaou, 2009). The outcome are new ship design methods that allow deviation from descriptive rules if it can be shown that an equivalent safety level can be obtained. This significantly opens the solution space for novel solutions, and new modes of operation, if we think in terms of concept exploration. In those terms, it constitutes a design parallel to resilient operations in which operations may deviate from what was intended. Applications of risk-based ship design include design of naval combatants, with strong emphasis on ship survivability (Boulougouris & Papanikolaou, 2013), improved methodologies for damage stability analyses (Karolius & Vassalos, 2017) and the design of arctic marine transportation systems, within a simulation framework (Bergström, Erikstad, & Ehlers, 2016).

2.2.3. Fleet size and mix

A very important consideration in ship design is the role of the vessel within the larger fleet. In the systems engineering literature, this is sometimes referred to as a problem of designing a "system-of-systems", following Maier (1998). Compared to the design of integral structures like ships, determining the fleet size and mix requires that we account for interaction effects among assets that are spread out geographically.

The fleet size and mix problem has been studied in relation to the optimization of maritime logistics within the operations research community (Pantuso, Fagerholt, & Hvattum, 2014). Perhaps closer to the perspective of practitioners of special vessel design, is work undertaken to improve fleet synthesis (Doerry & Fireman, 2009), and to develop measures of effectiveness for naval fleets (Gawande & Wheeler, 1999; Hootman & Whitcomb, 2005; Martens & Rempel, 2011; Rains, 1999).

This subsection will only discuss fleet size and mix problems, discussed as a *marine design problem*. Note that the topic of systems-of-systems will be readdressed in Sections 2.3. and 2.5, going deeper into the relationship between systems-of-systems and latent capabilities, and systems-of-systems in maritime contingency planning. In those sections, the focus is on how existing resources can be combined into new systems-of-systems in response to a rapidly evolving needs for functional unity. Section 2.5. will also revisit operations research methods applied to emergency response.

Fleet size and mix from the operations research perspective

Determining the fleet size and mix, like ship design, is a strategic decision problem. Strategic decisions have a long planning horizon as opposed to tactical decisions, which concerns planning horizons from months up to a year, and operational decisions, which may concern weekly, or day-to-day decisions (Christiansen, Fagerholt, Nygreen, & Ronen, 2007). For the optimization literature on fleet size and mix, central questions include:

1. *What is the optimal number of ships in the fleet?*
2. *What are the right ships to invest in?*

The fleet size and mix problem has often been framed as a mixed-integer program. Recent variants of the fleet size and mix problem make use of two-stage or multi-stage stochastic programming, as future uncertainty strongly affects the value of the fleet, and hence the future decisions made with respect to deployment of ships, as well as chartering decisions. A review by Pantuso et al. (2014) finds a number of flaws with common applications of the fleet size and mix problem. First, relatively few references include future uncertainty. Second, whole fleets are seldom acquired simultaneously. Rather than being designed, fleets evolve over time. Hence, a more interesting problem is that of fleet *renewal*:

3. *What is the right way to update the fleet composition, given the existing fleet?*

A number of papers handle the fleet renewal problem by use of stochastic programming, mostly regarding the optimal fleet renewal strategies for a shipping company operating liner services for rolling cargoes (Pantuso, Fagerholt, & Wallace, 2016, 2017). For the fleet renewal problem, strategic decisions include newbuilding and acquisition of second-hand vessels, as well as sales and scrapping. Strategic decision-making is supported by tactical-level decisions regarding routing, deployment and chartering options. An alternative is to delegate the optimization to the tactical or operational levels, as it becomes easier to reliably model the decision problem when facing only short-term uncertainties (de Neufville, 2000), and leave strategic scenario planning and fleet synthesis to be explored in concert by the decision-makers. Other tactical planning models that can serve this purpose include routing, scheduling, and fleet deployment problems, in which vessels in the fleet are matched to possible missions (Christiansen et al., 2007).

Fleet size and mix from the naval ship design perspective

Parallel to the development of operations research-based methods for fleet size and mix, a practitioner-driven literature on measures of effectiveness to guide fleet synthesis exists. In this literature, fleet-level capabilities are the focus rather than individual ship capabilities (Doerry & Fireman, 2009; Martens & Rempel, 2011; Rains, 1999). Measures of effectiveness for fleets of special vessels, and in particular naval fleets, are very different from the profit-derived measures supporting commercial shipping decisions (Andrews, 2018; Gawande & Wheeler, 1999; Hootman & Whitcomb, 2005).

Gawande & Wheeler (1999) suggest that measures of effectiveness on a case-by-case basis are needed for governmental organizations, as no standardized measures for returns on investment exist. They present an econometric model for use in the development of measures of effectiveness for the US Coast Guard. Internal resource allocation is cited as one of the applications of their model, for example drawing on mathematical programming methods to allocate vessels to the missions that provide the greatest marginal benefit.

Rains (1999) argues for mission effectiveness on the fleet level as the real driver for ship design decisions, rather than ship performance. He develops a set of measures of effectiveness that are used in the analysis of alternative fleets, or “force structures”, based on capabilities aggregated across several assets. A number of such measures of effectiveness for the missions of the fleet can be developed and traded for analysis of alternatives and decision-making, for example in correspondence with design of experiments (Hootman & Whitcomb, 2005; Martens & Rempel, 2011) and multi-attribute decision-making (Keeney & Raiffa, 1993). Note also the strong emphasis on effectiveness as a function of technical and operational capabilities, requiring a thorough understanding of the ship capabilities to derive vulnerability and availability measures, while also being some aggregate across multiple vessels.

Future uncertainty and renewal plans within this environment have also been considered. For example, the impact of increasing vessel service lives on the force structure has been discussed (Doerry & Fireman, 2009; Koenig, Nalchajian, & Hootman, 2009) Due to changing political and economic conditions, ship replacement policies in large navies are also subject to changes, with evidence showing that service lives are normally extending (Koenig et al., 2009). Doerry & Fireman (2009) argue for a fleet-level capabilities assessment taking into account both the fact that the ships acquired will have long, uncertain service lives, and that they should enter into the fleet, and not just be part of the current newbuilding program. In summary, research on issues related to naval fleet synthesis moves towards i) a stronger emphasis on measures of effectiveness, rather than fleet performance, and ii) a move towards viewing the synthesis problem as embedded within a highly complex strategic decision-making context and within an organization that is strongly influenced by the political process.

2.2.4. Summary of marine systems design

The literature on marine systems design has moved from purely technical considerations to a multi-disciplinary perspective that accounts for the operational and commercial context within which a ship will work. With respect to the contextual aspect of ship design, extensive research regarding the place of a new ship within a larger fleet has also been undertaken. Exploratory approaches to study synthesis and analysis of ship alternatives within future operating environments are becoming more common in the literature. Still, the role of a new ship within the fleet, and operational opportunities for the ship in alternative missions remains a consideration that deserves further research. For example, research could address the differing roles a ship takes in the fleet over time. Overall, the approach taken to marine design in this thesis, sees ships, multi-functional special vessels in particular, as “physically large and complex systems” (Andrews, 1998). This has implications for the application of certain concepts from engineering design theory. Still, grounding ship design in central concepts from engineering design remains useful for understanding how a business case or some other need is materialized through a physical structure. Design research has dealt extensively with future uncertainty and issues for the operational phase of the lifecycle but there is little research that connects design theory with the need for resilience and contingency planning.

Specifically, the marine systems design literature supports the connection between Research Objective 1 and Contribution 1. The literature also provides a grounding for the taxonomy of offshore support vessel functionality that answers to Research Objectives 2 and 4, and adds to Contribution 3. Furthermore, the fleet size and mix literature provides part of the background for Contribution 5, in which a deployment problem is used to evaluate alternative fleet configurations. Finally, this review has given a thorough overview of the most important challenges and complexities that face marine systems in a lifecycle perspective.

2.3. Towards latent functional capabilities

We now move to study functions during the operational phase of the lifecycle. As opposed to function modelling during the design phase, where functional specifications are used to direct the search for physical solutions, other behaviours may be exploited in this phase. In this, we increasingly take the engineering systems perspective by discussing how humans and organizations can take advantage of the opportunities represented by latent functions. The engineering systems perspective that incorporates social and managerial dimensions beyond the technical dimensions enable us to think about how latent functions can be translated into latent capabilities. From this perspective, the system is not "finished" once it has been designed. Rather, the system continues to evolve after its delivery as new needs emerge, given that its managers are sufficiently proactive.

2.3.1. Defining and modelling functions

Our starting point for defining and modelling functions will be the perspective that functions can be construed as a combination of a verb and a noun (Hirtz et al., 2002; Pahl & Beitz, 1996). For example, functions can be statements such as "transport humans", "provide energy", or "transmit signals". De Weck et al. (2011) define functions as a combination of processes and operands, that these processes operate on. Magee & de Weck (2004) present a collection of generic processes and operands that can be used to describe nearly all technical and socio-technical (engineering) systems. For a generic framework for function modelling, we refer to Hirtz et al. (2002), who present a detailed, generic functional structure for engineering design.

The question of what exactly function means has recently been extensively discussed in the literature (Crilly, 2010, 2015; Eckert, 2013; Erden et al., 2008; Vermaas, 2013). Are functions what the system was intended to do, or is it what the system can do? Erden et al. (2008) find that most works on function modelling embed at least some subjectivity, within their definition of "function". For that reason, they consider functions as a subjective link between the human intent (stakeholder needs) and the objective structure (physical form). Eckert (2013) argues that there are considerable differences between the German language (Hubka & Eder, 1988; Pahl & Beitz, 1996) and English language (de Weck et al., 2011; Gero, 1990; Gero & Kannengiesser, 2004; Suh, 1990) literature regarding the extent to which intent is embedded in the definition of function. According to Eckert (2013), in the German literature, "functions" seem closer to a description of physical behaviours, than necessarily implying the intent of the designers. Still, it is not a completely objective concept even in the German literature, as it is used to guide the design of systems that accommodate stakeholder needs (Erden et al., 2008; Pahl & Beitz, 1996).

On the other hand, Gero (1990) explicitly splits function and behaviour in the function-behaviour-structure (FBS) framework. Welch & Dixon (1994) use a similar distinction to propose that innovative design can result from separating function and behaviour, and use bond graphs to illustrate this. Similarly, in axiomatic design, the desired output of the system is referred to as functional requirements (Suh, 1990), indicating that functionality provides a direction for the synthesis of form, in accordance with the design axioms. De Weck et al. (2011) define functions as the "desired behaviours", while Crawley, Cameron, & Selva (2016) state that functions are "simply what the system does". For increasingly complex systems, including socio-technical systems, functional *emergence* is what causes a system to be worth more than the sum of its parts (Crawley et al., 2016). Similarly, for socio-technical systems Kroes, Franssen, Poel, & Ottens (2006) point out that functions emerge from the interplay between the system and its human operator, who may choose to follow or not follow a prescribed "user manual" that outlines how the system is intended to function. An interesting question then becomes whether the non-prescribed system uses that are available during the operational phase, but not intended by the designers, should be considered functions.

Vermaas (2013) argues that a co-existence of definitions of functions are useful, as this enables the use of a variety of different design methods. This argument can be extended to the operational phase, where the function of a system will be highly dependent on the system environment (Crilly, 2010, 2015; Rhodes & Ross, 2010). For example, Crilly (2015) argues that functionality needs to be stated in the terms where "the function of S is R in Z", meaning that the function R of a system S, depends on the context Z. Further, Z is contingent on system boundaries perceived by a human observer. Hence, for thinking about alternative ways a designed system can function in its operational phase, it is useful to separate two types of functions:

- The functions that were intended and recognized during the design phase.
- The functions that were neither intended nor recognized during the design phase, but that can be recognized and become useful in the operational phase.

2.3.2. Manifest and latent functions

The distinction above leads us to adopt Merton's (1968) concept of manifest and latent functions for engineering systems. Merton (1968) introduced the term "latent function" in his sociological function analysis, to refer to the unintended and unrecognized effects of policy introduction into a complex social system. We here restate Merton's (1968) generic taxonomy of functions:

- **Manifest functions:** The intended and recognized consequences of policy.
- **Latent functions:** The positive, but unintended and unrecognized consequences of policy.
- **Dysfunctions:** The negative, unintended and unrecognized consequences of policy.

In the context of designed systems, manifest functions refer to those functions that the designers intend and recognize that the system should perform. Manifest functions represent what will be considered the functional specifications, or requirements from the design perspective. Latent functions represent the use of system elements intended for some functional requirement, to fulfil some other functional requirement that arises later, or to fulfil a functional requirement that other system elements have lost their ability to perform.

Figure 12 presents the extended needs-function-form mapping for a system when we consider the latent relations between form (design parameters $\boldsymbol{DP}$) and function (functional requirements $\boldsymbol{FR}$), and between function and customer needs $\boldsymbol{CN}$. The notation is based on Suh (1990). Through sequential design synthesis and analysis, a physical system is derived. After the closure of the design process, other unanticipated, but useful, behaviors can be discovered, giving rise to latent functions. This is indicative of the existence of a one-to-many abductive approach moving from form to function, as there are potentially a large number of functions, in addition to its intended functions, that a system can perform. Concretely, a system described by the set $\boldsymbol{DP^A}$ could be designed for meeting the set of functional requirements $\boldsymbol{FR^A}$, but could also be able to meet other sets of functional requirements, for example $\boldsymbol{FR^B}$.

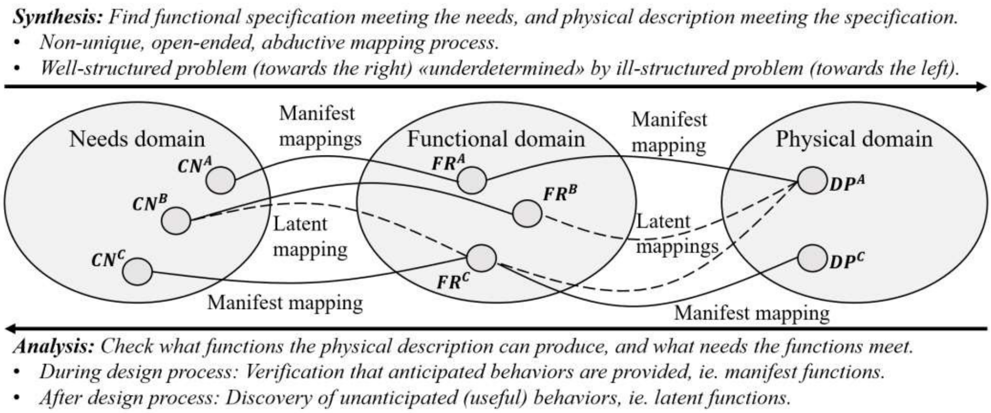

Figure 12: Needs-function-form mapping model with notation based on Suh (1990), distinguishing manifest and latent mapping[2].

The separation between manifest and latent functions is used by Crilly (2010) among several other categorizations, in his review of technical, social, and aesthetic functions that can be derived from technical artefacts. Crilly (2010) points to the manifest function of a car as being to provide transportation. Besides that main function, the car can also function as a barricade, blocking a street during a riot, or if sufficiently expensive, it functions as a signal of the owner's wealth.

Umeda & Tomiyama (1995) define a redundant function as a "function that can be realized by other physical features than the feature that realizes the function in its normal state". While functional redundancy could be explicitly designed for, it may exist unintentionally, and without recognition. Such unintended and unrecognized redundancies can be considered latent functions. In the case where a functional redundancy is truly latent, there is a need for working outside the bounds of the system uses prescribed by the "user manual" that dictates how the system should operate. Functional redundancy is proposed as a design principle for increased reliability (Erden et al., 2008), and for increased resilience (Madni & Jackson, 2009).

Marine examples
What do the points outlined above entail for a marine system? An overview of examples of latent functions in the marine technology context is given in Table 4. Note that we here focus on single ships, and ship systems, rather than functions in marine transportation systems, as those were provided to introduce latent functions in Chapter 1.

[2] The term "underdetermined" is used in Figure 12. This term was used by Goel & Pirolli (1989) to describe the fact that many *well-structured* representations can exist for each *ill-structured* problem.

Table 4: Examples of manifest and latent functions in marine systems.

System/Feature	Manifest functions	Latent functions	Reference
Ship ballasting system	Increase weight to lower centre of gravity (CoG).	Counteract changing CoG due to flooding of subdivisions.	(Karolius & Vassalos, 2017)
Ship crane	Lift cargo.	Produce roll movement.	(Sodhi, 1995)
Generator in floating wind turbines	Produce energy.	Dampen vibrations.	(Zhang, Nielsen, Blaabjerg, & Zhou, 2014)
Platform supply vessels	Transport containers, wet and dry bulk cargoes.	Search and rescue, accommodation	(Cusumano, 2017; Pettersen, Asbjørnslett, Erikstad, & Brett, 2018).
Anchor handling, tug, supply vessel (AHTS) in ice management	Hoist anchors, tow rigs.	Tow icebergs.	(Borch & Batalden, 2015; McClintock, McKenna, & Woodworth-Lynas, 2007)
Water cannon on OSV in ice management	Fire-fighting.	Deflect small ice masses (growlers and bergy bits).	(McClintock et al., 2007)
OSV propeller in ice management	Move the ship.	Deflect small ice masses (growlers).	(McClintock et al., 2007)

The examples in Table 4 deserve some more explanation. First, ballasting is normally done to ensure that the unladen ship is weighted down, lowering the CoG to improve initial stability. In a flooding situation, Karolius & Vassalos (2017) argue for an increased use of sensor technology to obtain information about the state of a damaged ship quickly, whereupon targeted counterballasting can take place to adjust the CoG, thereby improving damage stability. Second, a report on icebreaking technology published in the 1990's (Sodhi, 1995) claims that cargo ships in earlier times that got stuck in ice, used their cranes to swing heavy cargoes sideways, producing a rolling movement that helped the vessel wiggle free. This is a clear example of a latent function for the crane. The manifest function is to "lift cargo", whereas "produce roll movement" is the latent function. In modern icebreakers, heeling tanks are used for this purpose (Sodhi, 1995). Third, an example from offshore wind, in applications of control theory to control of offshore floating wind turbines, it has been proposed that use of active generator torque can dampen the negative impact of lateral tower vibrations due to wind and waves (Zhang et al., 2014). The manifest function of the generator is to "produce energy", while the latent function is to "dampen vibrations". Fourth, platform supply vessels that normally transport supplies to offshore oil platforms, possess characteristics like a large deck area and good manoeuvrability, making them especially fit for search and rescue operations, and for accommodating a large number of people (Pettersen, Asbjørnslett, Erikstad, et al., 2018).

Lastly, a notable case is that of ice management operations in the offshore oil and gas industry. In oil and gas exploration offshore Newfoundland, vessels with towing capabilities are often required, due to the need to tow icebergs that are at risk of collision with offshore installations (McClintock et al., 2007). AHTS vessels are often engaged in these operations (Borch & Batalden, 2015), as they are outfitted with sizeable towing winches, and have adequate bollard pull ratings. The main manifest functions of an AHTS vessel are to "hoist anchors" and "tow rigs", whereas the latent function can be described as "tow iceberg", in this case. Using the process-operand definition of a function (Pahl & Beitz, 1996; de Weck et al., 2011), the iceberg towing example is one in which the process of towing is similar in the manifest and latent cases, while the operand (iceberg) is what makes the "tow iceberg" function latent. Alternatives to towing include spraying water on icebergs, or propeller washing, which consists of creating a thrust to deflect the ice. McClintock et al. (2007) provide several examples of this, as shown in Figure 13.

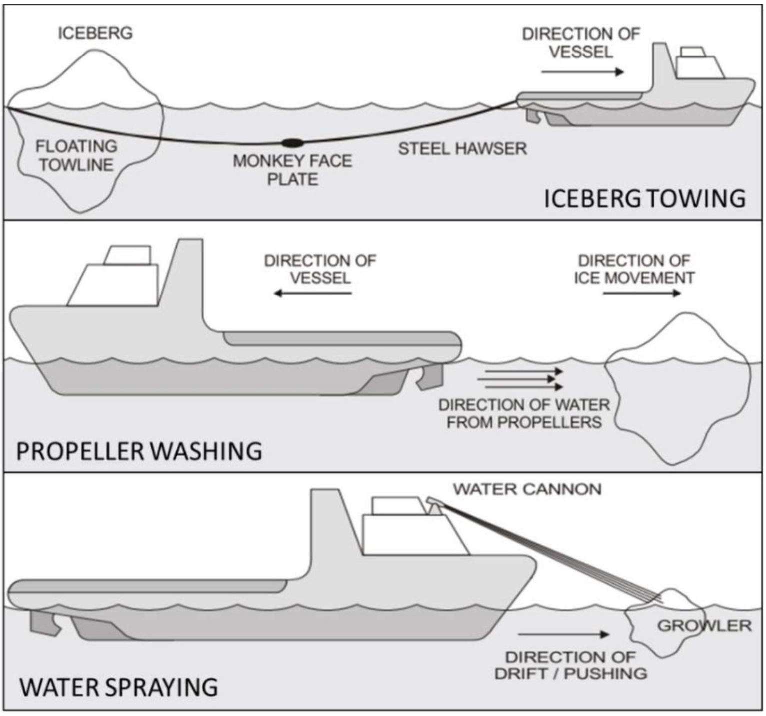

Figure 13: Modes of operation for offshore vessels in ice management (McClintock et al., 2007).

The technical aspects of *latent functions* have now been outlined, but there are remaining issues with respect to socio-technical aspects, as well as the relation between latent functions and emerging phenomena in systems-of-systems. In the next section, we explain how the existence of latent functions may give the system additional capabilities beyond what it was designed for.

2.3.3. Latent functional capabilities

The characterization of latent functions alone does not capture the complete story. Beyond realizing that latent functions may exist and that these may be useful, there is a need for addressing how an organization can manage these functions effectively, and take advantage of them. The degree to which latent functions can be exploited will henceforth be referred to as latent capabilities.

We here discuss work that has presented useful perspectives on this. First, we summarize the framework for managing unarticulated value in engineering systems by Ross (2006), relating it to the "ilities". Second, seminal work on how latent capabilities can be managed is reviewed, leading up to the discussion of system resilience in Section 2.4. Third, the relation to the supersystem level is reviewed, serving as an initiation of emergency response issues further discussed in Section 2.5.

A framework for managing unarticulated value in engineering systems

Ross (2006) develops a classification scheme for uncovering latent value in systems, to enable sustained value delivery through the lifecycle. He uses the term *unarticulated value* to describe system characteristics that contribute to value, without being communicated between stakeholders. This framework represents one approach to uncover capabilities that were neither intended nor recognized during the design process and hence enables exploitation of latent capabilities. The classes *free latent value*, *combinatorial latent value*, and *accessible value*, are particularly interesting to discuss.

Accessible value indicates that an attribute that provides value can be accessed through a change of the design variables of the system (Ross, 2006). In other words, a change in the value the system delivers, or the functions a system performs, is driven by a change in physical form. Generally, real options "in" systems constitute a right, but not an obligation to execute changes in the function or form (Wang & de Neufville, 2005). Identification and valuation of options "in" systems are discussed at length in the literature on changeability (de Neufville & Scholtes, 2011; Fricke & Schulz, 2005; Ross, 2006; Ross et al., 2008). Even though the value of options is difficult to quantify without knowledge of the statistical distribution of economic outcomes, simply knowing that options exist, by itself is valuable (Rehn, Pettersen, Garcia, et al., 2018). The increase in the *number of options* can at least *theoretically* be shown to increase expected net present value, if stakeholders know which alternative will be most beneficial (de Neufville & Scholtes, 2011; King & Wallace, 2012). On the other hand, Stopford (2009) argues that lateral cargo mobility, the number of alternative cargoes a ship can take, in most transportation segments equals one. This indicates that most ship owners assume that flexibility does not pay when traded off against efficiency. This indicates that much of the literature that attempts to value flexibility underestimates the uncertainty associated with the cost of reconfiguration. For complex systems, it is also often difficult to predict the physical and functional effects of design changes like retrofits (Clarkson et al., 2004; Rehn, Pettersen, Erikstad, & Asbjørnslett, 2018).

Combinatorial latent value reflects the value that can be achieved in the intermediate space between *accessible* and *free latent value*. Attributes in this class are achieved through a change of function without change of form, which corresponds to versatility (Chalupnik, Wynn, & Clarkson, 2013; de Weck, Ross, & Rhodes, 2012). In shipping, examples of versatility include market switching done without change of physical form, as in the case of oil-bulk-ore carriers (Sødal et al., 2008). This can be measured by the lateral cargo mobility (Stopford, 2009).

Another interesting set of cases of versatility in the maritime industry are multi-functional vessels designed to be able to swiftly switch between alternative mission types. This case of intentional unbounded functionality delimits latent capabilities: As versatility in the case of oil-bulk-ore carriers, multi-functional special vessels, or even USB-ports is designed for, the capabilities of these systems by definition are not latent. Still, other examples of versatility can be unintended from the point of view of the designers, and in that case, would exemplify latent capabilities. Hence, the definition of versatility proposed by de Weck et al. (2012) is only partially accepted here: not all types of versatility are measures of latent value.

By *free latent value,* Ross (2006) refers to the attributes that can provide value without being explicitly considered during the systems design process. *Free latent value* can be activated without any cost accruing to the decision-makers, as no change in system form or function is required. The only cost will be the required change of stakeholder perception of the system. This can be achieved by a reframing of the stated functions of the system, illuminating new opportunities beyond what stakeholders originally had in mind. The effects of framing on decision-making is well-documented in psychology (Tversky & Kahneman, 1981), and could impact what deviations from normal operation that can be accepted. It could be argued that such a reframing of purposes always will entail some kind of cost, as it requires a redefinition of operational procedures. Hence, aspects of both free latent value and combinatorial latent value are encompassed by what we call latent capabilities.

Figure 14 sets the conceptual framework for latent value into the context of the needs-function-form mapping model that is common in engineering design. Here, CN^M and CN^L refer to respectively manifest and latent customer needs, FR^M and FR^L refer to respectively manifest and latent functional requirements, whereas DP refer to design parameters describing the system. Demand for latent needs or functions are here triggered by a shift in the system context.

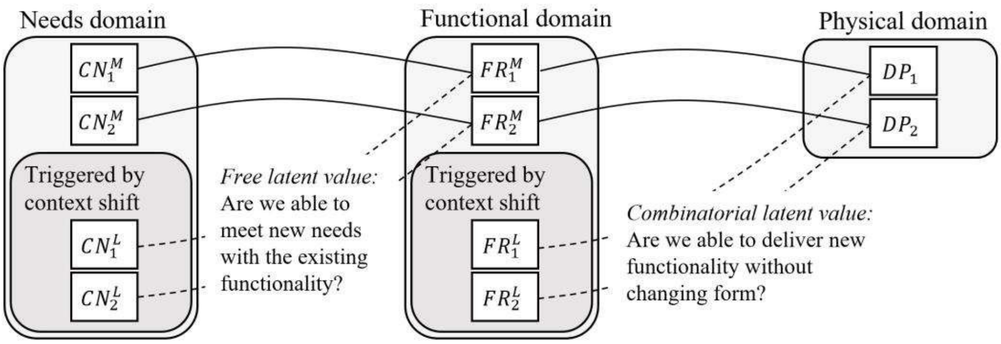

Figure 14: Free latent value and combinatorial latent value (Ross, 2006) in the context of the needs-function-form mapping model (based on Suh, 1990).

Organizational enablers and connections to resilience

We now discuss how a system can meet a new context or a disruption by delivering new functionality without changing its form. It is necessary to highlight the role of the organization responsible for managing and operating the system, in enabling the exploitation of latent capabilities. Awareness with respect to the opportunities represented by latent capabilities needs to be communicated throughout the organization, from management through to system operators and crews. Their role is more explicitly addressed in Figure 15, showing the human element as part of the resulting socio-technical system (designed artefact plus human operators).

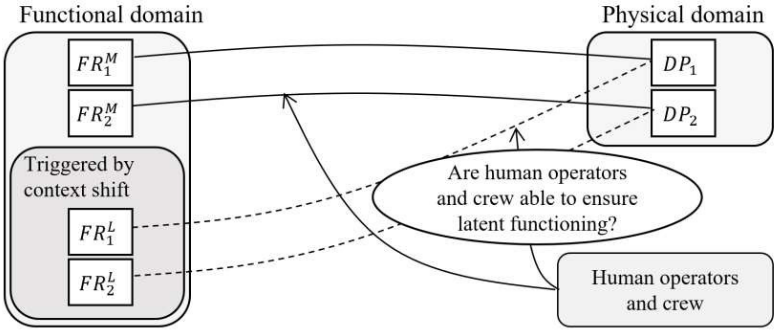

Figure 15: Function-form mapping model (based on Suh, 1990) extended with human actors.

Latent capabilities will best be maintained by organizations that seek to develop adaptive capacities. March (1991) addresses the trade-off between the commitment of resources for exploration of new opportunities, enabling adaptation, and exploitation of existing knowledge for increasingly efficient operations, arguing that exploration and exploitation must be balanced. An organization that does not allow exploration, will not take advantage of latent capabilities, as these lie beyond the prescribed operational procedures. Similarly, Sutcliffe & Vogus (2003) point out that adaptation is enabled by a work environment that allows for broad information processing, loosened managerial control, and excess work capacity. They point to the necessity of these factors for creating resilience. Resilience is the topic of Section 2.4.

Grøtan (2014) makes a case for adaptation and resilience in relation to compliance with existing regulation. By compliance alone, one can only make use of a small part of the operational opportunities, although these operations account for the purpose the system was designed for (represented in Figure 15 as FR^M). Adaptation greatly increases the number of opportunities that can be taken advantage of. Still, this may increase novel risks, in the form of "adaptive failures" (Grøtan, 2014), where the system is pushed beyond the limits for what actually entails a successful operation in terms of safety or quality. An example that highlights the importance of this, is the previously mentioned use of AHTS vessels in ice management operations. In these operations, Borch & Batalden (2015) report on difficulties relating to compliance, as iceberg towing lay far outside the scope of operations considered by the shipping company's existing quality management standards, even though the oil companies considered these operations "routine". This illustrates that it is important to specify *to whom* functionality is latent. Additionally, this hints at the importance of shared sensemaking in operations that require collaboration between organizations (Weick, 1993).

In conclusion for this short review of some organizational issues, management is responsible for assigning sufficient resources to ensure that crew obtains experience with unfamiliar modes of operation, responsible for ensuring that knowledge derived from previous experience is dispersed through the organization, and responsible for enabling new modes of operation to be implemented in a safe and reliable manner. The author is aware that there exists a large human factors literature, making use of field studies for more user-centric ship design (e.g. Rumawas, Asbjørnslett, & Klöckner (2017)), which could cast further light on this topic.

Latent functional capabilities and higher-level system characteristics

Latent capabilities can also be understood in relation to supersystems. Higher-level systems are sometimes described as systems-of-systems, defined by Maier (1998) as systems whose components are themselves systems with operational and managerial independence. A further elaboration of systems-of-systems is given by Boardman & Sauser (2006) via five main properties distinguishing these systems from other complex systems: *Autonomy*, meaning that constituent systems contribute to fulfilling the overall purpose by collaborating while being under independent management and operation. *Belonging*, meaning that constituent systems can choose whether to belong a system-of-systems or not. *Connectivity,* implying that the architecture of the system-of-systems is essentially a dynamically changing network. *Diversity,* meaning that a diverse set of behaviours are enabled by autonomy, belonging, and connectivity. Finally, *emergence,* meaning that the system-of-systems exhibits behaviours, and can fulfil functions that would be impossible to predict or to observe from studying any of the constituent systems. The resulting behaviour is indicative of latent capabilities as no one explicitly designed for this.

Uday & Marais (2015) motivate their survey of system resilience using a naval warfare system-of-systems. The system-of-systems they present comprise anti-submarine units, anti-mine units, and surface warfare units. These units can be decomposed into aircraft carriers, combat ships, unmanned surface and aerial vehicles, and helicopters, all of which perform different functions, but collaborate to deliver higher-level (emergent) military capabilities. These capabilities need not be inferred during the design of any of the constituent assets, and mission effectiveness will vary according to the geospatial distribution of assets. The collaboration among assets hence may result in capabilities emerging that are wholly latent. We can consider additional situations in which single systems perform different roles depending on the current environment. For example, consider a platform supply vessel that enters a contract for a primary mission concerning transportation of supplies to locations offshore. While performing the function "transport supplies", it also performs the latent function "partake in emergency infrastructure", as it in a case where there is a need for emergency response, it will act as part of that response. Still, its contribution to mission effectiveness will partially be a function of the characteristics of other assets in the emergency infrastructure. For engineering systems, Crilly (2015) argues that the supersystem level offers new challenges for systems design research, hinting at the theoretic relevance of considering latent capabilities:

> *"If a system plays many roles in many supersystems, how should we specify which of these roles are the functions of interest? Second, if a given role is collectively performed by many systems, how should we specify which of these systems is the functional one and which are supporting that functioning system?"*

A simple conceptual model that captures the essence of how latent functions can emerge on the system-of-systems level, is provided in Figure 16. This model extends a simpler conceptual model representing the "dual nature of technical artefacts" presented by Kroes et al. (2006), reflecting that function in most technical systems emerges through interaction with a human agent. The figure introduces two technical systems, each being operated by a human operator, to produce the manifest function. The collection of technical system and human operators is here referred to as a socio-technical system. The two operators interact, not necessarily intentionally, to produce a function on the system-of-systems level. That function is a latent function, as it is neither intended nor recognized before it emerges. It may nevertheless be of great value.

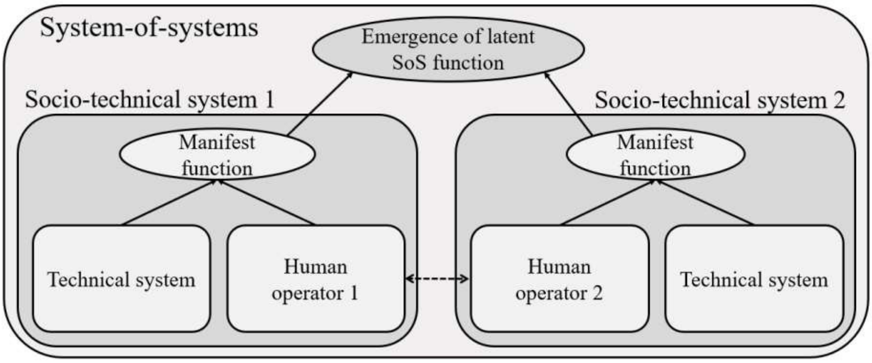

Figure 16: Emergence of latent system-of-systems function resulting from two socio-technical systems performing their manifest function, extending a model in Kroes et al. (2006).

2.3.4. Summary of latent capabilities

Latent functional capabilities are those capabilities that are neither intended nor recognized during design, defined after Merton (1968). Latent capabilities are not observable by designers (during the design process) but can be discovered after the design stage during the production and operations stages. A taxonomy is given in Table 5. Further, latent capabilities can emerge from the combination of designed artefacts (like ships) into higher-order systems (like fleets), when that gives rise to capabilities that were not considered during the design of the artefact itself.

Table 5: Distinction between manifest and latent capabilities.

Status of capabilities during design		**Intended?** Yes	No
Recognized?	Yes	Manifest	Manifest
	No	-	Latent

Examples from marine technology were given to illustrate that there is actual relevance in understanding the capabilities of a marine system, beyond its intended and recognized functionality. Relations with similar concepts like changeability were also addressed. The position taken in this thesis is that latent capabilities are particularly useful when facing uncertainties, often disruptive events, that were not explicitly considered during design. In particular, latent capabilities contribute to versatility (ability to change function without change of form), enabling mission flexibility.

With respect to the research problem and contributions of the thesis as a whole, the previous literature on concepts similar to latent functions and latent capabilities show that there is room for more research on latent capabilities. Research Objectives 2 – 4 and Contributions 2 – 4 develop the latent capabilities concept in further detail, and in particular its relationship to resilience. Next, resilience is reviewed.

2.4. Resilient engineering systems

2.4.1. Background on resilience

Resilience in engineering originated as the ability of a material to regain its shape after being bent, in the early 1900's (de Weck et al., 2011; Park, et al., 2013). A redefinition of the direction of complex systems came in the 1970's, as Holling (1973) used resilience to describe properties of ecological systems. Resilience was then used by Wildavsky (1988) to show that efforts to reduce risks through anticipation of hazards do not always work as intended. Instead, Wildavsky (1988) argued that resources sometimes should be aimed at enabling systems to cope with and learn to bounce back from failure, as this is more effective than attempting to avoid all harm. These arguments resonated with normal accident theory (NAT) (Perrow, 1999), which argues that some accidents for complex, tightly coupled systems are inevitable, or "normal". Adding redundancy to such systems would further increase complexity, and hence increase, not reduce disruption risks. Opposite to NAT, High Reliability Organization (HRO) theory argues that many organizations succeed in avoiding accidents over time, by adapting. Laporte & Consolini (1991) point out that HROs work under circumstances that do not tolerate failure, in which i) failure of routine production processes will threaten the overall capacity of the organization to perform, ii) there are strong public pressures to ensure reliable operations, and iii) that the HRO has allocated significant resources towards ensuring reliability. HRO research influenced the development of "resilience engineering" as a safety management paradigm, signified by a move to a more dynamic and adaptive perspective on risk and uncertainty (Weick & Sutcliffe, 2007; Hollnagel, 2011).

Resilience was introduced into operations management around the same time as resilience engineering was developed as a safety management concept. Events like the 9/11 attacks and the 1995 Kobe Earthquake gave rise to a large body of research, starting from Cranfield University in the UK (Christopher & Peck, 2004) and the Massachusetts Institute of Technology in the US (Rice & Caniato, 2003; Sheffi, 2005). Supply chain risk research has focused on disruption risk (Craighead, Blackhurst, Rungtusanatham, & Handfield, 2007; Kleindorfer & Saad, 2005), strategies for enhanced resilience building on flexibility and redundancy (Rice & Caniato, 2003), as well as improvements in business continuity planning (Zsidisin, Melnyk, & Ragatz, 2005). For a review of the growing literature on supply chain risk, see Heckmann et al. (2015).

Resilience is considered one of multiple "ilities" for management of uncertainty in engineering systems (de Weck et al., 2011), with strong organizational connotations (Dekker, Hollnagel, Woods, & Cook, 2008; Weick & Sutcliffe, 2007). For the organizational perspective we refer to Sutcliffe & Vogus (2003), who review resilience for three layers of organization; the individual level, the group level, and the organizational level. They argue that resilient response to threats leads to positive adjustment through loosening of control, utilization of slack in the organization, and broadening of information processing. The resilient response is contrasted with rigid responses that lead to negative adjustment, due to tightened control and a focus on conservation of organizational resources. Similar arguments are made by Reason (1990), who in discussions of the contribution of latent human errors in accident causation made the distinction between organizations that fail to meet safety regulation, organizations that meet the regulations, and organizations that set safety targets exceeding the expectations, achieving this by operating in unordinary ways.

2.4.2. Definitions of resilience

The immense interest from varied disciplines in resilience has contributed to significant confusion as to the exact meaning of resilience, as with many other "ilities" (Mekdeci, Ross, Rhodes, & Hastings, 2015; Sheard & Mostashari, 2008; Woods, 2015). Several definitions are suggested in Table 6.

Table 6: Resilience definitions from the literature[3].

Reference	Domain	Resilience definitions
(Holling, 1973)	Eco.	"… a measure of the persistence of systems and of their *ability to absorb change and disturbance* and *still maintain the same relationships* between populations and state variables."
(Wildavsky, 1988)	Soc.	"… the capacity to cope with unanticipated dangers after they have become manifest, learning to bounce back."
(Foster, 1993)	Eng.	"… the ability to accommodate change without catastrophic failure, or the capacity to absorb shocks gracefully."
(Asbjørnslett & Rausand, 1999)	Man.	"… a system's ability to return to 'a new stable situation after an accidental event'."
(Rice & Caniato, 2003)	Man.	"… an organization's ability to react to an unexpected disruption, such as one caused by a terrorist attack or a natural disaster, and restore normal operations."
(Sutcliffe & Vogus, 2003))	Org.	"The maintenance of positive adjustment under challenging conditions."
(Christopher & Peck, 2004)	Man.	"… the ability of a system to return to its original state or move to a new, more desirable state after being disrupted."
(Allenby & Fink, 2005)	Eng.	"the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must."
(UN/ISDR & UN/OCHA, 2008)	Man.	"The capacity of a system, community or society potentially exposed to hazards to adapt, by resisting or changing in order to reach and maintain an acceptable level of functioning and structure."
(Dekker et al., 2008)	Eng.	"A resilient system is able effectively to adjust its functioning prior to, during, or following changes and disturbances, so that it can continue to perform as required after a disruption or a major mishap, and in the presence of continuous stresses."
(Richards, 2009)	Eng.	"… the ability of a system to recover from disturbance-induced value losses within a permitted recovery time."
(Neches & Madni, 2013)	Eng.	"… the ability of a system to adapt affordably and perform effectively across a wide range of operational contexts, where context is defined by mission, environment, threat, and force disposition."
(Chalupnik et al., 2013)	Eng.	"… the ability of a system, as built/designed, to do its basic job or jobs not originally included in the definition of the system's requirements in uncertain or changing environments."
(Goerger, Madni, & Eslinger, 2014)	Eng.	"A resilient system in DoD is; trusted and effective in a wide range of mission contexts; is easily adapted to many others through reconfiguration and/or replacement, and; has predictable, graceful degradation of function."

[3] Eco. – Ecology, Eng. – Engineering, Man. – Management, Org. – Organizational science, Soc. – Social science.

Table 6 shows several definitions that are directly in opposition. For example, the United States Department of Defense (DoD) perspective on resilience (Goerger et al., 2014) contradicts the definition provided by Chalupnik et al. (2013). Where Goerger et al. (2014) suggest that resilience can be achieved by reconfiguration, Chalupnik et al. (2013) limit resilience to adaptation to new situations without change of form. Hence, from the latter perspective, a resilient system should be able to perform several functions by being multi-functional, or versatile – “being able to change its function without changing its form” (de Weck et al., 2012). Considering the swift onset nature of context changes and disruptions that resilience is meant to counter, the perspective that resilience relies on a versatile design, is arguably more useful for this thesis. An effective and swift response to disruption should not rely on design principles that demand time-consuming and costly reconfigurations or retrofits.

We define resilience as “the ability of a system to be recovered from a disrupted state to an improved state”, and focus on latent capabilities as the means to achieve this. The move to resilience is further demonstrated by the realization that risk management strategies that aim to predict future hazardous events and introduce barriers to mitigate the corresponding risks are bound to fail, unless risk management continually is adapted to changes in system state and environment (Park et al., 2013; Sutcliffe & Vogus, 2003; Weick & Sutcliffe, 2007; Weick, 1993; Woods, 2015). Resilience is accommodated by organizations that are able to make sense of situations that are far from what can be expected and creatively improvise in the face of adversity (Grøtan, 2014; Sheffi, 2005; Weick, 1993), suggesting that resilient systems should be operable beyond the boundaries of normal operation and adapt to continually evolving situations (Woods, 2015).

2.4.3. Principles for system resilience

Addressing the semantic problem of resilience, Sheard & Mostashari (2008) present a framework for system resilience discussions, for creating a common understanding of how the term is used. They consider the following five elements to define system resilience; time periods, systems, events, required actions, and preserved qualities. They further define several principles for creating resilience, including system-specific principles, and principles for the management, analysis and design of resilient systems. The design principles they propose include designing in redundant capacities or margins, creating loose coupling that will limit failure propagation, and control structures for development and operation.

Asbjørnslett & Rausand (1999) present a framework for vulnerability assessment, in which that concept is contrasted to risk assessment, where vulnerability assessment addresses an extended set of threats and hazards and an extended set of intended and unintended consequences. They distinguish resilience and robustness by considering that robust systems should resist disturbance, while resilient systems can deviate from their normal operating conditions. Similarly, Park et al. (2013) see resilience as an emergent characteristic of what an engineering system does, rather than a static property that can be designed. Consequently, resilience should be thought of as a complement to risk management, with a focus on evolving system capabilities to cope with uncertainty.

Madni & Jackson (2009) outline an extensive list of heuristics for enabling resilient engineering systems. Among the suggested principles are functional and physical redundancy, the ability to reorganize, the roles of human back-up and creativity, avoidance of complexity, graceful degradation, and so on. The availability of these principles during design and operation will depend largely on the context and type of disruptions facing the system, its architecture, and on the judgment and experiences of the decision-makers. Table 7 presents design principles for resilience, as stated by Madni & Jackson (2009).

Table 7: Excerpt of management principles for resilience (adapted from Madni & Jackson (2009)).

Design principle	**Description**
Functional redundancy	Several alternative components can perform the same function.
Physical redundancy	Duplication of components to protect against failure of function.
Reorganization	System restructuring after external change.
Human backup	Humans backing up automated systems in case of failure.
"Human-in-loop"	Humans should support the need for creative problem-solving.
Predictability	Systems should behave predictably.
Complexity avoidance	Minimize complexity, similar to the second design axiom (Suh, 1990, 2001).
Context spanning	Systems should be able to survive (survivability).
Graceful degradation	Systems should degrade in a controlled, gradual manner.
Drift correction	Monitor and control drift towards brittle states by timely preventive action.
"Neutral state"	Systems should be able to prevent further damage until problem diagnosis.
Inspectability	Systems should allow for easy human intervention.
Intent awareness	Systems and humans should have a shared model of intent.
Learning/Adaptation	Continuously update knowledge base to adapt and improve the system.

For an extended list of principles for resilience in engineering systems, see Jackson & Ferris (2013). Some of these heuristics support several other non-functional requirements (like safety and reliability), and some of them seem contradictory (like complexity and redundancy, see Perrow (1999)). For a discussion on what distinguishes resilience strategies and strategies for enhancement of reliability, see Uday & Marais (2015). Uday & Marais (2015) hold that for components and simple systems, principles for reliability are adequate, while for more complex systems, or systems-of-systems, resilience is needed in the case where failures occur, despite measures to make these complex systems reliable. In such cases, resilience is ensured, for example, by human intervention. This corresponds, for example, to previous discussions on HRO and latent capabilities in engineering systems. There is a clear link between these principles and points made in Section 2.3.

Richards (2009) presents design principles for designing survivable engineering systems, with application to aerospace systems. He considers resilience as a third principle for ensuring survivability, adding value in the post-disruption phase. Here, resilience implies an active intervention into the disrupted system to replace components or repair the engineering system. Replacement indicates substitution of system components, while repair indicates restoration of system components, both for improvement of performance after a disruption. In marine technology, survivability can describe a naval vessel's vulnerability to targeted attacks (Boulougouris & Papanikolaou, 2013), and its ability to recover by enabling certain damage controls.

Woods (2015) suggests that resilience is used to describe four concepts that are similar, but not the same. First, resilience is seen as the *ability to rebound* from disrupting events and returning to normal activities. In this perspective, resilience means that some capabilities need to be present in the system before the disturbance and hence relates more to those capabilities, than what actions are taken once the disturbance occurs. Second, some authors view *resilience and* *robustness as the same concept*. Woods (2015) and others (Asbjørnslett & Rausand, 1999) argue that this is erroneous, as robustness is only possible to ensure if we have been able to model all possible disturbances. For events of that are very improbable, but have very large consequences, that is clearly impossible. The third perspective sees resilience as *graceful extensibility*. Hence, this perspective asks how system resources can be stretched to accommodate the new conditions. This is opposite of brittleness, which characterizes systems whose performance declines immediately when exceeding its boundaries. Fourth, resilience is the *sustained adaptability* of systems that are layered networks. By sustained adaptability, Woods (2015) means the mechanisms that enable systems to adapt to a variety of circumstances over longer time horizons. To design for sustained adaptability, we need to know the architectural characteristics and design principles that enable continued functioning.

Grøtan (2014) studies operational resilience within a framework of regulatory compliance, and Grøtan (2017) adapts the core concepts from the discussion by Woods (2015), into four *levels* of resilience within the Training for Operational Resilience Framework. The two first levels, *explication* and *interpretation* are based on compliance with regulations. *Explication* makes tacit, but existing practices visible, while *interpretation* allows for selection for the best actions in the face of uncertainty among a set of pre-defined actions. The latter two levels, *sensemaking* and *improvisation* are based on deviation from prescribed operations, within some larger "margin of manoeuvre" (Grøtan, 2017). *Sensemaking* allows for the creation of options partially beyond the intended and recognized modes of operation, whereas *improvisation* means that controlled, but improvised deviation to cope with the unexpected. The risk of "adaptive failure" hints at a need for managerial control to encapsulate the limits for what constitutes acceptable improvisation.

The need for organizational structure in situations of sensemaking and improvisation is supported by the fact that the latter characteristics resulting from individual action, and needs to be communicated (Weick, 1993). In Weick's (1993) analysis of the 1949 Mann Gulch wildfire, it is found that the leader of a team of firefighters was unable to communicate his solution of setting a fire in front of himself to escape the fire encroaching from behind. The rest of the team misunderstood this creative problem-solving, and instead attempted to run away, resulting in the death of most crew members. This example shows that sensemaking or improvisation is insufficient for resilience if organizational structures collapse.

2.4.4. Measuring resilience

Like with the qualitative definitions of resilience, there is little agreement among the proposed resilience metrics. Most measures of resilience in the literature make use of the following three parameters; the change of performance through disruption ΔQ_r, the duration of disruption ΔT, and the cost C_R of restoring the system to a stable state. Incidentally, these three dimensions are used to evaluate the resilience of a marine transportation system by Omer, Mostashari, Nilchiani, & Mansouri (2012). For a thorough review of resilience measures and metrics, see Hosseini, Barker, & Ramirez-Marquez (2016). They decompose the proposed metrics into general and structural-based measures, where general measures are divided according to whether they are deterministic or probabilistic, whereas structural-based measures encompass optimization and simulation models.

The performance profile over time for a resilient system is illustrated in Figure 17. After an initial period in which the system operates as intended, a disruption occurs that significantly degrades the system to a disrupted state. From a disrupted state, the resilient system will be able to recover its functioning and return to an improved, stable performance level. The disruptive event can cause the performance to drop below a performance threshold that defines whether the system functions. Below its performance threshold, we can refer to this event causing loss of functionality as a failure mode (Rausand & Høyland, 2004), at some level in the functional hierarchy of the disrupted system. Similar visualizations of resilience are provided by several papers (Ayyub, 2014; Bruneau et al., 2003; Zobel, 2011). Boulougouris & Papanikolaou (2013) use a similar graph to visualize naval ship vulnerability, and recoverability through immediate damage control measures after a successful enemy strike. In relation to the common bow-tie model, the disruption in Figure 17 constitutes the accidental event (Asbjørnslett, 2009), whereas the degradation following the event can be reduced through barriers. Vulnerability assessments (Asbjørnslett & Rausand, 1999; Berle, Asbjørnslett, & Rice, 2011) go beyond the bow-tie by considering a more extensive set of recovery actions that help restore the system.

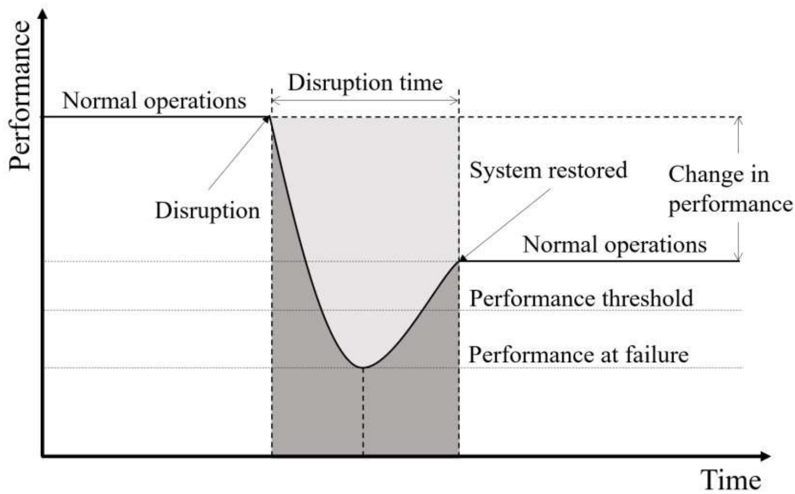

Figure 17: Performance variation over a time period, as an indicator of resilience (Asbjørnslett & Rausand, 1999).

Numerous additional sources propose practical resilience metrics that aim to support decision making (Ayyub, 2014; Bruneau et al., 2003; Farid, 2015; Francis & Bekera, 2014; Zobel, 2011). Bruneau et al. (2003) measure community resilience against earthquakes by assuming an instantaneous failure and a linear recovery profile, which considers the time it takes to recover the system performance completely. In this model, failure is completely brittle, meaning that the system hits its worst performing state immediately after a disruption. Zobel (2011) proposes a resilience function that takes decision-maker preferences regarding the trade-off between the loss of performance due to disruption, and the disruption time. Both Bruneau et al. (2003) and Zobel (2011) assume that recovery will fully restore performance to the levels observed pre-disruption. On the other hand, many other measures of resilience accept deviation between pre- and post-disruption performance levels (Hosseini et al., 2016), and accept some permanent degradation. For example, resilience can be construed as the ratio between post-disruption performance and pre-disruption performance (Farid, 2015; Francis & Bekera, 2014).

Among the most comprehensive suggestions for resilience measures, are those presented by (Ayyub, 2014, 2015). Ayyub (2014) measures system resilience according to Equation (4).

$$R_e = \frac{T_i + F\Delta T_f + R\Delta T_r}{T_i + \Delta T_f + \Delta T_r} \tag{4}$$

In Equation (4), $\Delta T_f = T_r - T_f$ and $\Delta T_r = T_f - T_i$. T_i refers to the time a disruptive event is initiated, before which the system performance is given by Q_i, T_f refers to the time the disruption is completely manifest, while T_r refers to the time recovery is completed to a state where performance is Q_r. F refers to a failure profile that measures the robustness or redundancy of the system. R refers to a recovery profile that measures the quality of the actions resorted to during the recovery efforts.

A more practical resilience metric is presented in Equation (5), developed due to the impracticalities of developing good measures of F and R (Ayyub, 2015). In Equation (5), T_e refers to the end of the planning horizon, over which we are interested in measuring system resilience.

$$R_e = 1 - \frac{(T_r - T_i)(Q_i - Q_f)}{2Q_i T_e} \tag{5}$$

There are multiple issues with applying the resilience metric proposed in Equation (5) as well. The measure assumes a brittle failure profile and full recovery to the initial performance level. Further, it assumes a given planning horizon, meaning that resilience becomes dependent on an arbitrary time period unless the measure is applied to an operation with a well-defined duration.

In summation, most resilience metrics studied do not capture in a single metric all dimensions of the problem, and hence should be applied with caution. Rather than concluding on a single, correct operationalization, we suffice with considering resilience in terms of the trilemma proposed in Figure 18. It is likely that there will be a trade-off between minimization of deterioration, disruption time, and cost of recovery in most cases.

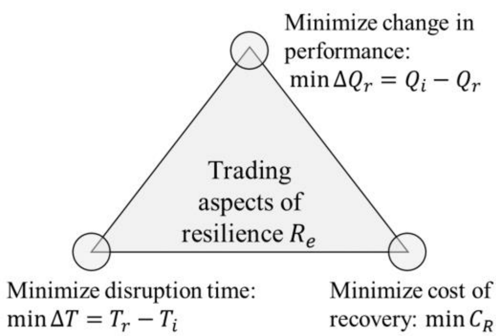

Figure 18: The resilience triangle. Resilience can be increased by minimizing performance degradation, disruption time, and cost of recovery (Pettersen, Erikstad, et al., 2018).

2.4.5. Summary of resilience

The term “resilience” requires careful definition. In this thesis, resilience is defined as “the ability of a system to be recovered from a disrupted state to an improved state”. A resilient system is characterized by the minimization of change in performance (permanent degradation), minimization of disruption time, and minimization of recovery costs. Resilience is not an alternative, but rather a complement to compliance with rules, regulations, and existing operating procedures. Furthermore, resilience requires a change of mindset with respect to risk management, in which system operations are continuously monitored and adapted to emerging needs. Hence, even though the basic definition above fits an example of “resilience as rebound” (Woods, 2015), as a reactive mechanism to cope with disruption, this picture changes when taking the engineering systems perspective, to overlap with perspectives of “resilience as graceful extensibility” and “resilience as sustained adaptability”.

To achieve resilience as defined above, latent functional capabilities offer some promising advantages. By exploiting existing resources, the duration and costs of the disruption may be limited. The search for a common metric for resilience remains inconclusive but highlights the importance of comparing alternative means to recover from disruption.

This review of resilience grounds Research Objective 2 in theory and provides a starting point for Contribution 3 and 4. For Contribution 3, the review of resilience definitions and measures provides a basis for the development of models to evaluate whether a response to disruption by latent capabilities, enhances resilience more than alternative strategies. For Contribution 4, understanding resilience as an emergent property with strong organizational connotations, is useful when developing a method for assessment of latent capabilities for contingency planning.

2.5. Maritime contingency management

Important reasons for developing resilient marine engineering systems are i) the need for addressing disruption risks faced by marine systems during operations, and ii) for exploiting existing marine systems in emergency response and disaster relief operations.

We first cover operational disruptions in marine operations and then move to study how marine systems can provide a response to crises. Our study of the latter type of contingencies is limited to the response to large-scale crises, major emergencies, disasters, and catastrophes. According to Altay & Green (2006), these are the events that may require a cross-functional response. Hence, these may need to be addressed by the use of resources not initially intended for emergency response. Providing a similar delimitation, Galindo & Batta (2013) define disaster operations management to concern events that seriously disrupt the functioning of communities, that exceed community resources to cope with the event, and that require non-standard procedures.

2.5.1. Operational disruptions of marine systems

Operational disruption risk in marine supply chains, especially from low-frequency, high-impact events, was studied by Berle, Rice, et al. (2011) and Berle, Asbjørnslett, et al. (2011). Berle, Rice, et al. (2011) identify key functions in the marine transportation system, to establish what failure modes marine supply chains are vulnerable against. They adopt the failure mode concept from reliability engineering, which refers to loss of critical functionality (Rausand & Høyland, 2004). The outcome is an improved understanding of what functions to prepare to restore, in case of failures. In a follow-up paper (Berle, Asbjørnslett, et al., 2011), they develop a formal vulnerability assessment (FVA) applying the same failure mode thinking to low-frequency, high-impact events. The framework adapts the International Maritime Organization's (IMO) formal safety assessment (FSA), which is commonly used to improve maritime safety (IMO, 2015), for vulnerability assessment in maritime logistics. In FVA, the hazard focus in FSA is complemented with a focus on restoring the ability of a system to perform its mission. This main stages in the FVA methodology are presented in Table 8. Where the "hazard focus" can be seen as the process to make marine systems compliant with IMO guidelines, the "mission focus" goes beyond that, enhancing resilience while remaining compliant.

Table 8: Formal vulnerability assessment (FVA) (Berle, Asbjørnslett, et al., 2011).

Steps	Description	Hazard focus (FSA)	Mission focus
0	Preparation	Define system, parameters, criteria, boundaries	
1	Hazard identification	What may go wrong?	Which functions/capabilities should be protected?
2	Vulnerability assessment	Investigation/quantification, most important risks	Investigation/quantification, all relevant failure modes
3	Vulnerability mitigation	Measures to mitigate most important risks	Measures to restore functions/capabilities
4	Cost/Benefit assessment	Cost/Benefit assessment	
5	Recommendations for decision making	Recommendation and feedback to assessment	

The primary insight from Berle's work for this thesis is that for low-frequency, high-impact events, identification of failure modes leads us to develop contingency plans on basis of functional criticality. When the scenario leading up to an event is unknowable, we may have to be satisfied with understanding the consequences of a loss of functioning. Hence, by identifying critical functions, we become able to plan how those functions can be replaced, possibly by taking advantage of latent capabilities. This awareness does not require knowledge about the probability of the particular failure event.

Strategies for recovery of disrupted marine supply chains are presented by Mansouri, Nilchiani, & Mostashari (2010) and Omer et al. (2012). Mansouri et al. (2010) introduce a three-step resilience assessment and decision-making framework for port infrastructure. They propose a vulnerability assessment followed by proposing various strategies for resilience. Last, a decision analysis using tools like decision trees and real options analysis is performed, to establish the favoured means to increase resilience. Omer et al. (2012) apply the proposed framework and combines it with system dynamics and a network optimization model to assess resilience. The latter finds a parallel in ship routing and deployment, where disruptions due to temporary production shutdown and bad weather are handled through a combination of simulation and mixed-integer programming (Christiansen et al., 2007). Common policies for increased robustness in these cases include rerouting and change of vessel speed.

2.5.2. Managing large-scale emergencies

Emergency management addresses the need to protect systems, society and the environment from large-scale accidents and natural disasters. Similar to the increase in research on engineering system resilience, as covered in Section 2.4, there has been a rise in focus on disaster resilience, or the resilience of society and the environment towards disasters (Allenby & Fink, 2005; Gilbert, 2010). Emergency management structures the planning phases for disturbances into four, after McLoughlin (1985), as i) mitigation, ii) preparedness, iii) response, and iv) recovery. These phases are categorized either as pre-event (i and ii), or post-event (iii and iv) planning (Tufekci & Wallace, 1998). This planning process is often referred to as the disaster cycle (Ayyub, 2014; Gilbert, 2010; UN/ISDR, 2005). A similar three-phase structure is used by Kovács & Spens (2007) in their proposed framework for disaster relief logistics. They refer to the phases of disaster relief operations as i) preparation, ii) immediate response, and iii) reconstruction.

Emergency management research reviewed spans from the study of humanitarian and disaster relief operations to emergency response planning models in operations research. The latter category is covered in the next section. In the maritime emergency context, Mileski & Honeycutt (2013) presents a framework for flexible pooling of available resources in the event of a maritime disaster. They base their approach on the case of the Macondo oil spill that followed the blowout that sank the Deepwater Horizon semi-submersible rig. During the Macondo oil spill, there was a large increase in the offshore vessel activity, indicating that this could also represent a business opportunity for ship owners. Kaiser (2016) studies the overall offshore support vessel activity based on automatic identification system (AIS) data, finding an increase of 40 % in the amount of activity in the months after the Deepwater Horizon accident.

Humanitarian relief is relevant for this thesis as an analogue to applications of marine systems to sudden-onset demands outside the intent or recognition of designers. Humanitarian logistics operations utilize the adaptive capacities of complex supply networks that are able to rewire their connections and meet the new, unexpected demands of emergency scenarios (Day, 2014). Kovács & Spens (2007) point out that large-scale emergencies demand an immediate response, making it necessary to deploy existing supply chain resources at once, even though knowledge of the situation may be very limited. Similarly, Oloruntoba & Gray (2006) argue that agility (the ability to change fast) must be a key property in humanitarian relief operations, due to the need to swiftly adjust to meeting the right demand. The benefits for commercial actors taking part in humanitarian logistics range from commercial social responsibility to strategic commercial concerns (Van Wassenhove, 2006; Vega & Roussat, 2015). Van Wassenhove (2006) points out that an agile, adaptive approach to humanitarian operations corresponds to properties that can provide companies with a competitive edge when facing other types of disruptions. Hence, participation in humanitarian relief can be seen as a source of organizational learning. Further, the importance of standardization and modularity in equipment and organizations for humanitarian supply chains is highlighted by Jahre & Fabbe-Costes (2015). Vega & Roussat (2015) review the role of logistics service providers in humanitarian supply chains, and identify three main roles for companies involved, according to whether they see humanitarian relief as a commercial social responsibility commitment, as a source of ad-hoc contracts, or as a strategic business opportunity.

From the maritime perspective, good examples of commercial actors partaking in humanitarian relief are the use of roll-on, roll-off carriers for delivery of goods to disaster-struck areas (Berle et al., 2012; Wilberg & Olafsen, 2012), and the use of offshore vessels in search and rescue missions during the Mediterranean refugee crisis (Cusumano, 2017). Berle et al. (2012) consider the case of supplying Haiti after the 2010 Earthquake, while Wilberg & Olafsen (2012) propose pre-positioning of relief equipment on vessels in commercial operations, to enable an agile response. The parallel from these examples to the concept of latent capabilities for emergency response justifies this discussion of humanitarian logistics research.

2.5.3. Decision models for maritime emergencies

Reviews and critical perspectives

Decision support methods have long been applied to large-scale marine emergency management. Given the foundations of operations research within defence applications (Checkland, 2000), this is not surprising. In recent years, several review papers have been written summarizing the general literature on emergency response planning, taking a slightly pessimistic tone regarding the applicability of many methods that are commonly used for other problems studied in operations research.

Altay & Green (2006) summarize the literature on what they call “disaster operations management”, arguing that the term “management” implies a degree of control not always found in situations that can be termed “disastrous”. As disasters are events with a high degree of societal importance, where the needs of multiple stakeholders with multiple objectives must be accommodated, it is difficult to determine what constitutes the best decision (Altay & Green, 2006). Simpson & Hancock (2009) review the first fifty years of emergency response planning in operations research. They conclude that the operations research literature largely has addressed well-defined problems in which management can access data that is deterministic, possibly containing epistemic uncertainty or data that is uncertain, but for which reliable historical records exist and that hence can be well-represented probabilistically. They explicitly distinguish "routine" emergencies that occur frequently, like ambulance deployments, from emergencies that are less frequent, and hence are more ill-defined. Galindo & Batta (2013) present an updated review following Altay & Green (2006), finding a few major developments beside an increase in the number of case studies in the literature. They recommend further study of coordination among actors in the emergency response value chain, and the introduction of new techniques and methods like "soft OR[4]" (see Checkland (2000) or Mingers & Rosenhead (2004)). Further, to improve the relevance of decision models, they suggest statistical analysis of the underlying problem situations to derive realistic model data, and measures of effectiveness for techniques to assess model goodness of fit.

The criticism articulated by the above-mentioned review articles resonate well with perspectives given earlier in Chapter 2, including Rittel & Webber's (1973) formulation of the *wicked problem*, or Ackoff's (1979) reflections on the distinction between a *mess* and a *problem*. The more recent reviews (Altay & Green, 2006; Galindo & Batta, 2013; Simpson & Hancock, 2009) show that the issues discussed by Ackoff, Rittel and Webber in the 1970's persist in emergency management.

For marine emergency response, the interest in decision support tools greatly increased during the 1970's and 1980's, in particular for management of oil spill response resources on various planning horizons, ranging from strategic via tactical to operational. Maritime problems were among the first emergency response situations to be studied using methods from operations research (Caunhye, Nie, & Pokharel, 2012). The remainder of this subsection covers the main literature on applications of techniques from operations research to marine emergency response and shares a methodical foundation with the fleet size and mix literature addressed in Section 2.2. While these are both grounded in operations research, these bodies of literature seem to be largely disjoint, even though they both concern issues of optimizing a geographically dispersed system-of-systems characterized by functional unity, without physical unity. A notable difference is that the fleet size and mix literature commonly focuses purely on economic objectives for commercial shipping applications (Pantuso et al., 2014, 2016). On the other hand, measures of effectiveness in the resource allocation models for emergency response seem to focus on a much wider set of objectives, something that is also suggested in the naval fleet planning literature (Hootman & Whitcomb, 2005).

The resource allocation models discussed herein often consider equipment, and can hence be seen to address what should be done to meet specific functional requirements (demands) on a subsystem level. Therefore, questions often relate to what combinations of equipment to use, and where to locate this equipment, be it on ships, or easily available at onshore bases for installation on ships in the event that something happens.

Applications to oil spill response

Among the earliest applications of resource allocation models to oil spills, are tactical (Charnes, Cooper, Karwan, & Wallace, 1979; Psaraftis & Ziogas, 1985) and strategic models (Belardo, Harrald, Wallace, & Ward, 1984; Psaraftis, Tharakan, & Ceder, 1986) that attempt to optimize the response. Charnes et al. (1979) model resource allocation for major pollution incidents using a goal programming formulation, in which the objective is to target an optimal quality and risk level, in three stages of oil spill response; offloading, containment and removal.

[4] OR – Operations research

Psaraftis & Ziogas (1985) present an optimization procedure for allocating resources for the clean up of specific oil spills, by minimizing a weighted sum of the response and damage costs. They use a dynamic program that repeatedly solves a series of knapsack subproblems that determines whether specific oil spill equipment should be used. Belardo et al. (1984) derive a partial set-covering model for the strategic location problem for oil spill response equipment. The model applies a multi-objective approach and seeks to maximize the probability that various types of oil spills will be covered. Their extended approach to the maximal covering model takes into account the differences in equipment demand, based on the fitness of addressing specific types of oil spills. Psaraftis et al. (1986) develop a strategic model for allocating clean-up equipment to locations with a high associated risk of oil spill. The model minimizes costs associated with opening facilities, acquisition of capabilities, expected costs of mobilization, transportation and clean-up, and expected costs due to environmental damage and damage to the equipment.

The strategic and tactical levels are considered together in a sequence of papers published in the mid-1990's (Srinivasa & Wilhelm, 1997; Wilhelm & Srinivasa, 1996, 1997), that strongly focused on describing the heuristic solution approaches applied. In the tactical case, they minimize the response time (Srinivasa & Wilhelm, 1997; Wilhelm & Srinivasa, 1997), while in the strategic case they minimize costs of the contingency plan (Wilhelm & Srinivasa, 1996). Iakovou, Ip, Douligeris, & Korde (1997) develop an integer programming model for optimizing the allocation and capacity of clean-up equipment, selecting storage facility sites, type and number of clean-up systems, and policies for equipment deployment. Hence, the proposed model combines strategic and tactical decisions.

More recent oil spill response models have included modelling of the oil spill physics. Zhong & You (2011) include physical modelling of the oil spill in the operational decision context and solve the optimal planning using a multi-objective mixed-integer programming model. Grubesic, Wei, & Nelson (2017) use a simulation model to model the physical spread of the oil spill and solve the tactical planning problem using a mixed-integer program for a number of discrete oil spill scenarios derived by simulation. Both of these models are deterministic mathematical programs, even though the problem is solved for several individual scenarios.

Verma, Gendreau, & Laporte (2013) address oil spill response equipment location and capabilities offshore Newfoundland, using a two-stage stochastic programming problem with recourse. The first-stage decisions, i.e. decisions made before uncertainty is resolved, include both allocation of equipment facilities and equipment acquisition decisions, representing the strategic decisions in the problem. The second-stage decisions represent the tactical decisions that support the strategic decisions and are to be made after the uncertainty is resolved. These include the deployment of equipment to specific sites, which influences the amount of oil the emergency response system is able to contain. For generic formulations of recourse problems and an introduction to stochastic programming, see Birge & Louveaux (2011) or King & Wallace (2012).

Garrett, Sharkey, Grabowski, & Wallace (2017) study the problem of oil spill response in the Arctic, where a key challenge is the lack of emergency infrastructure. They present a mixed-integer program in which the objective is to minimize the importance-weighted completion time of a set of emergency response tasks. The fulfilment of model objectives is dependent on the amounts of resources that can be mobilized from certain locations, subject to a task schedule, and the resource amounts allocated to these locations.

Other applications to marine emergency response

Among other common applications of operations research methods to marine emergency response planning are search and rescue (Brachner & Hvattum, 2017; Karatas, Razi, & Gunal, 2017; Pelot, Akbari, & Li, 2015; Razi & Karatas, 2016) and emergency towing (Assimizele, Royset, Bye, & Oppen, 2018). In terms of targeted response times, search and rescue and emergency towing operations may be even more pressing than oil spill clean-up, due to the short time people survive in water, and the great consequences of ship grounding.

Pelot et al. (2015) compare a number of model formulations for maritime search and rescue. They start from a maximal covering location problem and apply a number of previously published extensions of that model as a means to support resource allocation for maritime search and rescue. The extensions of the original model include considerations of partial coverage, capacity limits for response units, probabilistic coverage, and multiple objectives. The results show that the capacity limit model and the probabilistic model emphasize improved response time and balanced workloads, whereas the total coverage is reduced as a consequence, compared to the pure maximal covering location problem formulation.

Brachner & Hvattum (2017) study the problem of combining safe personnel transport with helicopters with planning of emergency preparedness in the Barents Sea and suggest to combine routing with covering in a mathematical model, solving the problem via a heuristic solution method. The model seeks to minimize the overall path length to locations offshore. The problem highlights the importance of seeing available resources, assets both for transport and preparedness, as constituents in a single supersystem. This is especially important in the Arctic, where there is very limited existing infrastructure, creating a need for contingency planning.

Razi & Karatas (2016) develop a multi-objective, mixed-integer programming model for locating search and rescue boats in the Aegean sea, a relevant problem due to the great number of migrants attempting to cross the Aegean from Turkey to Greece. The objective function consists of terms that minimize response time, costs, and the mismatch between supply and demand for resources. In a follow-up, Karatas et al. (2017) combine an integer programming approach with a discrete event simulation model to address search and rescue by helicopters. The optimization model first finds a configuration based on the selection of helicopters and bases for these, by minimizing response time. The simulation is run for the resulting configuration and changed in correspondence with the simulation results.

Emergency towing missions is addressed by Assimizele et al. (2018), who seek to determine the optimal positioning of tugs along the Norwegian coast. Assimizele et al. (2018) present a non-linear binary program to minimize costs associated with oil spills from grounding accidents, which is made linear with little resulting optimality gap. The cost elements include clean-up, socio-economic, and environmental costs, and the decisions are made to dynamically locate the tugs in a given area at a given time. The model is tested on the actual emergency towing system of the Norwegian Coastal Administration for Northern Norway. The results on real case data show that there is significant potential in using the model to determine vessel allocation.

The literature on resource allocation using methods from operations research provides a mature toolbox for assessment of many problems in the management of fleet systems. The tools offered, combined with relevant measures of effectiveness can provide insights to the optimal deployment of existing or hypothetical fleets, as well as more objective measures of modes of operations for fleets, relevant with respect to latent capabilities.

2.5.4. Summary of maritime contingency management

Like achieving system resilience, contingency planning can be greatly improved by considering latent capabilities. This section has studied several related topics ranging from disaster operations management and humanitarian relief operations to operations research methods that address emergencies. Humanitarian relief and military logistics offer several examples that show the value of latent capabilities, such as the use of roll-on, roll-off carriers as an especially versatile platform for delivering cargoes when functioning of port facilities are disrupted. Furthermore, operations research methodology stems from the Second World War, a time when these new techniques mainly constituted a means to improve operations of existing military assets, over a short planning horizon. Successful applications of operations research (OR) to contingency management include the development of many models for resource allocation towards marine emergencies, including oil spills and search and rescue operations. The use of these methods also feeds back into support for design decision-making by enabling evaluation of alternative fleets, in addition to their intended use, which is to identify the best use of existing assets in the shorter term. A drawback of OR methodology is the inability to address very rare events with great consequences, *disasters*, a problem which has been commented on and connected to the "wicked problem" in the OR context by Simpson & Hancock (2009).

With respect to the concrete research objectives, the material reviewed in Section 2.5. is important for Research Objective 4 and 5 in particular, and provides additional support for Contribution 4 and 5. Concerning Contribution 4, existing literature on vulnerability assessment and disaster management drawing on the capabilities of maritime logistics systems represent a useful theoretical perspective. For the link between Research Objective 5 and Contribution 5, the mathematical programming approaches to design and deployment of emergency response systems provides the primary methodical background.

2.6. Evaluation and summary of the review

The review summarizes the literature with relevance for the research objectives. A rather wide scope of research has been consulted. Academic journals and conference proceedings in engineering design, marine design, operations research, and systems engineering are the most cited sources in this thesis. An overview of the publications that have been cited the most by this thesis, is presented in Table 9.

Table 9: Overview of the ten most-cited journals and conferences in the thesis.

Journals	No. of papers
Research in Engineering Design	10
European Journal of Operational Research	9
International Marine Design Conference	9
Transactions of the RINA Part A: IJME[5]	8
Systems Engineering	8
Naval Engineers Journal	7
Reliability Engineering and System Safety	5
Journal of the Operational Research Society	5
Design Studies	5
Management Science	5

To reflect that the thesis considers the "state of the art" at the time of its publication with a majority of recently published material, Figure 19 plots the number of sources cited against the year published.

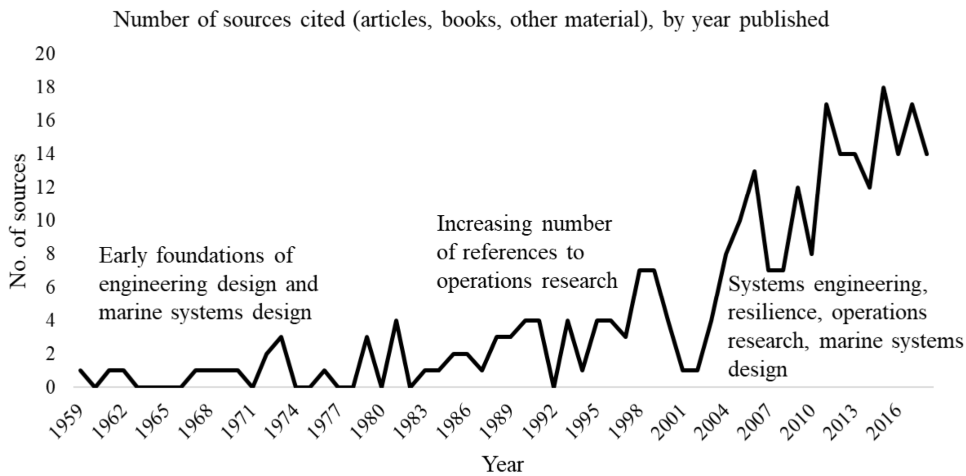

Figure 19: Number of citations by year of publication.

[5] RINA –Royal Institution of Naval Architects, IJME – International Journal of Maritime Engineering

From Figure 19, we observe that a clear majority of references are recent articles, with a smaller number of important early contributions. To a large extent, the early references represent milestones in the development of the fields and document ideas that have been very influential for the thesis. Early references are mostly related to engineering design and marine systems design. An increase in the number of operations research references is seen in the 1980s. More recent references are more evenly spread across the topics that have been reviewed. The recent literature includes references focusing on socially complex issues within the engineering context, as exemplified by the "engineering systems" literature (de Weck et al., 2011).

2.6.1. Summary

We finalize the review with some remarks. Engineering design, including marine systems design, naturally focuses on meeting explicitly stated functional requirements. Research on complex engineered systems and resilience has increasingly taken an "engineering systems" perspective, meaning that there is a recognition that systems evolve beyond their initial design during the operational phase. Among the developments seen in systems design is a focus on handling future uncertainty, but there has been little focus on resilience from a design perspective. Operations research provides a toolset for improved utilization of existing resources, and increasingly focuses on advancing the sophistication of modelling techniques.

With reference to Section 1.1. and 1.2., the literature review supports the fulfilment of research objectives (RO) and the backing for the contributions (C) as follows: **Section 2.1.** provides the systems design background which is relevant for RO 1 and RO 3, and connects these to C 1 - C 3. **Section 2.2.** reviews the marine design background and has relevance for all ROs, except RO 4, and connects these to C 1, C 3 and C 5. **Section 2.3.** discusses the conceptual background for latent capabilities, connecting RO 2 – 4 to C 2 – 4. **Section 2.4.** relates the need for connecting resilience and latent capabilities (RO 2), to new models and methods (C 3 and C 4). **Section 2.5.** connects RO 4 and RO 5 to C 4 and C 5, providing an overview of contingency management and emergency response in the maritime domain.

3. Research design

This chapter positions the thesis according to the research methodology and methods applied in the research. It also revisits the research process that resulted in this thesis.

3.1. Research methodology

Research methodology comprises techniques and analytical tools that can be applied to gather data and gain knowledge from analyses. Research "methodology" refers to a wider concept than research "method". Methodology implies consideration of why specific methods are appropriate to answer a question (Kothari, 2004), and hence explains why the choice of method will differ between fields of research (Checkland, 2000). This subsection positions the research in terms of *methodology*, while the next subsection will present the research *methods* used.

Research methodology can be categorized in numerous ways. The most common is the distinction between quantitative, qualitative, and mixed research (Creswell, 2014). Quantitative research develops knowledge by establishing causal links between observed phenomena, through hypothesis testing, as well as the development and use of mathematical models. Quantitative research can be divided into *inferential*, *experimental*, and *simulation* approaches (Kothari, 2004). *Inferential* research infers relationships or characteristics on basis of a database of observations. *Experimental* research utilizes a partially controlled research environment to observe the effect of some variables on other variables. *Simulation* research relies on a constructed environment in which the behaviour of a system can be observed under controlled conditions. Qualitative research seeks to understand phenomena through observations, interviews, or in-depth review of case studies. *Mixed* research draws on both qualitative and quantitative research methodology (Creswell, 2014).

While engineering research normally leans towards the quantitative end of the spectrum, due in part to the fact that engineering must rely on mathematical models, it is undeniable that engineering research often contains elements of both qualitative and quantitative research methodology. Even the natural sciences rely on preliminary explorations of phenomena from a qualitative perspective, in order to make it possible to quantitatively analyze them (Kuhn, 1961). In organizational science, Weick (1995) points out that data must be grounded in theory, but that data sometimes deviates from theory, necessitating theorization. Theorization implies a view of theory development as a process, rather than a final product. Qualitative work like the formation of concepts, propositions and hypotheses will be part of this process before models can be formed to analyze data quantitatively. From the perspective of logistics research, Kovács & Spens (2005) highlight the need for abductive reasoning as opposed to deduction and induction, in situations where real-life phenomena deviate from phenomena that can be explained by existing theory. In a recent article, Szajnfarber & Gralla (2017) argue that engineering researchers should develop skills in qualitative research, as certain situations cannot be effectively addressed through a purely quantitative research methodology. Circumstances where research in engineering should employ qualitative research methodology, include situations with understudied phenomena, situations in which it is difficult to extract systems from their environment, and situations in which existing theory is inadequate for forming hypotheses or explaining observations.

Besides the qualitative versus quantitative distinction, research is often classified according to the following criteria (Kothari, 2004):

- *Descriptive* as opposed to *analytical*: Does the research aim to derive facts *describing* a specific state-of-affairs, or does the research *evaluate* current facts to derive new facts?
- *Applied* as opposed to *fundamental:* Does the research aim to derive solutions for *real-life* problems faced by society or organizations, or does the research aim to contribute to the *general body of knowledge*?
- *Conceptual* as opposed to *empirical:* Does the research aim to develop *theory*, or does the research aim to derive knowledge about the relationship between a set of independent and dependent variables from *experiments or empirical data*?
- *Other research typologies:* Several additional classifications exist, but are primarily variations on the above-mentioned research classes:
    - *One-time* as opposed to *longitudinal*: Is the research confined to a single time period, or is the research carried out over several time periods?
    - *Clinical* or *diagnostic:* Is the research aimed at studying a very small sample size, or a single, in-depth case study?
    - *Conclusion-oriented* as opposed to *decision-oriented:* Is the researcher free to study a problem and conceptualize it as he wishes, or is the researcher studying a problem defined by an external decision-maker? *Decision-oriented* research can either be *descriptive*, concerned with how people make decisions in real situations; *prescriptive,* concerned with recommending good decisions for real people in real situations; and *normative*, concerned with determining optimal decisions for rational agents in idealized situations (Bell, Raiffa, & Tversky, 1988).

According to these perspectives, this PhD project is categorized as *conceptual, mixed quantitative-qualitative* research. Table 10 shows that there are both *descriptive* and *analytical* elements and both *applied* and *fundamental* elements of this research. Along the *descriptive-analytical* axis, the *descriptive* elements constitute documentation of case studies, while the *analytical* implies derivation of new facts about latent capabilities, meaning this classification perhaps should include *synthesis* as well as *analysis*. Along the *applied-fundamental* axis, the *applied* elements signify that we strive for impacting design and operation of ships, whereas the *fundamental* elements signify a need for reassessing certain concepts in systems design.

Table 10: Classifying the thesis on descriptive-analytical and applied-fundamental dimensions.

Descriptive versus analytical	**Descriptive**	**Analytical**
	Derives new facts through case studies. In particular, the offshore case study from Main Article 1 that is further outlined in Appendix C was formative for the research.	Uses current facts from the design and operation of ships to derive new facts about latent capabilities. This is done in Main Articles 2, 3 and 4.
Applied versus fundamental	**Applied**	**Fundamental**
	Provides insights that are potentially useful to the maritime industry. The implications for the industry are discussed in Chapter 5 of the thesis.	Provides insights that have fundamental implications for research on systems design, as shown by the partial refutation of axiomatic design in Main Article 2.

Furthermore, the research is mainly *conceptual* because it aims to develop theory, rather being mainly *empirical*. This is not to say that we do not use data. The research draws on small samples in the form of case studies and incident reports, upon which novel conceptual insights are synthesized. Even though the thesis contains *clinical or diagnostic* elements, making *case study research* a relevant method (Yin, 2006), classifying this research as mainly *empirical* would require that we test a set of hypotheses in the real world, to establish the actual relationship between a set of dependent and independent variables (Kothari, 2004). Finally, this research is an example of a *mixed quantitative-qualitative* approach. This is attributed to the need for developing theory, namely concepts like latent capabilities, on the boundary between several disciplines, in correspondence with the conceptual and exploratory focus mentioned above. Further, this research is *one-time*, rather than longitudinal, as it does not observe phenomena over a longer time but focuses on single events and the response to these, through the focus on evidence from case studies and incident reports. Finally, the research is, to an extent, an example of *decision-oriented* research with a *prescriptive* focus (Bell et al., 1988). The research also contains *conclusion-oriented* elements, as it focuses on the free conceptualization of the objectives, rather than focusing on meeting the needs of an external, industrial decision-maker.

3.2. Research methods

Research methods refer to techniques and tools that are applied when conducting research. Kothari (2004) distinguishes between i) research methods concerned with the collection of data, ii) techniques for deriving relationships between data, and iii) assessment of the research outcome. In this research, a mix of quantitative and qualitative methods have been used for these purposes. Beyond this, we should further clarify that some of this research effort has been aimed at studying design and decision support methods, as shown by the focus on design disciplines in the literature review. These methods are mostly quantitative and will be covered in Section 3.3.

With respect to the research methods that have been applied to the research, we can make the following categorization:

- **Defining the problem:** Defining unit of analysis, system context, research context, research objectives
- **Data collection:** Case studies including unstructured interviews, review of incident reports, industry-provided vessel data
- **Deriving relationships:** Development of conceptual frameworks, hierarchical decomposition of function and form, development of various design decision-making models
- **Methods for assessment:** Internal checks of consistency for concepts, validation and verification of models

This combination of research methods was chosen to elucidate the research problem from multiple angles. For example, case studies were used due to the desire to understand cases more in-depth. Vessel databases were consulted to parametrize design spaces and provide input for the decision-oriented methods. The development of a conceptual framework for latent capabilities was a necessary step to ensure that the concepts and theorization were well grounded in theory. Additional review of incident reports ensured a grounding in practice. The research remains largely exploratory and conceptual as verification that the latent capabilities concept can be applied in other real-world settings, beyond those found in incident reports and other case studies, would have been very time-consuming.

The theoretical approach was developed and informed through a continuous literature review, which particularly influenced the development of the conceptual framework. The literature is summarized in Chapter 2 of this thesis. Some additional aspects that help develop and position this thesis are:

- **Systems thinking:** This thesis as a whole does not seek to *reduce* the situations studied by considering only one type of method or model, even though approaches like axiomatic design are used in individual papers. For an elaboration on the importance of general design insight over results from design models, and for our realization that any reduction of an ill-structured problem to a decision model is essentially a design problem by itself, see Main Article 1.
- **Interdisciplinarity:** Consequently, an interdisciplinary approach is taken, in correspondence with the engineering systems perspective. There is much to learn from several disciplines that map onto the research problem at hand. See also the discussion above.
- **Collaborative learning:** Collaborative learning is characterized by symmetric agent relationships, with positive interactions between correspondingly knowledgeable agents that have different areas of expertise (Dillenbourg, 1999). Many of the ideas that are presented in this thesis, were developed in close collaboration with two other PhD students working on similar topics related to uncertainty in ship design, Carl Fredrik Rehn and Jose Jorge Garcia Agis. This collaboration started with the offshore case study used in Main Article 1. In addition, the collaboration helped frame Main Article 3.

3.2.1. Defining the problem

Unit of analysis

The unit of analysis for this research is the marine *engineering system*. By *engineering system,* we mean "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 et al., 2011). We are specifically interested in the maritime domain, even though some examples from outside this domain has been used, like the Apollo 13 spacecraft. Further, we study systems that range from the third to the fifth levels of complexity for technical systems outlined in Table 2 (Hubka & Eder, 1988). Hence, systems under consideration as units of analysis range from high-level ship subsystems and equipment, via the ship level, to the level of the fleet.

The corresponding unit of analysis for each of the main papers of this thesis are presented in Figure 20. Main Article 1 develops a ship design space determined on basis of several descriptive elements, including ship subsystems and main dimensions. Main Article 2 is limited to understanding subsystems as design parameters for the overall system. Main Article 3 decomposes functions and equipment for offshore ships and discusses collaboration between vessels for the emergency response mission on the fleet level. Main Article 4 presents a fleet deployment model and hence accounts for geospatial complexity in the measurement of effectiveness.

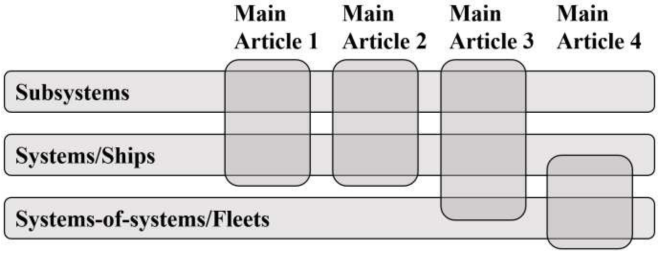

Figure 20: Units of analysis for the main articles.

Research objectives
A motivation for the research is to understand what it takes for the above-mentioned systems to become resilient. The problem statement of the thesis is captured in a single research question, which highlights the investigation of the relationship between resilience and physical, functional and operational characteristics of marine engineering systems. A preliminary insight is that latent capabilities represent an unexplored area of knowledge. On this basis, the research question is structured into five objectives, that are answered in the main articles.

3.2.2. Data collection
Data sources for this thesis include case studies, including unstructured interviews, review of incident reports, review of other industry-provided data, as well as vessel databases.

Case study research
Yin (2006) points to the case study as an empirical investigation of a "contemporary phenomenon within its real-life context", with the additional remark that there is often a blurry boundary between phenomenon and context. Hence, when the purpose is to understand complex socio-technical phenomena, case study research provides novel insight, and can also act as a starting point for structured explorations of the unit of analysis. While single case studies provide very small sample sizes, and the approach has been criticized for being impossible to generalize from, it is instrumental in defining exemplars and deepening knowledge for the unit of analysis, beyond what would be possible from surveying a large number of observations (Flyvbjerg, 2006). Insights into specific events are hence well-served by a case study approach. Appendix C describes the case study for the SIMOSYS[6] project that strongly contributes to the development of Main Article 1 and instigates an investigation of the Deepwater Horizon accident case studied in Main Article 3.

Review of incident reports
Reviews of incident reports from specific events are an important source of empirical knowledge for this thesis. Like the in-depth case study, these reports provide deep *diagnostic* insights regarding how a specific operational disruption was resolved. An example is Weick's (1995) recount of his analysis of the Mann Gulch disaster (Weick, 1993), that resulted in knowledge about the relationship between the collapse of sensemaking and organizational

[6] SIMOSYS was a *Knowledge-building project for industry (KPN)* supported by the Norwegian Research Council from 2014 – 2017. Partners in the project were NTNU, MIT, Ulstein International, and DNV GL. The main objective of SIMOSYS was to develop new knowledge for management of risk and uncertainty in marine systems design (Erikstad, 2014).

structures. Hence, review of reports is useful to study the relationship between resilience and latent capabilities, even if the efforts to recover are unique to the case found.

Especially important sources for insights regarding the relationship between latent capabilities and resilience are used in Main Article 2 and Main Article 3, and include the mission report for Apollo 13 (Cortright, 1970), the memoirs of Apollo flight director Eugene Kranz (Kranz, 2000), various reports on the Deepwater Horizon accident (Deepwater Horizon Study Group, 2011; Graham et al., 2011), and the subsequent oil spill response efforts (British Petroleum, 2010).

Vessel databases
Vessel data is used in two ways. First, to contribute to the development of parametric design models that are used for applications of epoch-era analysis and tradespace exploration in Main Article 1, and as input data for the vessel- and mission-related parameters in the model in Main Article 4. Second, vessel databases are used in the development of Main Article 3 to give insights into the function-form relations for typical offshore ships. The latter point gives an understanding of what vessel characteristics enabled certain offshore support vessels to support the Macondo oil spill response.

3.2.3. Deriving relationships

Conceptual framework and literature review
A conceptual framework has two main purposes: First, the conceptual framework should position the research within the existing literature. Second, the conceptual framework should reflect the author's synthesis of the existing conceptual background and theory. Hence, it both provides an overview of existing knowledge, identifies gaps in the existing work, and identifies and clarifies contradictions that exist in the literature (Pruzan, 2016).

Development of a conceptual framework by studying several different research disciplines contributes significantly to this PhD project due to significant contradictions between concepts developed by different disciplines. This leads to the discovery that several common principles for successful systems design and operation are in opposition. For example, in Main Article 2 we find that there are inherent trade-offs between enhancement of resilience and compliance with axiomatic design theory and show this in the context of the Apollo 13 incident. Such contradictions would not have been discovered if the literature review was merely used to re-state the findings and identify gaps in previous research within one field.

Hierarchical decomposition
Systematic decomposition of relevant offshore support vessel characteristics, and development of a taxonomy for such characteristics, is performed in Main Article 3 to increase the understanding of the role of latent capabilities played in the response to the Macondo oil spill. The vessel characteristics that are studied included conventional missions and emergency response missions, functionality, and subsystems typical in offshore vessels. Descriptions of these elements are provided and support a synthesis of new modes of operation, based on latent capabilities, to address the needs prompted by specific emergencies.

Design and decision support methods
See the section on "Decision-oriented methods".

3.2.4. Assessing validity

For this PhD project, validation relies on two primary considerations; i) ensure that concepts developed are internally consistent and that they explain phenomena in the real world, and ii) ensure that the decision-oriented methods used provide real insights.

The first point is accomplished mainly by seeking conceptual validation through ensuring internal consistency, and by identifying additional cases that fit the conceptual framework that was developed (Kovács & Spens, 2005; Szajnfarber & Gralla, 2017). For example, the latent capabilities concept has been validated by identifying cases in which this concept constitutes a means to derive some novel insight for real-world applications. This is done in Main Article 2, applying the case of the Apollo 13 spacecraft, and Main Article 3, applying the case of the Macondo oil spill. Additional examples are provided in Supporting Paper 4, including anchor handlers used for ice management, and platform supply vessels used for search and rescue during the Mediterranean refugee crisis.

In addition to conceptual validation as covered above, for decision support models, relevant for Main Article 1 and Main Article 4, validation can be decomposed into data validation, conceptual model validation, and operational validation (Sargent, 2013). Did we possess realistic data for the model? Did the model output represent what we would observe from the real system? In Main Article 1, the model applied was based on actual data from a ship design process, even though the discussion in the paper primarily concerns how difficult it is to develop a well-defined model from an ill-defined design problem. In Main Article 4, the model largely applied data representative of coast guard vessels, their capabilities, and geographical operating region. With respect to operational validation, both papers present simplified versions of actual problems, with an emphasis on exploring trade-offs between performance metrics, rather than recommending decisions. Further, due to our inability to implement the solutions proposed by the models in the real world (too costly and too time-consuming), we cannot make a definite conclusion regarding the operational validity of the models.

3.3. Decision-oriented methods

Decision-oriented methods have been awarded their own section, to differentiate from what may be considered "research methods". Prescriptive and normative decision-making research (Bell et al., 1988) implies a concern with "ought" rather than "is", reflecting what Simon (1996) calls the "sciences of the artificial". The need for differentiation between decision-oriented research and science is further reflected by a difference in reasoning processes applied (Coyne et al., 1990; Eekels & Roozenburg, 1991). A short overview of the central design and decision support methods used in the main papers is given here.

Axiomatic design

Axiomatic design outlines two design axioms, the independence axiom and the information axiom, as guiding principles for design (Suh, 1990, 2001). For further details on axiomatic design, see Chapter 2. Axiomatic design models are used to conceptualize latent capabilities in the function-form mapping in Main Article 2.

In Main Article 2, an axiomatic design model is used as an example of an existing prescriptive theory for systems design that opposes central principles that enable resilient operations. Hence, this research negates certain aspects of axiomatic design, especially the focus of that theory on functional independence. A concern for the focus on axiomatic design and the use of the function-form mapping model derived from axiomatic design is that this represents a limiting frame for the understanding of the concept of latent functioning. The concept of latent capabilities is therefore presented without considering axiomatic design implications in Main Article 3.

The Responsive Systems Comparison method

The Responsive Systems Comparison (RSC) method is a generalized systems design methodology based on multi-attribute tradespace exploration and epoch-era analysis (Ross et al., 2009). This method is divided into three overall steps; i) *information gathering*, in which objectives are formulated, objective hierarchies, design variables and epoch variables are elicited and parametrized, ii) *alternatives evaluation*, in which the models mapping from needs through function to form are defined mathematically, using all available knowledge, and iii) *alternatives analysis*, in which alternative systems are evaluated in possible epochs and eras, representing static and dynamic scenarios respectively (Schaffner, Ross, & Rhodes, 2014).

Part of the motivation for modelling the design of a complex offshore support vessel using the RSC method was to test the method on a case from outside the domain of complex systems normally addressed using tradespace and epoch-era analyses. Commonly, the RSC method has been applied to non-commercial problems, like military systems, where there is no revenue, and hence value is measured via other means, like a multi-attribute utility function (Ross et al., 2004).

The RSC method is applied to the offshore support vessel design case in Main Article 1. The main work was undertaken through workshops with two other PhD students, Carl Fredrik Rehn and Jose Jorge Garcia Agis, and in collaboration with Ulstein International and the Systems Engineering Advancement Research Initiative (SEAri) at Massachusetts Institute of Technology.

Use of the method can easily be combined with other decision support models, such as the fleet deployment problem presented in Main Article 4. In that case, the deployment problem serves the tactical planning aspects, while the strategic planning aspects are considered in an epoch-era framework.

Covering problems from operations research

The maximal covering problem is used in Main Article 4 as a basis for the fleet deployment model developed to capture emergent behaviour arising from fleet-level interactions among service vessels. For maximal covering problems, the objective is to maximize coverage of some demand within an acceptable distance of service (Owen & Daskin, 1998). Facilities or assets are then assigned to a subset of the nodes but should be assigned in such a way that the importance-weighted coverage of demand at all nodes is maximized.

In the context of this thesis, the facilities to be located can be concretely thought of as vessels to be deployed to some specific operational area. There are significant rewards associated with deploying ships so that they cover other operational areas. In Main Article 4 this modelling principle is extended to heterogenous missions, and to heterogeneous fleet capabilities. The problem formulation therein is a deterministic, mixed-integer program.

3.4. Research process

In this section, we describe the research process as it unfolded. For a high-level overview of main deliverables set against a timeline for the project, see Figure 21.

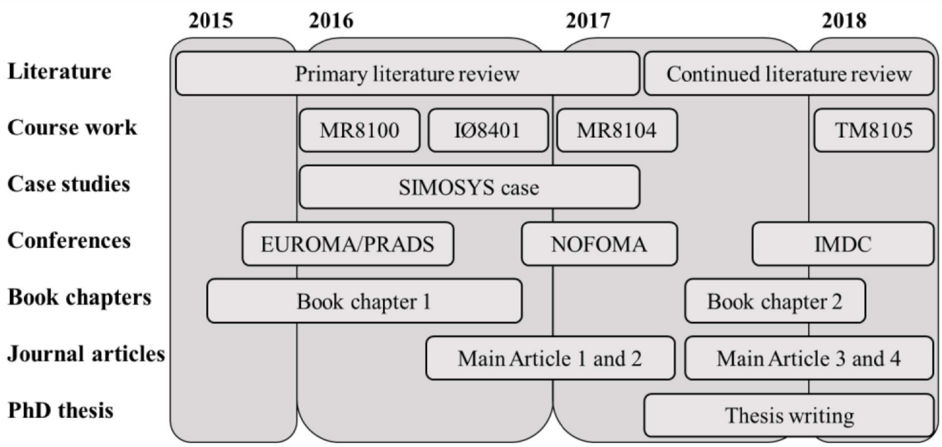

Figure 21: Research timeline.

The primary literature review began in August 2015, and early research objectives that were continuously revisited, were explored through what is referred to as "Book chapter 1" (Pettersen, Asbjørnslett, & Erikstad, 2018) and two early conference articles (Supporting Paper 1 and 2) published at the EurOMA (European Operations Management Association) Conference in Trondheim (Pettersen & Asbjørnslett, 2016b), and at the PRADS (Practical Design of Ships and Other Floating Structures) Conference in Copenhagen (Pettersen & Asbjørnslett, 2016a). At this stage, my research project was largely focused on the development of design methodology aimed at improving the resilience of fleet size and mix and maritime service vessel logistics. In this phase, the primary unit of analysis was the fleet, understood mainly as a collection of assets providing different types of functionality. In the sense that the focus was on developing methodology, the early direction was mainly decision-oriented research.

Alongside work on these publications, I attended a course in ship design theory (MR8100) and a compulsory course in research methodology (IFEL8000) and took part in developing the SIMOSYS case study documented in Appendix C with two other PhD students, and the project partners Ulstein International and SEAri at MIT. The case study itself was mostly developed through meetings and workshops in Ulsteinvik and Trondheim, while the Responsive Systems Comparison method was applied to the case through several workshops in Boston. Through this collaboration, I extended the scope of my research to include systems design and operation for single vessels.

In the fall of 2016, we continued working on the SIMOSYS case study which led to the publication of Main Article 1 (Pettersen, Rehn, Garcia, et al., 2018). Main Article 1 has a clear decision-oriented focus, applying the Responsive Systems Comparison method. In addition, I attended a course in optimization under uncertainty (IØ8401) and started developing Main Article 2 (Pettersen, Erikstad, et al., 2018). The basis for Main Article 2 was theory reviewed in MR8100, reviews of the literature on system resilience, reviews of incident reports, and insights from the SIMOSYS case study. In terms of research methods, this included both data collection and derivation of the conceptual framework, to establish the relationship between resilience, system design and latent capabilities. Main Article 2 also drew on axiomatic design, meaning there was also a component of decision-oriented research.

In the spring of 2017, we submitted Main Article 1 and 2 to international journals. In addition, I wrote Supporting Paper 3 (Pettersen, Buland, & Asbjørnslett, 2017) in collaboration with master student Marius Buland, for the NOFOMA conference in Lund, Sweden, arranged by the Nordic Logistics Research Network. I also attended a course on advanced topics in maritime logistics (MR8104), mainly focused on applications of techniques from mathematical programming on marine systems design.

In the fall of 2017, development of Main Article 3 (Pettersen, Garcia, Rehn, et al., 2018) and Main Article 4 (Pettersen, Fagerholt, & Asbjørnslett, 2018) commenced. The ideas for Main Article 3 had been initiated through the SIMOSYS case, with some work undertaken while developing Main Article 2. Main Article 3 further explored topics from the two previous main articles, investigating whether latent capabilities were a determinant for emergency response efforts in the aftermath of the Deepwater Horizon accident. Compared to the reductionist approach of Main Article 2, where an axiomatic design model was used to describe and define latent functions, Main Article 3 takes a more holistic approach and discusses managerial aspects in greater detail. The model formulation for Main Article 4 was also initiated, evaluating fleet effectiveness by modelling deployment as a maximal covering problem. In addition, development of this thesis itself began. The second book chapter (Pettersen & Asbjørnslett, 2018) was developed mainly during the fall of 2017, following a previously published chapter on vulnerability assessment (Asbjørnslett, 2009). In addition, Supporting Paper 4 (Pettersen, Asbjørnslett, Erikstad, et al., 2018) was developed for the International Marine Design Conference in Helsinki, based mainly on the ideas from Main Article 2 and 3.

During the spring and summer of 2018, I submitted Main Article 3 and 4 and wrote this thesis. In addition, I finished the obligatory course work, by attending a course on discrete event simulation methodology (TM8105). Review of relevant literature continued nearly to the submission of the thesis, to ensure an up-to-date review for the thesis.

The author has also been active as a co-author of several additional papers, in addition to the work directly relevant for this thesis. These articles have largely concerned ship design accounting for future uncertainty (Garcia, Pettersen, Rehn, & Ebrahimi, 2016), including specific considerations of flexibility and retrofits (Pettersen & Erikstad, 2017; Rehn, Pettersen, Garcia, et al., 2018; Rehn, Pettersen, Erikstad, & Asbjørnslett, 2016; Rehn, Pettersen, Erikstad, et al., 2018), the interaction between ship design and shipping company strategies (Strøm et al., 2018), and the influence of partially differing stakeholder needs (Garcia et al., 2018).

In the next chapter, we present the results of the thesis and draw the high-level connections between research objectives, the main articles and the contributions.

4. Results

4.1. Research problem

The PhD project resulted in four main articles, either published in or submitted to peer-reviewed international journals. Several conference articles and co-authorships on other articles supported the efforts to develop the four main articles. Some of these are listed as supporting papers. The main articles document results and constitute the primary output of this PhD project. This chapter shows how the main articles answer the research question, which was:

> *"What is the relationship between characteristics designed into marine systems, the ability to recover from operational disruptions, and the ability to respond to swiftly emerging demands?"*

As shown in Figure 1, this question captures both the relationship between the marine system and recovery from operational disruptions, and the relationship between the marine system and the ability to perform emergency response. These relationships are studied at a high level, specifically focusing on the characteristics that were neither intended nor recognized during design, the *latent capabilities.* The thesis shows how these capabilities contribute to resilience by enabling recovery. In the remainder of this chapter, we systematically go through the research objectives, the main articles, and the contributions that document in more detail how the research question has been answered. The relationship between the research objectives, the main articles, and the contributions is shown in Figure 22.

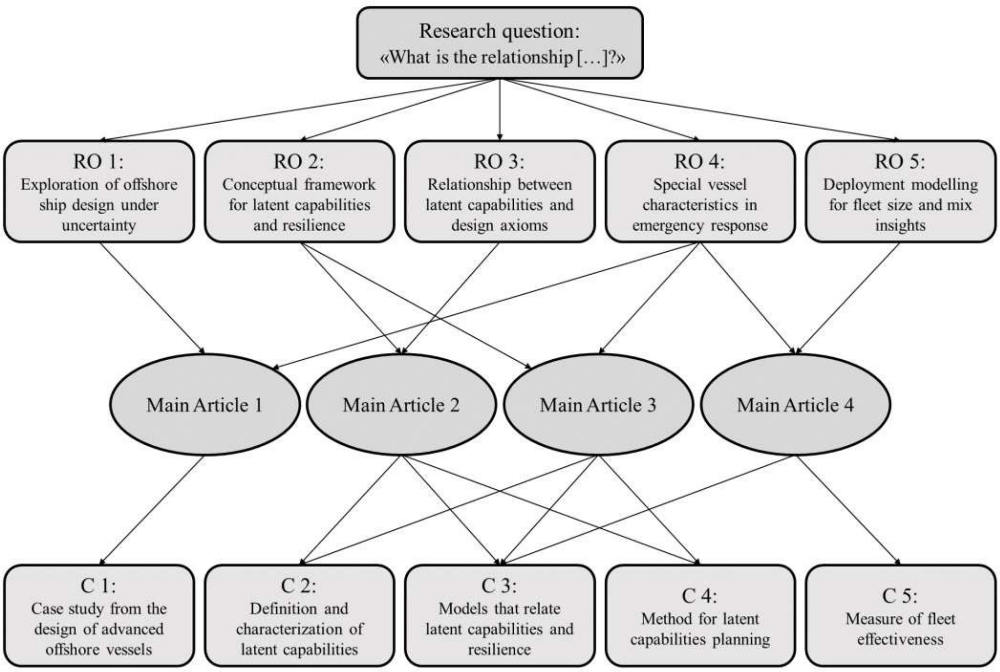

Figure 22: Relationship between research question, research objectives, main articles, and research contributions.

4.1.1. Research Objective 1

Explore challenges in the ship design problem that arise due to future uncertainty and differing stakeholder expectations.

The first research objective (RO 1) was initiated through the collaboration with two other PhD students on a ship design case from the offshore service industry. Through the case study and application of the Responsive Systems Comparison method, we derived knowledge about problems that arise in the conceptual ship design phase when there is significant uncertainty regarding stakeholder expectations and the future commercial and operational environment. RO 1 maps onto Contribution 1, mainly through Main Article 1, as shown in Figure 23.

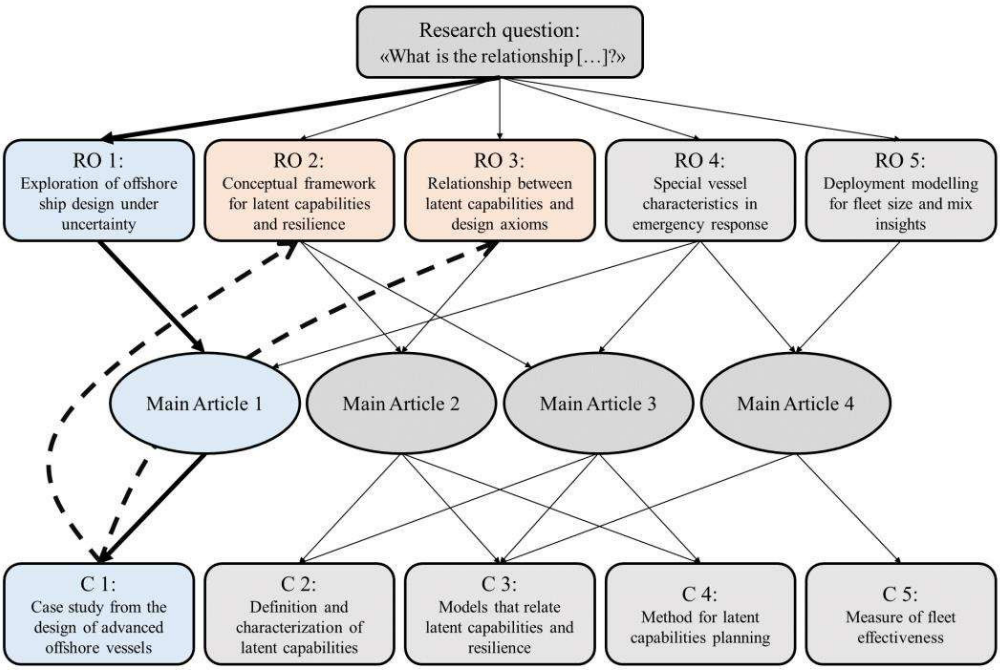

Figure 23: Relationship between Research Objective 1 and the contributions.

Even though this research objective primarily maps onto the first contribution, the insights that were gathered, also influenced the formation of the other research objectives. A key insight from working with RO 1 was that the selection of decision-making models, like the selection of the final design, is a type of design process. As two decision-making models will value different characteristics, some characteristics that are emphasized and contributes to system value according to one model, may not show up as important in another. The result is that the design phase concludes without a full exploration of system characteristics, and the scenarios in which these characteristics can contribute to value. Hence, the recognition that latent capabilities could be an interesting research topic, was partially derived from RO 1.

4.1.2. Research Objective 2

Develop a conceptual framework for characterizing latent capabilities for enhancing system resilience.

The second research objective (RO 2) is met by a thorough literature review of concepts similar to latent capabilities, resilience, and engineering design theory, as well as the development of models and methods that address how latent capabilities contribute to resilience. This was largely motivated by the observation that many marine engineering systems meet operational disruptions or system-external emergencies by utilization of capabilities beyond what was intended and recognized during design. Hence, RO 2 maps onto Contributions 2 - 4, primarily through Main Article 2 and 3, as shown in Figure 24.

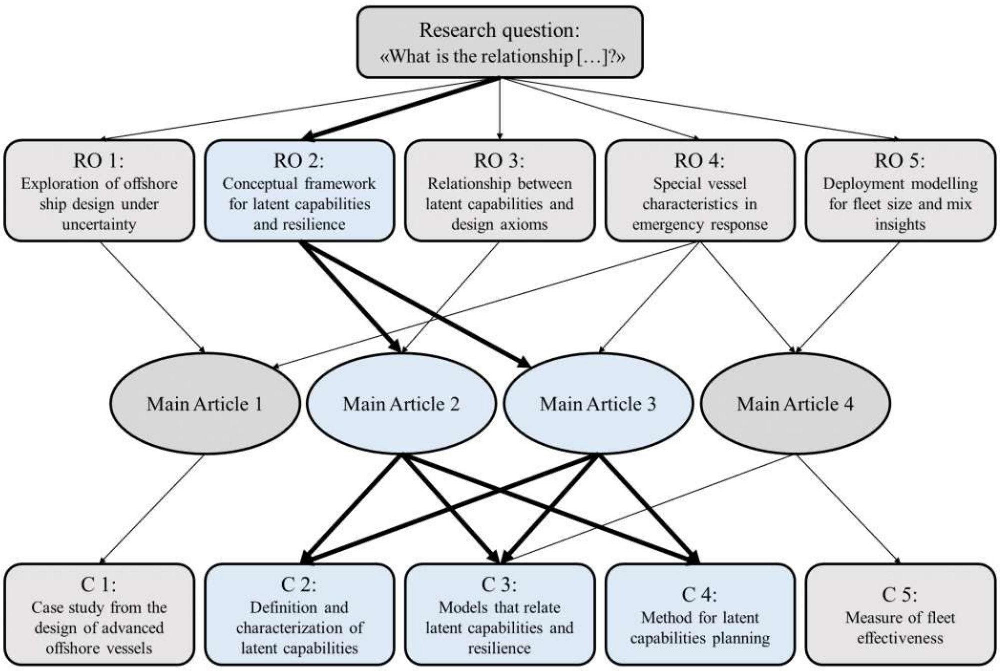

Figure 24: Relationship between Research Objective 2 and the contributions.

The conceptual framework developed to meet RO 2, hence consists of a definition of latent capabilities as “the capabilities of a system neither intended nor recognized”, after Merton (1968), as well as a limitation of when this term is applicable. Applicability is limited temporally and perceptually as follows: Latent capabilities are, by definition, not considered *during* the design stage, but can be made active *after* designing, hence during later stages of the lifecycle.

Additionally, the conceptual framework includes examples of how latent capabilities can be modelled through an axiomatic design framework (Suh, 1990), or by decomposition of the component and functional hierarchies of a complex system. The direct connection between resilience and latent capabilities is derived via performance measures in Main Article 2. Main Article 3 offers a qualitative perspective.

4.1.3. Research Objective 3

Investigate the relationship between latent capabilities, and axiomatic design theory.

The third research objective (RO 3) is met in Main Article 2. Axiomatic design was chosen as a design framework for two reasons: First, axiomatic design promises a more scientific approach to design, based on two design axioms. The design axioms seek to maintain independence among functional requirements and to minimize the information content of the system (Suh, 1990). Second, axiomatic design offers a simple model for the function-form mapping in design, which is useful for illustrating the concept of latent functional capabilities. Figure 25 illustrates the relationship between RO 3 and the research contributions.

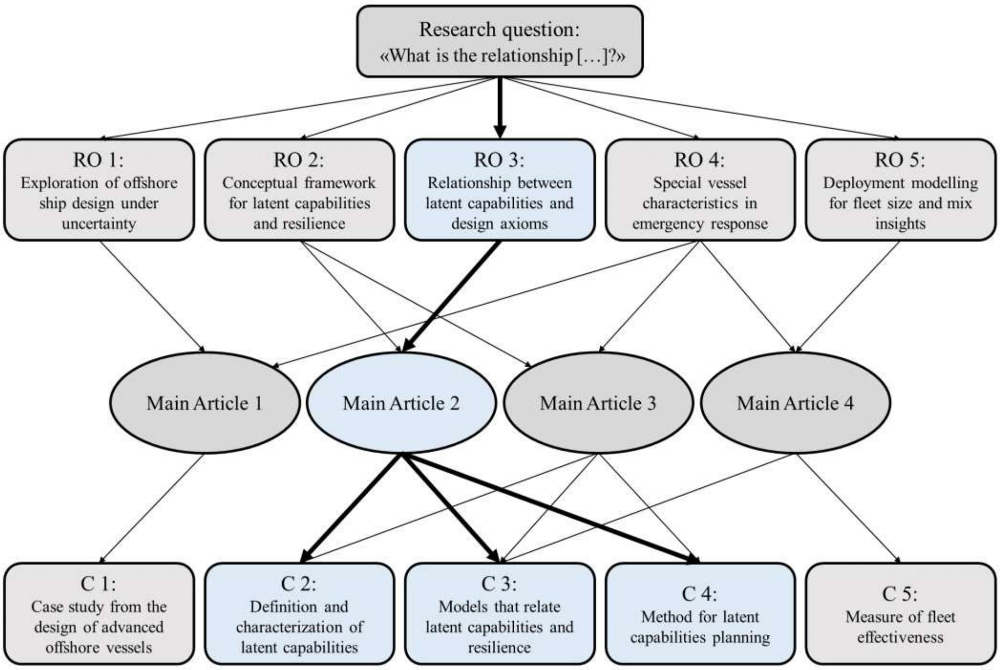

Figure 25: Relationship between Research Objective 3 and the contributions.

RO 3 is met by Main Article 2, in which the function-form mapping model is used to illustrate what latent capabilities imply for the fulfilment of the design axioms. The concept of latent capabilities partially refutes axiomatic design. First, the independence axiom completely counteracts latent capabilities. The independence axiom favours a situation without functional coupling, as this makes the system simpler to design and operate. Second, latent capabilities indicate that an increase in information (about secondary ways to operate), is beneficial, countering the benefits associated with a reduction of complexity. Rather, the results in Main Article 2 show that resilience can be improved *because of* the added complexity associated with deviating from the design axioms.

4.1.4. Research Objective 4

Investigate the design characteristics that enable complex service vessels to generate value in unconventional emergency response missions.

The fourth research objective (RO 4) maps onto every contribution in some sense. RO 4 is key to defining latent capabilities in a special vessel context, and to making models and methods that capture the resilience of these vessels, as in Main Article 3 and 4. These articles have a strong focus on emergency response missions. Emergency response was chosen because these operations require the utmost in terms of resilience and adaptability, due to the sudden-onset nature of emergencies. Further, emergency response is an appealing research area across several units of analysis, due to the impact of vessel interaction effects and fleet effectiveness. RO 4 is also captured in Main Article 1, in which the *unarticulated*, *unexplored*, and ultimately *ill-structured* or *wicked* aspects of offshore ship design were highlighted. What is communicated between stakeholders is not obvious, hence their intended uses for a vessel may deviate, resulting in latent capabilities. Figure 26 illustrates the relationship between RO 4 and the research contributions.

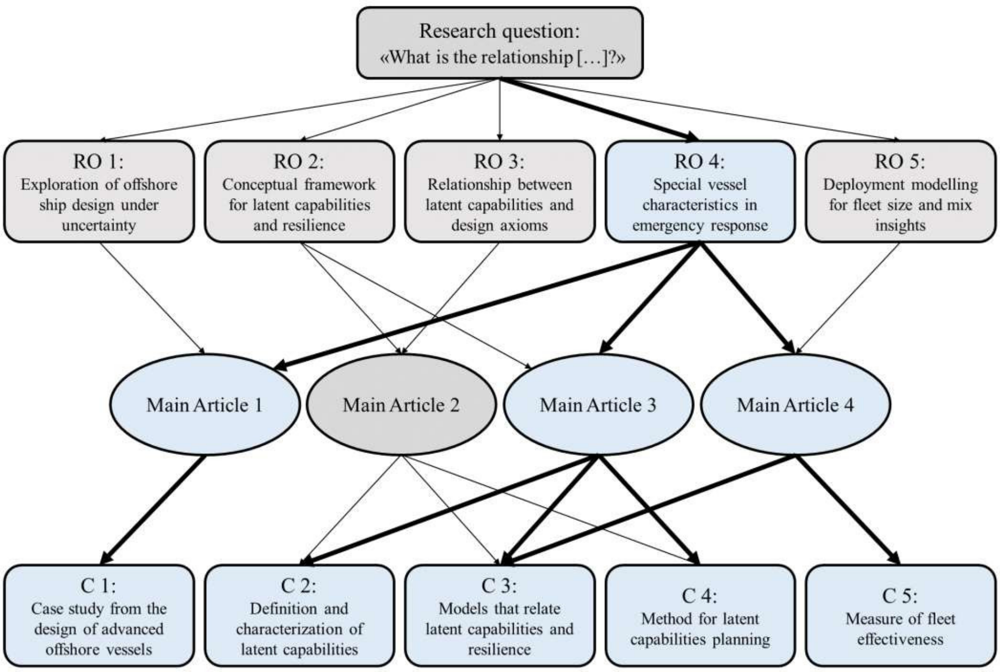

Figure 26: Relationship between Research Objective 4 and the contributions.

The design characteristics of special vessels are explored for offshore vessels in Main Article 1 and 3, and for coast guard vessels in Main Article 4. In Main Article 3, structural and functional breakdowns provide a qualitative approach to the identification of latent functions. In Main Article 1 and 4, design characteristics of special vessels are used as input for decision support methods. Additionally, Main Article 4 is distinctive as it shows the effect of geospatial complexity and emergent behaviour on fleet-level characteristics.

4.1.5. Research Objective 5

Develop a deployment model that effectively captures fleet performance towards emergency response missions that are not assessed during ship design.

The fifth research objective (RO 5) is met by the use of tools from the operations research domain. Fleet size and mix decisions for marine engineering systems like the coast guard and emergency response require that we account for how tactical deployment will be performed, in order to derive measures of effectiveness for evaluation of alternatives. For this objective, a shift in the system boundaries to the fleet level is required. Figure 27 illustrates the relationship between RO 5 and the research contributions.

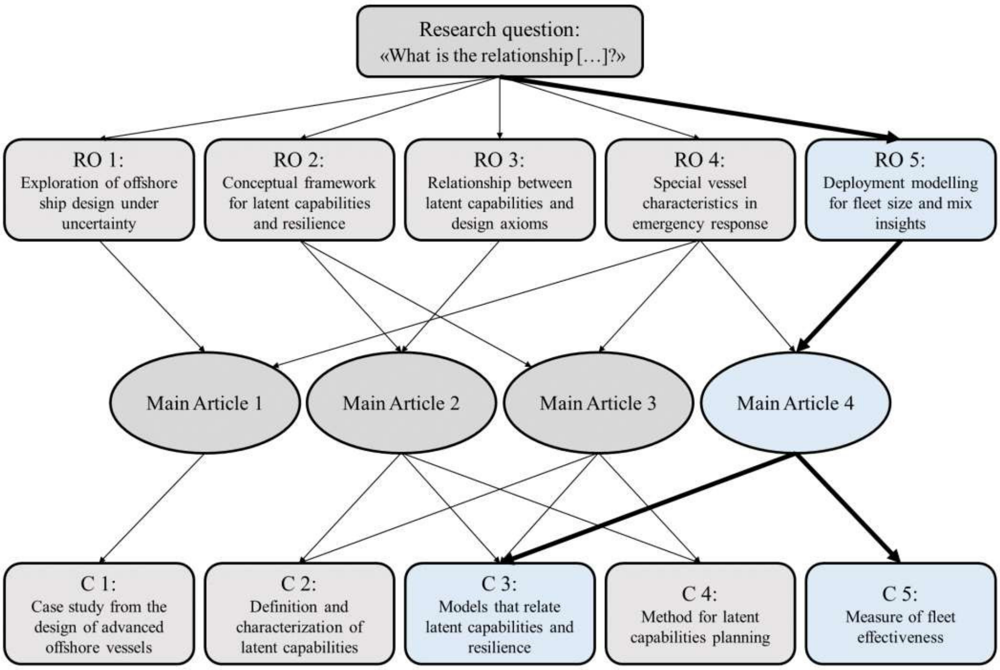

Figure 27: Relationship between Research Objective 5 and the contributions.

RO 5 maps onto Contribution 5, which derives a measure of effectiveness from the fleet deployment model. To the author's knowledge, it is the first model to consider a maximal covering problem structure for a tactical fleet planning problem. The model also constitutes the first time a tactical fleet deployment problem is set into the context of epoch-era analysis for strategic scenario planning.

RO 5 also maps onto Contribution 3, as an improvement in the objective function in the mathematical program proposed in Main Article 4 corresponds with a situation in which it becomes more likely that a vessel will be available to respond quickly with the appropriate functionality in case of an emergency. Hence, optimizing fleet deployment corresponds to improving the resilience of the fleet.

4.2. Summary of publications

4.2.1. Main 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, Vol. 34, No. 1, 2018, pp. 72-83.

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 investigates the problem of designing complex service vessels using the Responsive Systems Comparison method, starting from the offshore case study described in Appendix C. We were able to extract insights regarding ill-structured design problems with future uncertainty and multiple stakeholders from applying the method on this case. Some of these insights instigated my interest in latent capabilities.

Main author contribution: Jorge Jorge Garcia, Carl Fredrik Rehn and I wrote the paper together, developed the case, applied the methodology, and performed the analyses. The development of the paper was a collaborative effort, with an equally shared workload, done through several workshops in Trondheim, Ulsteinvik, and Boston, organized through the SIMOSYS project.

Co-author contributions:

- *Jose Jorge Garcia & Carl Fredrik Rehn:* See details above.
- *Bjørn Egil Asbjørnslett, Per Olaf Brett & Stein Ove Erikstad:* Discussed the ship design implications, read and commented on the paper drafts.
- *Adam M. Ross & Donna H. Rhodes:* Discussed the methodology and our approach to using it on the ship design case, read and commented on the paper drafts.

4.2.2. Main Article 2

Exploiting latent functional capabilities for resilience in design of engineering systems
Pettersen, S. S., Erikstad, S. O., & Asbjørnslett, B. E.
Research in Engineering Design, Vol. 29, No. 4, 2018, pp. 605-619.

Abstract: In this paper, we address latent functional capabilities, capabilities that were neither intended nor recognized in the design process. We propose that latent capabilities can improve the resilience of engineering systems, enabling recovery of performance after disruptive events. Engineering systems are designed to meet their functional requirements, and have a limited ability to avoid critical failures. Normally, redundancies are put in place to reduce the impact of potential disruptions, adding to cost and complexity. An alternative is to uncover latent capabilities that can be used to recover from disruption by altering the function-form mapping. Existing design methods focus on intended, manifest functionality, and do not consider latent capabilities. With basis in design theory, we show that latent capabilities can enhance resilience, and demonstrate this using two illustrative cases. Further, we propose approaches to uncover latent capabilities in systems design, and discuss implications of using latent capabilities to enhance resilience.

Relevance to the thesis: This paper introduces latent functional capabilities as a key enabler of resilience in engineering systems. The paper argues that the use of latent capabilities, that exist as multiple elements of system form can deliver the same function, is counter to Suh's axiomatic design theory. The paper also presents a review of resilience definitions and metrics.

Main author contribution: I wrote the paper in its entirety and developed the approach and the cases.

Co-author contributions: Stein Ove Erikstad and Bjørn Egil Asbjørnslett initiated the paper topic, on basis of my essay for the PhD course "MR8100 – Theory of Marine Design", connecting the latent capabilities idea to resilience. They also discussed the topics and paper drafts with the main author throughout the writing process.

4.2.3. Main Article 3

Latent capabilities in support of maritime emergency response
Pettersen, S. S., Garcia, J. J., Rehn, C. F., Asbjørnslett, B. E., Brett, P. O., & Erikstad, S. O.
Submitted to Maritime Policy and Management.

Abstract: This paper proposes that latent capabilities can support needs that emerge during large-scale emergency response situations, in which the demand for assistance exceeds the capabilities of dedicated emergency infrastructure. Latent capabilities refer to system functional resources that were neither intended nor recognized during the design phase. Latent capabilities represent an opportunity for ship owners to adapt to swift changes in operating context, respond to new demands that emerge in such conditions. Hence, latent capabilities provide a substantial strategic advantage. As a proof-of-concept for latent capabilities in emergency preparedness, the response to the Macondo oil spill is used as a case study. The case shows that the collaborative efforts of advanced offshore vessels provided latent capabilities that were decisive in shutting down the leaking well. Applying a methodology for latent capabilities assessment to offshore support vessels, we identify enablers of latent capabilities that can be exploited through contingency planning.

Relevance to the thesis: This paper serves as an example of how latent capabilities can be exploited in a marine emergency response situation. It builds on the offshore construction vessel case study in Main Article 1, and documents how the application of an ad-hoc fleet of OCVs contributed to well containment and oil spill recovery after the Deepwater Horizon accident. The paper also presents a methodology for latent capabilities assessment and decomposes system, function and cost structures for offshore support vessels.

Main author contribution: The background for this paper was the collaboration through the SIMOSYS project with Ulstein and MIT. The themes treated in the paper were uncovered and developed through several workshops in Trondheim, Ulsteinvik and Boston. I wrote the great majority of the paper.

Co-author contributions: Jose Jorge Garcia and Carl Fredrik Rehn collaborated with the main author on the case study. Jose Jorge Garcia also provided vessel data. Bjørn Egil Asbjørnslett, Per Olaf Brett and Stein Ove Erikstad critically reviewed the written material throughout the development of the paper. In addition, Bjørn Egil Asbjørnslett supplied the original version of Figure 3 in the paper.

4.2.4. Main Article 4

Evaluating fleet effectiveness in tactical emergency response missions using a maximal covering formulation

Pettersen, S. S., Fagerholt, K., & Asbjørnslett, B. E.

Resubmitted after revision to the Naval Engineers Journal..

Abstract: This paper concerns the evaluation of alternative fleets of advanced special vessels, like coast guard or emergency response and rescue vessels. The paper proposes a mathematical programming formulation of the Fleet Deployment with Maximal Covering problem and combines analysis of this problem with tradespace exploration and epoch-era analysis. A solution of the mathematical program provides an optimal deployment plan for a given fleet in a given context. The objective function value provides a measure of effectiveness for the fleet alternative. By evaluating the effectiveness of a set of alternative fleets in several alternative scenarios using epoch-era analysis, we obtain strategic insights about dynamic trade-offs and provide decision support for fleet size and mix planning. The paper reconciles the use of mathematical programming for measurement of fleet effectiveness with a design of experiments approach to concept exploration under uncertainty. The results show that it is effective to use mathematical programming for planning horizons with less uncertainty, and account for strategic uncertainties using the epoch-era framework.

Relevance to the thesis: The paper presents a tactical fleet deployment model, and combines it with epoch-era analysis. This implies a division of roles for decision support methods, in which mathematical programming is restricted to the most well-defined aspects of the problem. No optimization is applied to strategic decisions reflecting the importance of concept exploration. The latent capabilities perspective is captured by accounting for interactions among vessels as what gives rise to effectiveness beyond ship performances.

Main author contribution: I developed the approach, including the development of the mathematical programming model with the second author. I performed the quantitative analyses and wrote the paper.

Co-author contributions:

- *Kjetil Fagerholt:* Contributed with the development of the mathematical programming model and reviewed the paper drafts.
- *Bjørn Egil Asbjørnslett:* Reviewed and discussed the overall methodology and the paper drafts with the main author.

4.2.5. Supporting Papers

A short overview of important supporting papers is given here. As mentioned, several conference papers and book chapters were developed as initial explorations of the topics investigated in the main articles summarized above.

Supporting Paper 1
Designing resilient fleets for maritime emergency response operations
Pettersen, S. S., & Asbjørnslett, B. E.
EurOMA 2016, Trondheim, Norway.

Abstract: In this paper, we investigate the problem of designing resilience into a fleet for maritime emergency response operations. A broad set of events can trigger emergency response, requiring that a fleet of vessels for this purpose must contain a diverse set of functionalities. We can obtain significant gains in fleet resilience by taking advantage of functional overlaps between equipment installed on, or refitted onto the vessels. Combining design structure matrices and tradespace analyses with failure modes, we evaluate the performance of fleets for emergency response operations. The approach is illustrated with a small, qualitative case.

Supporting Paper 2
A design methodology for resilience in fleets for service operations
Pettersen, S. S. & Asbjørnslett, B. E.
PRADS 2016, Copenhagen, Denmark.

Abstract: In this paper, we present a new conceptual design methodology for increasing the resilience in complex operations involving a fleet of ships. The objective of the methodology is to support design decisions to reduce vulnerabilities facing complex operations. The steps of the methodology are; 1) Defining operational context and initial fleet system design; 2) Investigating failure modes, identification and criticality assessment; 3) Proposing redesign and redeployment actions at the vessel level to increase resilience, through flexibility or redundancy; 4) Evaluating proposed actions, through assessment of the alternatives. We illustrate this methodology using a small case from a maritime service operation. The results indicate the advantage of integrating design thinking into a methodology for more resilient maritime operations.

Supporting Paper 3
Redefining the Service Vessel Fleet Size and Mix Problem Using Tradespace Methods
Pettersen, S. S., Buland, M. O., & Asbjørnslett, B. E.
NOFOMA 2017, Lund, Sweden.

Abstract: **Purpose:** This paper addresses the problem of designing a fleet of service vessels to cooperate towards performing a set of operations under operation demand uncertainty. Emphasis is put on identification of compromises between alternative objectives in fleet design, and is relevant in analysis of fleet renewal programs. **Design/methodology/approach:** The methodological approach of the paper is tradespace exploration and epoch-era analysis. Rather than finding an optimal fleet composition directly, we explore a set of alternative fleet architectures, in terms of value and cost, across several possible contexts, finding fleet compositions that can be expected to deliver value over time. **Findings:** The paper illustrates the applicability of tradespace exploration and epoch-era analysis in a fleet composition problem. Through this, important trade-offs between alternative compositions are identified. **Research limitations/implications (if applicable):** One limitation of the current research is the simplifications made through the case study. These limitations could be addressed by including simulation of operations and considering fleet deployment. **Practical implications (if applicable)**: This paper provides stakeholders with new tools for asset management. An impact could be more cost-beneficial acquisitional decisions, and improved understanding of compromises that must be made when composing or updating a fleet of assets. **Original/value:** The paper applies tradespace exploration and epoch-era analysis in a new segment, and provides an aggregation of these methodologies to a fleet level. Insights in trade-offs typical for fleet size and mix decisions under uncertainty are generated, such as the choice between a smaller fleet of multi-functional vessels, and a larger fleet of less complex vessels.

Supporting Paper 4
Design for resilience: Using latent capabilities to handle disruptions facing marine systems
Pettersen, S. S., Asbjørnslett, B. E., Erikstad, S. O., & Brett, P. O.
IMDC 2018, Helsinki, Finland.

Abstract: This paper explores how the resilience of marine systems against disturbances can be improved by considering latent capabilities. With resilience is meant the ability of a system to recover and return to an acceptable, stable state of operations after a disruption. Latent capabilities are distinct from capabilities intentionally designed for, and often remain unrecognized even during the operational phases. Our proposition is that these capabilities can be uncovered after designing, and be used in the operational phase to restore system operation after disruption, or to answer to emergencies in the marine environment. Drawing on fundamental theories in design, we illustrate how the function-form mapping can be adapted in response to these needs. Examples from marine transportation and marine service providers will be given in support of our arguments.

4.2.6. Book chapters

Book Chapter 1

Designing Resilience into Service Supply Chains: A Conceptual Methodology
Pettersen, S. S., Asbjørnslett, B. E., & Erikstad, S. O.
In Khojasteh, Y. (ed), 2018. Supply Chain Risk Management: Advanced Tools, Models, and Developments. Springer.

Abstract: This chapter presents a methodology for designing resilient service supply chains. The approach combines system design methods with methods from risk assessment. Service supply chains consist of multiple assets, cooperating to fulfil an operation. Each asset has functionality to perform a set of tasks in the operation, and the combined functionalities of the fleet of assets must cover the activities the service supply chain are to perform. When a module in one asset in the fleet experiences loss of functionality, it constitutes a disruption in the service supply chain, a failure mode. The objective of the proposed methodology is to give decision support reducing the vulnerabilities of the service supply chain through design actions that can increase overall service supply chain resilience. The methodology consists of four steps. The first step includes breakdown of operation and service supply chain, mapping of modules to tasks, and selection of service supply chain configuration based on costs and utility. In the second step, failure modes are identified and their criticality assessed. In the third step, we propose design changes to reduce the impact of disruptions. These are evaluated in Step 4, where decisions regarding redesign are made. The recommendations from this methodology can be used to plan for how to redesign in the case of contingencies, or be used as part of an iterative process where the new information is incorporated in the evaluation of initial service supply chain design.

Book Chapter 2

Assessing the vulnerability of supply chains: Advances from engineering systems
Pettersen, S. S., & Asbjørnslett, B. E.
In Zsidisin, G., & Henke, M. (ed), 2018. Revisiting Supply Chain Risk (forthcoming). Springer.

Abstract: Vulnerability assessments focus on extended sets of hazards and threats, and seek to ensure that adequate resources exist to restore system functionality to a stable level within a reasonable amount of time. Multiple frameworks for vulnerability assessments in supply chains report on tools that can support this analysis. The purpose of this chapter is to inform supply chain researchers and practitioners of emerging trends and advances from engineering design that can benefit supply chain risk management, and set these in the context of a previously published methodology (Asbjørnslett, 2009) for vulnerability assessment in the supply chain.

Specific advances that will be addressed, include:

- Epoch-era analysis for structuring event taxonomies and scenarios.
- Failure mode thinking for low frequency, high impact (LFHI) events.
- Design structure matrices and axiomatic design principles for function-form mapping in the supply chain as a tool for ensuring adequate levels of redundancy, flexibility, and identification of latent functionality.

4.3. Contributions

This PhD project has resulted in five contributions that resolve the research problem. The contributions are documented in the main articles. Here, these are put into the context of the entire PhD project.

4.3.1. Contribution 1

An industrial case study from the design of advanced offshore support vessels with multiple stakeholders under uncertainty.

Contribution 1 is the case study developed in collaboration with two other PhD students, through the SIMOSYS project with Ulstein and MIT. The case study is documented in Appendix C and in Main Article 1. The case study shows how future uncertainty and partially misaligned stakeholder expectations impacted the design of a complex special vessel and spurred multiple changes during shipbuilding. Contribution 1 primarily answers to RO 1, as it serves as an exploration of ill-structured aspects of the ship design problem. Additionally, the case study gives an overview of the missions performed by offshore vessels, partially responding to RO 4. While Main Article 1 does not consider emergency missions, emergencies (post-Macondo) seemed to have been an *unarticulated* driver for the development of the offshore vessel studied in the case. Hence, this generated an interest in exploring latent capabilities. The relationship between research objectives and Contribution 1 are outlined in Figure 28. The connection between the case study and development of research objectives relating to latent capabilities are highlighted.

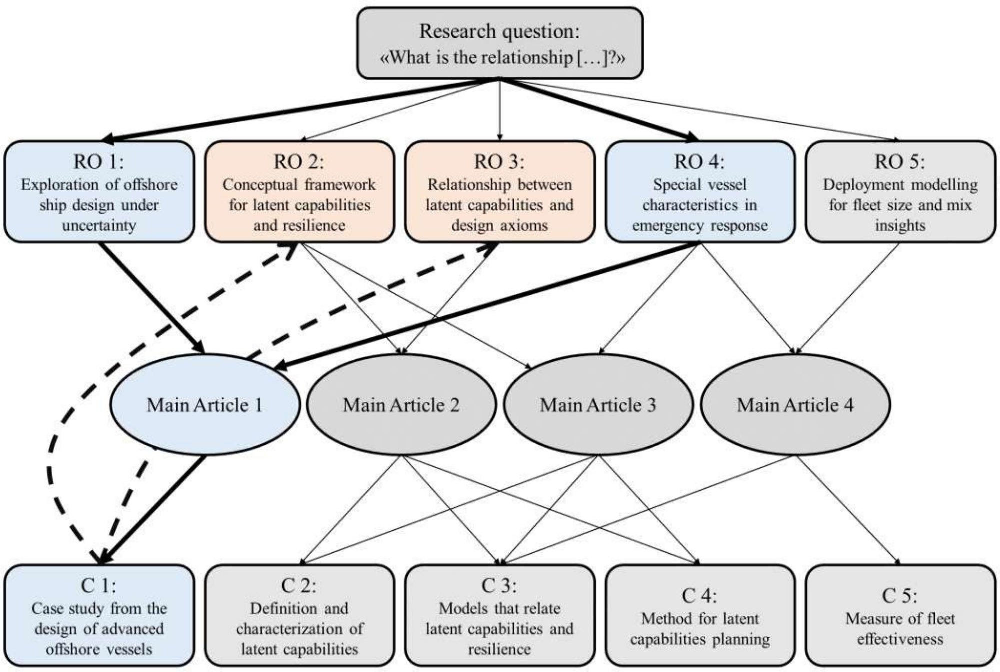

Figure 28: Moving from the research objectives to Contribution 1.

Contribution 1 produced the following insights beyond the case study itself:

- *An illustration that the creation of decision support models is a difficult design problem by itself, through what is referred to as the "two-stage abduction process".*
  Main Article 1 applied the Responsive Systems Comparison method on a design case study concerning a complex offshore vessel. The most important observation from the case studied in that paper related to the difficulty of designing *the decision support models* that represent the actual decisions facing key stakeholders. Model development becomes especially hard when there are multiple stakeholders with partially opposing preferences. Main Article 1 uses the term "two-stage abduction process" to indicate that there is first the problem of designing the decision support model, and then the problem of designing the vessel, as guided by that model.

- *An interest in exploring how unintended and unrecognized behaviours can be taken advantage of in marine systems.*
  The "two-stage abduction process" outlined in the discussion section in Main Article 1, motivates the further search for unintended and unrecognized behaviours that can be taken advantage of, without being explicitly designed for. Thus, Contribution 1 can be seen as an initiation of the process of developing the latent capabilities concept. For a design problem with multiple stakeholders, there may actually exist multiple perceptions of what the uses for the designed system will be. This indicates that certain vessel capabilities are *latent* to some stakeholders, or *latent* given specific decision support model formulations.

4.3.2. Contribution 2

A definition and characterization of latent functions and latent functional capabilities for engineering systems.

Contribution 2 partially answers the need for a conceptual framework for latent functional capabilities, an investigation of the relationship to design theory, and an investigation of special vessel characteristics, as shown in Figure 29.

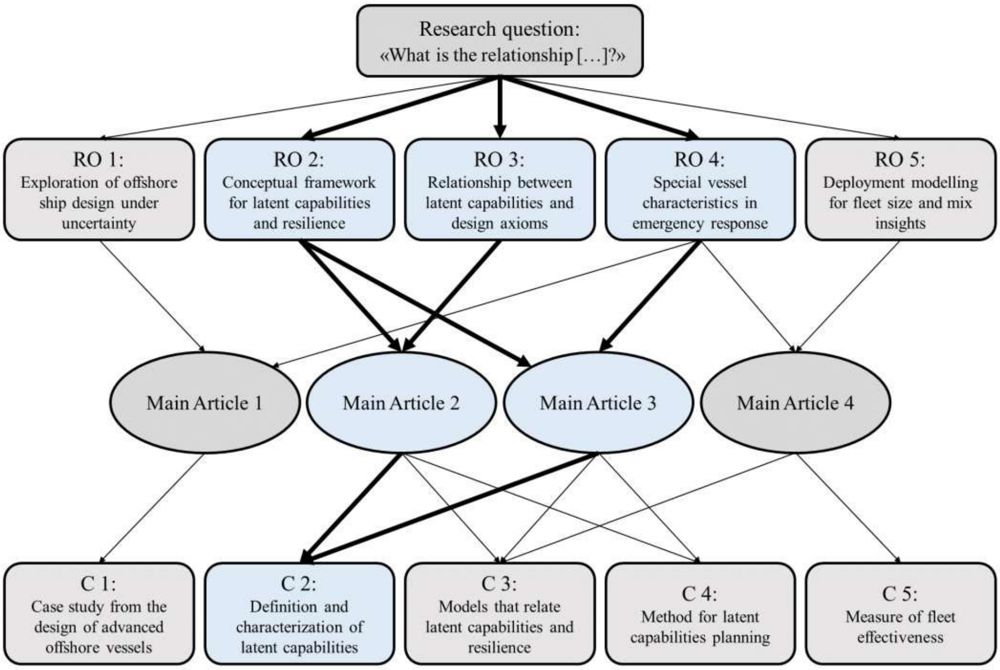

Figure 29: Moving from the research objectives to Contribution 2.

Contribution 2 can be summarized by the following points:

- *A definition of latent functional capabilities for engineering systems.*
  Starting from the definition of functions as a combination of a process and an operand (Pahl & Beitz, 1996), and the concept of latent functions (Merton, 1968), we define latent functional capabilities for engineering systems, as follows below:

  "Capabilities that were neither intended nor recognized during design, but have potential to be exploited and provide a benefit in the operational phase."

  This working definition positions the concept relative to the lifecycle phases for an engineering system. Latent capabilities are not considered in the design phase but may be discovered later, and be taken advantage of during the operational phase. Main Article 2 is the publication in which this topic was first studied. However, the stated definition here results from additional work on the topic, and an extended review of the systems design literature, compared to Main Article 2. Please note that we treat latent functional capabilities and latent capabilities as synonyms.

Note also that latent capabilities are a higher-level concept compared to latent functions. Where latent functions are restricted to a technical question of whether a given form can produce a function, latent capabilities encompass the degree to which the organization in charge are able to effectively exploit the latent functions in the operational phase. See the glossary in Appendix A for definitions of latent functions and latent (functional) capabilities.

- *A characterization of latent functional capabilities, including implications for concepts in systems design and operation, limitations and demarcations against similar concepts.*
  During the peer review process for Main Article 2, a recurring theme was the apparent contradiction that once *latent* capabilities are taken advantage of, they no longer can be considered *latent*, but become *manifest*. This lead to making the explicit statement that latent capabilities are those that were neither intended nor recognized during the design process. Making this even more clear, consider that the design process concludes when a description of a system, and a prescribed set of functions that the system should perform (i.e. a user manual), have been defined. Then, latent capabilities reflect system uses that emerge as beneficial during the operational phase, without these capabilities being intended or recognized. Main Article 3 explores this in a slightly more matured manner, as it was written largely after an additional elucidation of the topic in Supporting Paper 4. In Main Article 3, the terms *temporality* and *perception* are used to position latent capabilities:
    - *Temporality*; latent capabilities are identified after the design process closes.
    - *Perception*; latent capabilities were neither intended nor recognized by the designers.

  Additional limitations and demarcations against concepts that are similar to latent capabilities have also been explored, including concepts like functional redundancy, which was proposed as a design principle for resilient systems as shown in Section 2. A discussion of the implications for axiomatic design and system complexity was provided in Main Article 2. See also Contribution 3.

- *Relevant cases that motivate and illustrate the application of latent capabilities.*
  Several cases from previous operations have been provided to exemplify the benefits and challenges associated with exploitation of latent capabilities. First, Main Article 2 applies a fictional example in which an anchor handler uses its winch to extract an ROV deployed by a crane that fails and the real-life example of the Apollo 13 recovery. Second, Main Article 3 applies the Deepwater Horizon accident and the subsequent Macondo oil spill as an example in which the primary emergency response infrastructure was insufficient, and assistance by offshore support vessels was required. The offshore support vessels collaborated to provide functionality for other purposes than what was intended and recognized during design. Third, Supporting Paper 4 provides several cases, including the Macondo oil spill, ice management operations in the offshore industry, and the use of offshore support vessels in the Mediterranean refugee crisis for search and rescue.

4.3.3. Contribution 3

Two models that demonstrate how latent functional capabilities can enhance system resilience.

This contribution includes means to measure resilience, and to connect resilience and latent capabilities. The contribution includes models with relevance for systems design, on the level of single systems like ships, and a review of previous measures of resilience. A third model accounting for the fleet level is Contribution 5. The relationship between the research objectives and Contribution 3 are shown in Figure 30.

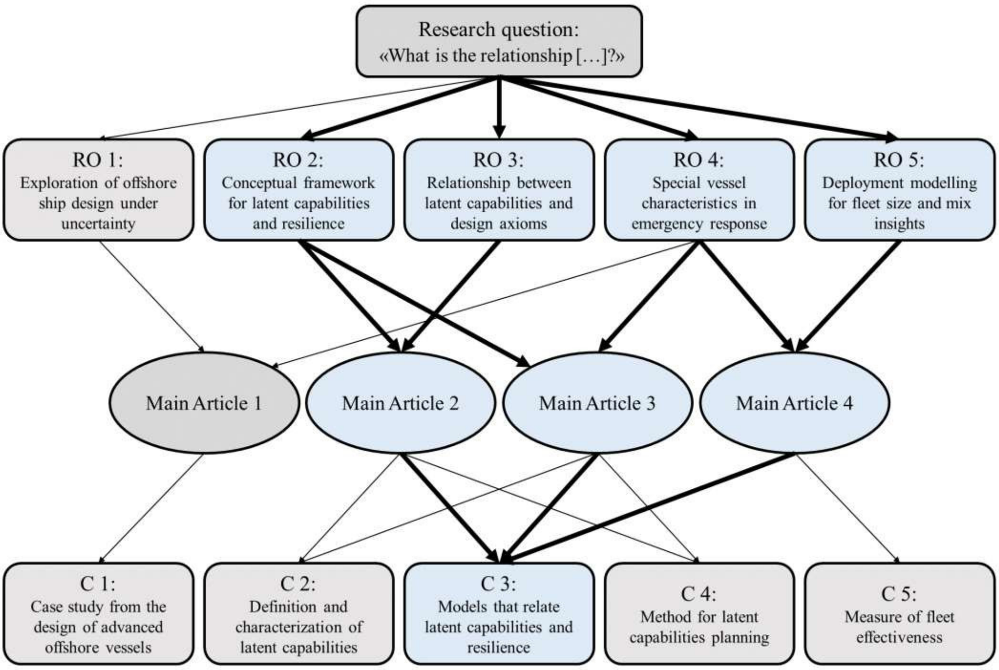

Figure 30: Moving from the research objectives to Contribution 3.

An overview of results that relate to this contribution is presented below:

- *A review of measures of resilience.*
  To evaluate how resilient strategies for coping with disruptions and emergencies are, there was a need to review measures and metrics that quantify resilience. Through this review, a great number of alternative resilience definitions and metrics exist. Research topics for which resilience metrics have been developed, ranging from civil engineering applications, including studies of societal resilience, through protection of critical infrastructures, to supply chain and operations risk management, to systems engineering, where relations to "ilities" like reliability and survivability are covered.

Little agreement exists regarding exactly how to measure resilience, but a few common denominators seem to underlie most quantitative resilience definitions. These common elements are the dimensions towards which resilience is measured, namely i) the change in performance between a pre-disruption state and a post-recovery state, which can be considered the magnitude of permanent performance degradation, ii) the disruption duration, or more precisely the time between the disruptive event, and the time of recovery to the post-recovery state and iii) the cost of recovery. For a detailed discussion, see Main Article 2, and Section 2.4. of this thesis. The importance of response time minimization is also discussed via the covering model for measuring fleet effectiveness, in Main Article 4.

- *Model 1: An axiomatic design model operationalizing latent capabilities in relation to resilience.*
  A model based on the function-form mapping relationship typically presented in axiomatic design was developed for some examples in Main Article 2, to illustrate the idea of latent capabilities. Axiomatic design holds that an ideal design has a one-to-one mapping between functional requirements and design parameters. The results from the analysis in Main Article 1 show that latent capabilities counter central aspects of axiomatic design while contributing to system resilience. The implications for system complexity are also discussed from this perspective in Main Article 2.

- *Model 2: A qualitative assessment of function-form mapping for offshore support vessels to identify latent capabilities.*
  Main Article 3 presents a qualitative model for the decomposed system and function hierarchies of an offshore support vessel. This supports the efforts to identify whether a vessel can provide latent functionality through a design catalogue approach. The system and functional structures were applied to the Macondo well containment operation, in which a number of vessels collaborated in an effort to close the leaking well.

4.3.4. Contribution 4

A methodology for identification, assessment, and contingency planning for latent functional capabilities.

This contribution responds to the need for a method for latent capabilities assessment and utilization of latent capabilities in contingency planning. The results from our approach to meeting RO 2 and RO 3, in particular, show that there are significant challenges when operating systems in an unintended manner. Figure 31 illustrates the relationship between the research objectives and Contribution 4.

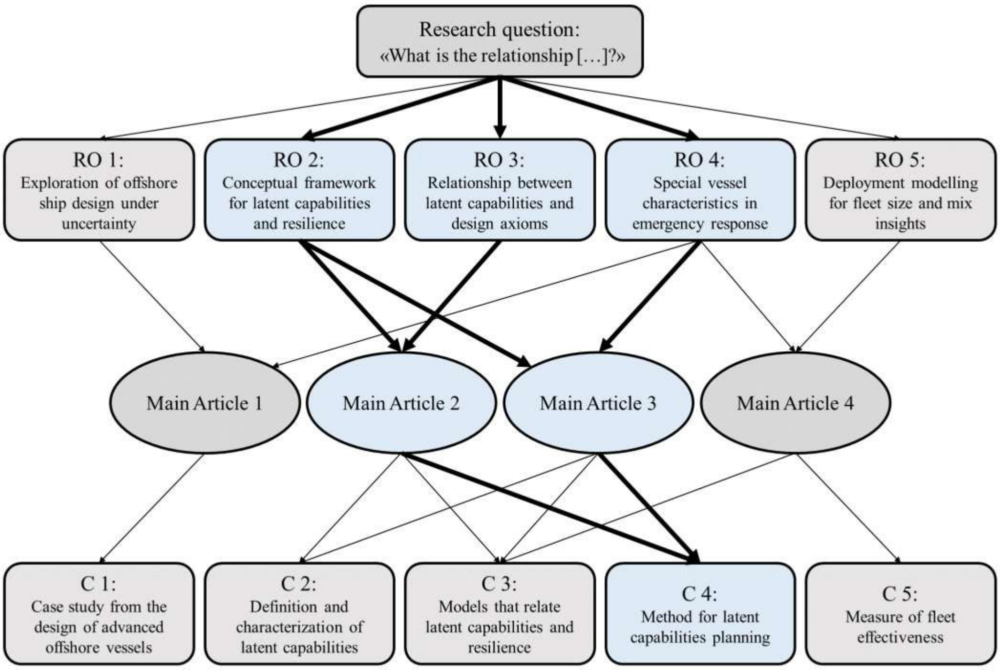

Figure 31: Moving from the research objectives to Contribution 4.

The development of a methodology for latent capabilities assessment started in Main Article 2 and was continued in Main Article 3. In Main Article 2, the structured approach for finding and planning for use of latent capabilities is described in two steps. Main Article 3 describes a more precise four-step approach. The four-step approach is shortly reiterated here:

0. **Prepare**; define system boundaries, descriptions, specifications, and investigate possible new functional requirements.
1. **Identify**; analyze system behaviours to identify latent capabilities. Study whether alternative ways of functioning are possible.
2. **Compare**; compare the effectiveness of applying latent capabilities with alternative strategies.
3. **Plan**; develop contingency plans for exploiting latent capabilities in case of disruptions or emergency response situations.

Key insights derived for this contribution are:

- *A distinction between searching for latent capabilities in the functional domain and in the needs domain.*
  This distinction relates to the level of abstraction appropriate for the identification of latent capabilities and is presented in Main Article 2. By latent capabilities in the functional domain, we refer to alternative physical means to fulfil a lost function (failure mode) or meet a new functional requirement due to an environmental change (e.g. due to emergency response missions). Value-based latent capabilities refer to an approach in which one abstracts from the lost function to the needs that function was meant to contribute to. An example of the latter is to reframe the problem situation in more generic terms, to increase the space of strategies available as a response to disruptions, and to readjust stakeholder preferences with respect to these opportunities (Ross, 2006; Tversky & Kahneman, 1981).

- *Development of criteria and constraints for exploitation of latent capabilities.*
  Main Article 2 discusses the development of resilience metrics for evaluating whether latent capabilities are better than alternative strategies, and finds an inherent trade-off between enhancing resilience and reducing system complexity. See Contribution 3 for a description of relevant parameters for use in the evaluation of resilience. Costs and constraints that need to be addressed as part of latent capabilities assessment are outlined in more detail in Main Article 3. Building on established cost structures for vessel economics (Stopford, 2009), we find that variable cost elements will be affected by exploitation of latent capabilities, including operational and voyage costs. Constraints exist in relation to compliance with contractual obligations with other actors in the value chain, as well as compliance with rules and regulation.

- *Application to the offshore support vessels in the Macondo oil spill response.*
  Main Article 3 offers an illustrative example of how the proposed methodology can be applied, using the example of the Macondo oil spill response. The case and offshore support vessels are described and put into the context of the emergency response situation. Key design characteristics for offshore vessels that are important to consider in emergency response situations are outlined. Vessel speed is important across all the possible missions, as a swift response is critical. This is tightly connected to another argument in favour of latent capabilities; in a disruptive state, there is little time to wait for purpose-built assets or to retrofit existing assets. One may need to take advantage of the resources that are available.

4.3.5. Contribution 5

A new measure of fleet effectiveness that captures emergence of latent functional capabilities on the system-of-systems level.

The final contribution is a new means to evaluate fleet effectiveness based on mathematical programming in combination with epoch-era analysis. The results quantify how well special vessels perform as part of an emergency preparedness infrastructure beyond the scope of their intended patrol missions. The fleet deployment model for special vessels is based on the structure of a maximal covering problem, and decides optimal vessel locations, given the available vessel capabilities and speed. As the objective function evaluates coverage of a set of missions that are secondary to the individual patrol missions of the vessels, this can be taken as an attempt to capture how additional (latent) capabilities emerge from vessel interaction effects on the fleet level. Figure 32 illustrates the relationship between the research objectives and Contribution 5.

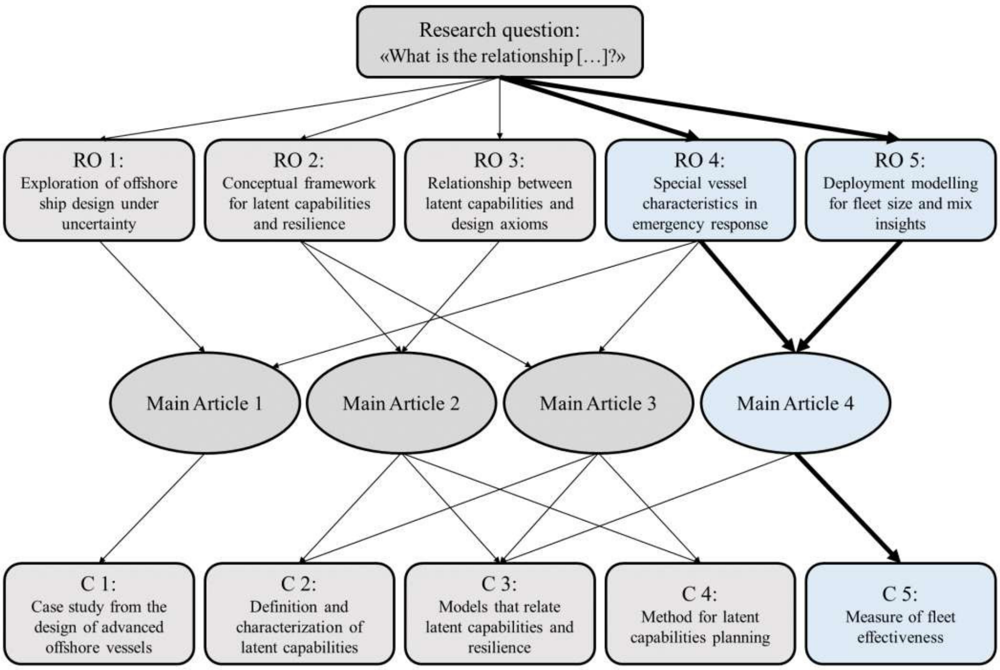

Figure 32: Moving from the research objectives to Contribution 5.

Specifically, this contribution consists of the following:

- *A fleet deployment model formulation starting from the structure of a maximal covering problem.*
  The model is presented in Main Article 4, and considers the objective of maximizing the importance-weighted (e.g. risk of emergency events) coverage of a set of possible emergency response missions, which are geographically distributed. The basic mission requirements for the system whose deployment we optimize, are given as constraints in the mathematical programming formulation. The formulation builds on

a generic maximal covering problem formulation (Owen & Daskin, 1998), with adaptations to account for vessel-mission compatibility, gradual covering and the diminishing marginal utility associated with covering the same area with multiple vessels.

- *Capture of the value of vessel interaction effects and emergence, that signify the existence of fleet level latent capabilities.*
  The fleet deployment models effectiveness on basis of response times and areal coverage, depending on the relative locations of vessels, hinting at a great geospatial complexity. The geospatial complexity determines the performance of the fleet, and shows the added value of accounting for vessel interaction effects. This forms the major relation to latent capabilities: Some properties of a given fleet configuration at a given time cannot be designed, but emerge as a result of vessels interacting across a geographical area.

- *A clarification regarding the use of decision support methodology based on the planning horizon under consideration.*
  The stated purpose of the fleet deployment model is to evaluate alternative fleet designs in different short-term *epochs*, but not to “optimize” the “design” of the fleet. The reason for this distinction is that the strategic planning horizon is significantly more uncertain. Rather than “optimize” across the strategic planning horizon, we take a design of experiments perspective and solve the mathematical program for the tactical fleet deployment model for many alternative fleets and for several alternative scenarios, or *epochs.* This approach provides results that enable exploration of many alternative fleet architecture, which allow a further understanding of trade-offs and compromises that must be accounted for in fleet size and mix.

5. Discussion and evaluation

This chapter discusses and evaluates the research. We will first comment on the validity of the approach and the results, and then discuss the practical implications of the thesis.

5.1. Evaluation of the approach

Chapter 3 of this thesis describes the research undertaken as "*conceptual, mixed quantitative-qualitative* research". This classification can be traced to the focus on the derivation of new knowledge based on the synthesis of existing theory from several disciplines, and on the derivation of new concepts and the relations between these.

Specifically, new concepts were developed starting from a set of case studies that included the study of a very complex ship design project, and an attempt to understand what the concept of resilience meant in relation to marine design. In this regard, this PhD project fits well with what Kovács & Spens (2005) refer to as abductive reasoning in research, where new theory is developed through synthesis of existing theory that does not match the observations. As predicted by the "exploration-exploitation" trade-off (March, 1991), exploration has come at the cost of more detailed analyses of larger data samples in this thesis. Hence, when it comes to theory development, this thesis must be taken as an effort to *theorize* about latent capabilities, rather than being seen as a *final theory* (Weick, 1995). The case study approach taken in the thesis may not generalize, and a broader collection of empirical evidence will add to the framework. For this reason, it is at this point more appropriate to refer to this thesis as an example of *conceptual* research, rather than *empirical* research, corresponding with the dichotomy in Chapter 3.

A threat to the validity of the approach is that there has been little focus on the use of existing data for application in latent capabilities assessment itself. This is partially a result of the approach taken, with a focus on broad theoretical exploration, and partially a result of the focus on high-end, more specialized offshore vessel segments. There is generally little public data on the day rates earned by vessels performing high-end offshore operations like offshore construction and light well intervention. Due to small market sizes, and a heterogeneous fleet, there is also less to learn from the formation of day rates for high-end special vessel segments, than for example from platform supply vessels and anchor handlers, which see a more homogenous market (Kaiser, 2015; Stopford, 2009). Further work to verify that latent capabilities assessment will constitute a positive contribution to the resiliency of ship owners and operators remains.

5.2. Discussion of the contributions

As outlined in Chapter 4, the main positive implications for the research community is access to a new conceptual framework, including models and methods, for addressing operational disruptions and emergency response, by exploiting existing system resources in a new way. While the thesis focuses on marine systems, it could influence research on the design and operation of engineering systems facing a high degree of uncertainty more generally. The interest in resilient engineering systems needs to be supported by approaches for enabling systems to bounce back from disruption. The constructs developed in this thesis meet this demand by offering a new way of thinking about how resilience can be achieved. While speculations regarding the impact of this research should be avoided, Book Chapter 2 (Pettersen & Asbjørnslett, 2018) which documents the latent capabilities concept in a supply chain risk management context, was accepted for publication without any revisions, demonstrating that there is an academic interest.

The research resulted in five contributions. The first contribution is a case study which documents a ship design project. The second, third, and fourth contributions relate to the development of the latent capabilities concept. The fifth contribution is a measure of effectiveness that captures capabilities that emerge due to the interaction between vessels in a fleet. We now turn to discussing these contributions individually.

Contribution 1 documents the design of a complex special vessel through a case study detailed in Appendix C and used in Main Article 1. The case is notable due to the impact of contextual uncertainty and unclear stakeholder expectations on the vessel design. Key insights derived from Contribution 1 relate to the *ill-structured* aspects of design. Applying the RSC method on the case, we find that decision support model design is by itself a design problem and illustrated the dependence of design decisions on the selection of decision support model. A different model formulation could highlight capabilities that are *latent* from the perspective of the original model formulation. The case study hence serves two valuable purposes: It documented the design process of a complex special vessel, and it helped initiate research on *latent capabilities.* A possible critique of the contribution is that a more thorough documentation of the case material, focusing on *what happened* in that process, could have been undertaken.

Contribution 2 define the latent capabilities concept. A challenge to the validity of this concept was highlighted by a reviewer of Main Article 2. The reviewer commented that latent capabilities *in design* are an oxymoron: If valuable capabilities are identified, why not just integrate these capabilities during design?

One answer to this problem is that integration of latent capabilities may hamper the manifest capabilities, obstructing the primary mission of the system. For example, if resources are spent to develop emergency response capability that will very seldom be used by introducing dedicated equipment for this, this equipment may physically and functionally interfere with the equipment intended for the mission of the vessel. This issue touches on classical discussions on the trade-off between redundancy and complexity (Perrow, 1999), and the wish for functional independence in axiomatic design (Suh, 1990, 2001).

Furthermore, if latent capabilities are made manifest and exploited during operations, they are not latent anymore. This is resolved by limiting the scope of what can be considered latent capabilities in two ways, drawing on Rhodes' & Ross' (2010) five aspects of complexity. First, there is a *temporal* argument: Latent capabilities are those capabilities that are identified *after* the closure of the design process. Second, there is a *perceptual* argument: Latent capabilities are identified by reframing what the *purpose* of some system or component is. For example, in the Apollo 13 case, when the need for life support emerged as the command and service module failed, one was able to think differently about what functions the lunar module should perform. Mission control and the astronauts were hence able to repurpose the lunar module to life support functions (Cortright, 1970). From the perspective of Apollo designers, unlike mission control operators and the astronauts themselves, these capabilities were absolutely latent. It is important to note that this does not negate the possibility that something that for an existing product may be considered a latent capability, can be implemented as a manifest capability for the next-generation of the product. It is naturally desirable that designers learn from operational experiences, and improve their products. Again, the Apollo 13 case can serve as an example: After the incident, the engineers reportedly considered to increase the dedicated life support functionality of the lunar module (Cortright, 1970).

Contribution 3 consists of the models that connect latent capabilities to resilience. First, it documents existing metrics of resilience, concluding that no single, aggregated resilience metric captures the concept adequately, as it requires the convergence of at least three, partially opposing objectives, minimization of permanent performance degradation, disruption time, and cost of recovery. Second, a critique of axiomatic design results from the application of the function-form mapping model, as this model is used to illustrate the benefits of functional coupling, which results from latent capabilities. While axiomatic design theory sees latent capabilities merely as symptoms of functional coupling that contributes to increased design complexity (Suh, 1990, 2001), and ideally should be avoided, the framework proposed in this thesis exploits these latent capabilities. The result is a more nuanced view of complexity, in which a complex system may be a more resilient system as it can exploit functional coupling to resolve disruptions and emergencies. Promising tools that can offer further insights into the relationship between latent capabilities and complexity include design structure matrices (Eppinger & Browning, 2012), and network science approaches that are currently applied for vulnerability analyses in marine systems design (Andrews, 2018).

Contribution 4 is an approach for latent capabilities assessment. Such an assessment will result in contingency plans that take latent capabilities into account, after the identification of latent capabilities, and cost-benefit analyses that compare latent capabilities to alternative strategies. Key aspects of latent capabilities that contribute favourably to resilience include agility (ability to change fast), and versatility (ability to change function without form). For the cases studied in Main Article 2 and 3, the benefits of swift response to disruption were highlighted, meaning that versatility generally would be favoured over retrofit of equipment to meet the change in operating context. No economic analyses were done to calculate the expected increases in profitability resulting from utilization of latent capabilities, except for a decomposition of the cost structure with comments on changes due to changes made to the operating profile. In Main Article 3, variable cost elements like operating and voyage expenses are shown to increase when taking advantage of latent capabilities. Limitations of latent capabilities that are addressed through the assessment include possible deviation from contractual obligations, as well as the impact of rules, regulation, and existing operating procedures in shipping. Human factors and organizational issues also constitute limiting aspects that need to be addressed for the successful exploitation of latent capabilities. As discussed by organizational theory (Weick, 1993; Sutcliffe & Vogus, 2003), creative, on-the-fly problem-solving at the individual level, needs to be migrated through the organization, for the solution to emerge as an effective response to the unexpected.

Contribution 5 is a measure of effectiveness for evaluation of fleet alternatives, derived from a fleet deployment model. The deployment model follows the structure of a maximal covering problem (Owen & Daskin, 1998), and captures vessel interactions beyond the single ship level. In this sense, characteristics that are valued by the model may hence be *latent* from the perspective of the single ship design problem. Furthermore, the model could also be applied to optimize the tactical deployment of any fleet of existing resources, including the possibility of assigning vessels to missions they were never intended for, but that they are capable of performing. To further illustrate the connection between *ill-structured* problems and *latent capabilities*, there is a need for exploring deployment models with alternative objectives.

5.3. Implications for practitioners

Key implications of the research are new means to support efforts for disruption and contingency management in the maritime industry, and other agencies with a stake in ocean activity. We will discuss the implications for four main groups of stakeholders; the maritime industry, regulatory bodies, governmental and non-governmental organizations.

5.3.1. Implications for the maritime industry

The commercial actors that could have an interest in the results of this research include shipping companies and other operators of marine systems, ship design companies, equipment manufacturers, and shipyards.

Shipping companies and other operators of marine systems

The ship in the design case reported on in Main Article 1 was strongly affected by the 2014 downturn in the oil price, which spurred a significant reduction in the profitability of most ship owners in possession of advanced offshore support vessels. As a result of the worsened market situation, a great number of vessels were taken out of service. The concepts outlined in this thesis may contribute to the improved business outcomes under such circumstances, by allowing new market opportunities to be identified through the recognition that a ship can perform more functions than considered in the design phase.

One example of this is the case of platform supply vessels acting in search and rescue operations, managed by non-governmental organizations or by Frontex[7] in the Mediterranean (Cusumano, 2017). For the owners of these vessels, deployment to these missions constituted an economically viable alternative to lay-up in a bad market situation (Pettersen, Asbjørnslett, Erikstad, et al., 2018). Another example is the collaboration among offshore support vessels independently managed and operated, during the well containment operations following the Macondo oil spill (British Petroleum, 2010; Mileski & Honeycutt, 2013), where the fleet offered capabilities far beyond what each vessel was designed for. A recommendation for ship owners is hence to think through possible markets, missions, and functions, to which they may be able to provide a service with existing assets, in addition to the markets, missions, and functions the existing assets were originally intended to serve. This could be particularly relevant for Arctic maritime activity, where privately owned assets likely will be required to take a larger role in emergency response, due to a lack of existing emergency infrastructure. Practical limitations to this include contractual obligations and sharing of the costs, which have to be part of determining charter-party conditions, as discussed in Main Article 3.

Ship designers

While ship design work mostly concentrates on delivering customized one-off designs, there have been some examples where series of vessels have been built from the same design. For the latter segment, benefits of considering latent capabilities particularly relate to seeing new uses and new markets for existing products. There is hence a marketing case to be made, based on latent capabilities. This point was made for engineering systems in general by Crilly (2010, 2015). For example, the Ulstein Group have investigated whether they can sell their PSV series PX121 towards customers that operate in other market segments than platform supply (Ulstein International, 2012). They found that the vessel could service certain emergency response

[7] Frontex is shorthand for the European Border and Coast Guard Agency.

functions without any major design changes, indicating that an added value could result for the customers.

Beyond latent capabilities, this thesis provides additional support for viewing ship design, special vessel design in particular, as a wicked or ill-structured problem, as previously discussed in the naval design literature (Andrews, 2011, 2018). This approach is also taken in Main Article 1 for offshore support vessels. The case study in Appendix C shows that emphasis needs to be put on the early phases of design, especially proper market analyses including clarification of performance expectations and risk assessments need to be performed among stakeholders. More elaborate practices with respect to future uncertainty may also negate the need for identifying latent capabilities, as more possible operational modes are considered in the design analyses. These insights have yet to fully penetrate the ship design community, although there are industry-based initiatives that aim to integrate business management perspectives in early-stage ship design consultation (Ulstein & Brett, 2015).

Equipment manufacturers

As for ship designers, latent capabilities represent a possible marketing opportunity for manufacturers of ship equipment or subsystems. From marketing a product towards only one application, additional uses may be found, creating an entrance to new markets. To an extent, the discovery of new product uses also constitute a risk to equipment manufacturers, as it may become apparent that certain tasks can be achieved in a simpler manner, not requiring purpose-built equipment.

Shipyards

Ship production and the role of the shipyard has been kept outside the scope of this research. Still, there are reasons to believe that built objects embed unintended and unrecognized features that may ease tasks during shipbuilding. A simple example could be portholes in the ship hull easing transport of equipment or material into the hull during outfitting of the vessel. This example has little direct relevance for the connection to resilience and emergency response but shows that latent capabilities are relevant for other phases of the lifecycle.

5.3.2. Implications for regulatory bodies

Regulatory bodies potentially affected by this research range from international bodies at the United Nations level, like the International Maritime Organization (IMO), through the national law and regulations of each flag state, to the classification societies.

The IMO is responsible for the overarching regulatory framework for international shipping. Hence, the exploitation of latent capabilities to cope with events in the maritime domain needs to be consistent with the rules and regulations set forth by the IMO. Given current moves towards a risk-based regulatory framework (Papanikolaou, 2009), the future may be open to more improvisation and deviation from the prescribed operation of equipment. This depends on how the benefits of latent capabilities are weighted against other risks. Regardless of the outcome of such analyses, it should be clear that regulatory issues constitute a serious constraint for exploiting latent capabilities, as discussed in Main Article 3.

For classification societies, the implications of the proposed concepts relate to the regulatory framework for the operation of marine systems. Are ships allowed to deviate from their intended operations in a manner that enables stakeholders to take advantage of latent capabilities? The

DNV GL standard on offshore marine operations states that "contingency planning should consider redundancy, back-up equipment, supporting personnel, emergency procedures and other relevant preventive measures and actions" (DNV, 2011). This indicates that assessment of latent capabilities could be interesting from a contingency planning standpoint, for example as an enabler of effective use of backup equipment. Exploration of latent capabilities for contingency planning or emergency response could also be integrated into existing services offered by the classification societies. For example, classification societies offer immediate assessment of remaining capacities such as damage stability in vessels after accidents, expected to further improve with increased use of sensor technology (DNV GL, 2015; Karolius & Vassalos, 2017). Similarly, assessment of remaining (latent) functionality after equipment failures could be an extension of that type of emergency service.

5.3.3. Implications for governmental organizations

For governmental organizations, the implications of the research are twofold. First, when striving for resilience via latent capabilities, there is naturally a need for compliance with national rules and regulations. Second, some governmental agencies can gain significantly from the identification of latent capabilities in existing commercial resources. The introduction of this thesis identified several examples of commercial marine transport supporting military operations ("Logistic Support for Operation Corporate," 1982; Rosendahl, 2015; Wilkinson, 1993). Government-initiated resource pools like the Vessels of Opportunity program organized in response to the Macondo oil spill (British Petroleum, 2010; Mileski & Honeycutt, 2013), illustrates the importance of utilizing existing commercial assets for emergency response. As articulated by Main Article 3, there are additional challenges concerning the development of resource pools. Challenges include organizational learning, especially from previous emergencies, training of personnel, effective contingency planning and deployment, and forms of compensation to owners of response assets. These constraints overlap with legal and contractual matters and need to be explored further, perhaps within a framework of marine policy.

5.3.4. Implications for non-governmental organizations

The impact of the research on non-governmental organizations was discussed in the introduction of the thesis, exemplified by the use of commercial assets in disaster relief. The use of commercial assets like offshore support vessels or roll-on, roll-off carriers in humanitarian relief operations is well-documented (Berle et al., 2012; Cusumano, 2017), and reflects an increasing interest in humanitarian logistics (Jahre & Fabbe-Costes, 2015; Kovács & Spens, 2007; Oloruntoba & Gray, 2006; Van Wassenhove, 2006; Vega & Roussat, 2015). As humanitarian organizations regularly piggyback off of resources normally part of commercial supply chains, these organizations exemplify a sector that can extract useful insight from this thesis.

6. Conclusion

6.1. Concluding remarks

The thesis initially asked the question:

> *"What is the relationship between characteristics designed into marine systems, the ability to recover from operational disruptions, and the ability to respond to swiftly emerging demands?"*

The research question was answered by reviewing a wide literature on design-related topics, consultation of case material, and development of the concept of latent capabilities as a means to achieve resilience. Both system-internal disruptions and system-external, sudden-onset emergencies were addressed. A conceptual framework for latent capabilities was established and supported by developing models and methods for assessment of latent capabilities. In that respect, the research question has been answered by bringing to light the characteristics of designed systems that exist without intent and recognition. The thesis identifies such characteristics for marine systems, ranging from ship subsystems, via vessels, extending to the fleet level. A special emphasis was put on complex special vessels, in particular, multi-functional offshore support vessels.

Concretely, the research question was met by a series of four articles from which the main contributions were the following:

C 1 An industrial *case study* from the design of advanced *offshore support vessels* with *multiple stakeholders under uncertainty*.

C 2 A *definition* and *characterization* of latent functions and *latent functional capabilities* for engineering systems.

C 3 *Models* that demonstrate how *latent functional capabilities* can enhance *system resilience*.

C 4 A *methodology* for identification, assessment, and contingency planning for *latent functional capabilities*.

C 5 A new *measure of fleet effectiveness* that captures *emergence of latent functional capabilities* on the system-of-systems level.

The contributions propose that a search for unforeseen capabilities can constitute a response to unforeseen events. Operating environments that were thought about during design readily enter into the design process by informing functional requirements. On the other hand, those operating environments that were not thought about can be addressed by exploiting latent capabilities. Hence, latent capabilities are shown to contribute to the recovery of system functionality, and the response to emergency situations, enhancing the resilience of marine engineering systems, communities, and the natural environment.

A variety of models and methods have been explored for assessment of latent capabilities, extending from the development of functional structures, axiomatic design models, and application of resilience metrics, to mathematical programming. We show that certain well-known incidents, such as the Apollo 13 incident and the Deepwater Horizon accident both were resolved partly due to a creative form of problem-solving in which systems were utilized in ways neither intended nor recognized during design. We conclude that revisiting the function-form mapping of existing marine systems may reveal capabilities beyond the capabilities originally intended. Revisiting the function-form mapping results in a deviation from the common principles of engineering design, through elimination of functional independence. A consequence is a partial refutation of axiomatic design theory, as an increase in complexity is likely justified by the increase in resilience. This added complexity reveals itself through a set of subsequent limitations to the applicability of latent capabilities, for example existing contractual obligations and operating procedures.

A possible outcome of the findings in the thesis is significant value added to stakeholders across the value chain of complex systems. Business opportunities can emerge for ship owners who are interested in innovating around modes of operation when necessary, either due to system-internal failures or emergency response needs. Similarly, ship design companies may take advantage of latent capabilities by tuning the marketing of existing vessel product lines to new business segments. To governmental and non-governmental organizations alike, latent capabilities assessment can represent a structured approach to identifying existing resources that can be applied in emergency response.

6.2. Further work

This research has taken a broad and quite exploratory scope, meaning that there are certainly many aspects of the concepts and methods outlined that remain to be researched. There are other valid perspectives on the relationship between the design characteristics of marine engineering systems, resilience, and emergency response, in addition to the framework of latent capabilities. Further work could be undertaken to address the research objectives in more detail:

First, RO 1 could be addressed further by exploring other challenges resulting from future uncertainty and unclear, differing stakeholder expectations in marine systems design. The added complexity associated with multiple stakeholders is one that has wide implications for design, often resulting in design changes after production commences, as seen in the SIMOSYS case study. Engineering design research aimed at minimizing the negative consequences of unclear expectations like late design changes will be valuable. In this thesis, it was observed how the case study approach combined with the application of systems design methodology initiated research on latent capabilities. This shows the power of the case study as a means to identify new research topics.

Second, RO 2 concerned the development of a conceptual framework for thinking about latent capabilities. The conceptual framework that was developed needs elaboration in several directions. First, there is a need for additional empirical evidence for the applicability of latent capabilities to improve our understanding of the boundary conditions. Additional evidence can be obtained through the following:

- Review of incident reports to learn from successful exploitation of latent capabilities.
- Field studies and sensor monitoring documenting actual operations, to identify disruptions that are resolved by improvisation.
- Interviews with stakeholders in the maritime industry, including ship owners, operators, designers, and equipment manufacturers to gain an understanding of the actual scope of differences between intended and actual uses of marine systems.

Second, there is a need for elaboration of the theoretical framework and methods for assessment. The following ideas can contribute to the further development of the conceptual framework:

- Clarification of commercial, operational, and technical conditions for exploitation of latent capabilities, including:
    - Investigation of latent capabilities as an enabler of future market flexibility, and as a means for marketing of existing ship design product lines towards new segments.
    - Investigation of issues related to compliance with existing contractual obligations with customers, rules and regulations in the maritime industry, human factors engineering, and organizational learning.
    - Investigation of technical feasibility, including physical modelling and development of simulation models for marine operations taking advantage of latent capabilities.
- Application of the method for latent capabilities assessment in combination with tools for system vulnerability assessment, preferably based on the use of historical data and case material supplied by industry.
- Research on marine policy implications and legal issues related to exploitation of latent capabilities, including the development of compensation schemes for ship owners with assets in government-initiated resource pools for emergency response.

Third, RO 3 concerned the relationship between latent capabilities and axiomatic design theory. While some conclusive remarks were made with respect to limitations of axiomatic design thinking during the operational phase, many similar matrix models mapping between function and form have proven useful. For example, design structure matrices have been successfully applied to improve understanding of system architectures generally. Detailed design structure matrices could likely be applied to get an overview of remaining capabilities in systems experiencing operational disruptions, or to identify functionality in available assets for resolving emergencies.

Fourth, RO 4 was to investigate the characteristics of special vessels that are useful in emergency response settings. Main Article 3 identified vessel functionality that can contribute to resolving complex emergencies like offshore oil spills, on basis of Macondo incident reports. Further work remains to investigate emergency response applications of other existing assets and to quantify changes in operating costs due to latent capabilities. This work can start from a review of mission profiles and functional structures of other ship types, which would also contribute to strengthening the empirical evidence for latent capabilities.

Fifth, RO 5 concerned development of fleet deployment models. Further research should investigate the trade-off between the output of alternative optimization models for fleet deployment. For deployment to emergencies, an interesting approach would be to study the trade-off between the different aspects of resilience, including minimizing response times, minimizing permanent degradation of the system through disruptions, and minimizing deployment costs. Understanding the difference in model output given dependence on the model structure would uncover solution aspects may be latent to the model in Main Article 4.

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Appendix A: Glossary

The glossary presents relevant concepts and definitions alphabetically. Some terms are structured, in order to increase the coherence of the glossary.

Agility: "The ability of a system to change in a timely fashion" (de Weck et al., 2012).

Changeability: "The ability of a system to alter its operations or form, and consequently possibly its function, at an acceptable level of resources" (de Weck et al., 2012).

Complexity: The information needed to describe an object, i.e. the information content (Braha & Maimon, 1998; Kolmogorov, 1983; Suh, 1999). An opposite of simplicity.
Rhodes & Ross (2010) refer to five aspects of complexity:

- *Structural complexity:* "related to the form of system components and their interrelationships".
- *Behavioural complexity:* "related to performance, operations, and reactions to stimuli".
- *Contextual complexity:* "related to circumstances in which the system exists".
- *Temporal complexity:* "related to dimensions and properties of systems over time".
- *Perceptual complexity:* "related to stakeholder preferences, perceptions and cognitive biases".

Engineering design: "… a process performed by humans aided by technical means through which information in the form of requirements is converted into information in the form of descriptions of technical systems, such that this technical system meets the requirements of mankind" (Hubka & Eder, 1987).
This is a more limited definition than that offered by Simon (1996) who states that "everyone designs who devises courses of action aimed at changing existing situations into preferred ones". We use design and engineering design interchangeably, and define it in accordance with Hubka & Eder (1987) unless otherwise stated.
Design is also often described as an open-ended process of mapping from function to form (Coyne et al., 1990; Suh, 1990). The design process is commonly parsed into the following phases:

- *Task clarification:* Elicitation of needs the system needs to meet, and tasks it should perform.
- *Conceptual design:* Definition of a principle solution, a concept, including functional structures and overall physical form.
- *Embodiment design:* Development of physical description of the system, a layout.
- *Detail design:* Documentation to a level sufficiently detailed for production to commence.

See also "Systems design".

Failure mode: Loss of critical functions in a system (Berle, Rice, et al., 2011). Loss of any such critical function would cause a disruption of ongoing operations.

Flexibility: "… ability of a system to be modified to do jobs not originally included in the requirements definition" (McManus & Hastings, 2006). Sometimes differentiated with *adaptability*, by reserving the term *flexibility* to changes instigated by system-external change agents (de Weck et al., 2012; Ross et al., 2008).

Form: The objects, and interrelations between objects, that constitute the physical system structure.

Function: What the system does (Magee & de Weck, 2004), ie. enact a conversion of some operand (matter, energy, signal) from an input state to an output state (Pahl & Beitz, 1996), by some process (transform, transport, store).

- *Manifest function:* Intended and recognized functions of a system (Merton, 1968), ie. its functions as designed.
- *Latent function:* Positive, unintended and unrecognized functions that can result from operating a designed system (Merton, 1968). See also "Latent (functional) capabilities".
- *Dysfunction:* Negative, unintended and unrecognized functions that can result from operating a designed system (Merton, 1968).

"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 than are embodied in those primary functional requirements. The ilities do not include factors that are always present, including size and weight (even if these are described using a word that ends in "ility")" (de Weck et al., 2011). Resilience exemplifies one "ility" which does not end in "ility".

Ill-structured problem: "…"ill structured problem" (ISP) is a residual concept. An ISP is usually defined as a problem whose structure lacks definition in some respect. A problem is an ISP if it is not a WSP (well structured problem)" (Simon, 1973).
See also "Wicked problem", which are a similar category of problems, yet imply a more pessimistic view on our ability to solve complex design problems through a well-defined structure.

Latent (functional) capabilities: Capabilities that were neither intended nor recognized during design, but that have potential to provide benefit in the operational phase, or the degree to which latent functions in an engineering system can be taken advantage of. See also "Functions: Latent functions".

Lifecycle: "The sequence of phases that an engineering system undergoes, which can be divided into three major parts: conceiving, developing, and deploying" (de Weck et al., 2011). An alternative segmentation of the lifecycle phases, which is preferable is *design*, *production*, *operation*, and *disposal*.

Operations research: "…is a discipline of applying advanced analytical methods to help make better decisions" (INFORMS, 2018). Also, "a scientific approach to executive decision making, including problem formulation, mathematical modelling, and system optimization" (de Weck et al., 2011). This discipline mainly seeks to manage systems in the operational phase of the lifecycle but can influence design as a means to *evaluate* alternatives.

Reliability: "The ability of an item to perform a required function, under given environmental and operational conditions and for a stated period of time" (Rausand & Høyland, 2004).

Requirement: "The properties that an engineered system is supposed to achieve, deliver, or exhibit" (de Weck et al., 2011).

Resilience: The ability of a system to be recovered from a disrupted state to an improved state. After Asbjørnslett & Rausand (1999), an opposite of vulnerability and a different concept from robustness.

Risk: The triplet of scenario, frequency and consequence (Kaplan & Garrick, 1981).

Robustness: "… a system's ability to resist an accidental event and return to do its intended mission and retain the same stable situation as it had before the accidental event" (Asbjørnslett & Rausand, 1999).

System: "A set of interacting components having well-defined (although possibly poorly understood) behavior or purpose" (de Weck et al., 2011). Types of systems that deserve a specific mention include:

- *Complex system:* "A system with components and interconnections, interactions, or interdependencies that are difficult to describe, understand, predict, manage, design, or change" (de Weck et al., 2011).
- *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 et al., 2011).
- *System-of-systems:* "A system-of-systems is an assemblage of components which individually may be regarded as systems, and which possesses two additional properties" (Maier, 1998); i) operational independence of the components, and ii) managerial independence of the components.
- *Technical system*: An artefact resulting from a production process, as the physical form by which humans achieve needs (Hubka & Eder, 1988).

Systems design: "The process of defining the components, modules, interfaces, and data for a system to satisfy specified requirements" (MITRE Corporation, 2014).

Systems engineering: "An interdisciplinary approach to derive, evolve, and verify a life-cycle balanced system solution which satisfies customer expectations and meets public acceptability"

[8]. Alternatively, “an interdisciplinary approach and means to enable the realization of successful systems” [9].

Two-stage abduction process: The process of developing a well-structured model of an ill-structured system design problem, is in itself characterized by the abductive reasoning of a design process (Pettersen, Rehn, Garcia, et al., 2018).

Uncertainty: “Things that are not known, or only known imprecisely” (McManus & Hastings, 2006).

Versatility: “The ability of a system to satisfy diverse needs for the system without having to change form” (de Weck et al., 2012). Latent capabilities represent a form of versatility.

Vulnerability: The properties of a system that “may weaken or limit its ability to endure threats and survive accidental events that originate both within and outside the system boundaries” (Asbjørnslett & Rausand, 1999).

Wicked problem: A problem which has the following ten characteristics (Rittel & Webber, 1973): i) “no definite formulation”, ii) “no stopping rule”, iii) solutions measured as good or bad, rather than true or false, iv) “no immediate, ultimate test of solution”, v) “one-shot operation” vi) unbounded set of possible solutions, vii) “essentially unique”, viii) “symptom of another problem”, ix) “choice of explanation of the problem determines the nature of the problem’s resolution”, and x) “the planner has no right to be wrong”. See also “Ill-structured problem”.

[8] Definition according to IEEE, see Blanchard & Fabrycky (2013).

[9] Definition according to INCOSE, see Blanchard & Fabrycky (2013).

Appendix B: Main Articles

Main 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, Vol. 34, No. 1, 2018, pp. 72-83.

Main Article 2:
Exploiting latent functional capabilities for resilience in design of engineering systems
Pettersen, S. S., Erikstad, S. O., & Asbjørnslett, B. E.
Research in Engineering Design, Vol. 29, No. 4, 2018, pp. 605-619.

Main Article 3:
Latent capabilities in support of maritime emergency response
Pettersen, S. S., Garcia, J. J., Rehn, C. F., Asbjørnslett, B. E., Brett, P. O., & Erikstad, S. O.
Submitted to an international journal.

Main Article 4:
Evaluating fleet effectiveness in tactical emergency response missions using a maximal covering formulation
Pettersen, S. S., Fagerholt, K., & Asbjørnslett, B. E.
Submitted to an international journal.

Main 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, Vol. 34, No. 1, 2018, pp. 72-83.

Journal of Ship Production and Design, Vol. 34, No. 1, February 2018, pp. 72–83
http://dx.doi.org/10.5957/JSPD.170012

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

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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.

Keywords: 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 & 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 & Hastings 2006). Actively considering uncertainty in the design process can result in solutions

Manuscript received by JSPD Committee March 15, 2017; accepted May 9, 2017.

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 & Schulz 2005; Ross et al. 2008b; Niese & Singer 2014; Chalupnik et al. 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 et al. 2011; Fet et al. 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. 2016b). Operations research methods include stochastic programming applied to issues in ship design like machinery selection under uncertainty (Balland et al. 2013; Patricksson & Erikstad 2016). Another recent approach uses Markov decision processes for evaluating ship design performance under uncertainty (Kana & 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; 1) multi-attribute tradespace exploration (MATE) and 2) epoch-era analysis (EEA) (Ross et al. 2009; Ross et al. 2008a). 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 et al. 2014), and a simplified OCV case (Keane et al. 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 OCV for a joint venture of two stakeholders with different preferences. Following this, the most significant contribution is 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 & 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 & 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 et al. 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 & 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 in the North Sea has been built with Ice Class, without really needing it (Garcia et al. 2016a). 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 et al. 2016). In this paper, we use multi-attribute utility (MAU) theory, as presented by Keeney and Raiffa (1993). The attributes must adhere with the following criteria; 1) completeness, representing all important aspects of decision-making, 2) operational, possible to measure, 3) decomposable, so that they can be broken into parts for easier evaluation, 4) nonredundant, so that the same attributes are not counted twice, and 5) minimal, so that the dimensionality of the problem is kept as small as possible. We here use an additive MAU function, on the following form:

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

U where 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 RSC method is used in this paper. The RSC method was originally presented in Ross et al. (2009) and Ross et al. (2008a), 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 MATE and 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 nine steps clustered into three 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.

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, the context and the system itself (Ross et al. 2009).

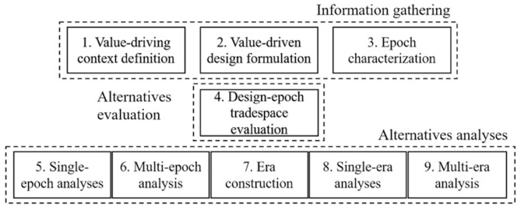

Fig. 1 The Responsive System Comparison (RSC) method (adapted from Schaffner et al. (2014))

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 et al. 2008a).

"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 & 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 modeling 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 is utility measures and costs for all design alternatives in all epochs. The required mapping between the value and the design spaces is shown in Fig. 2. In the figure,

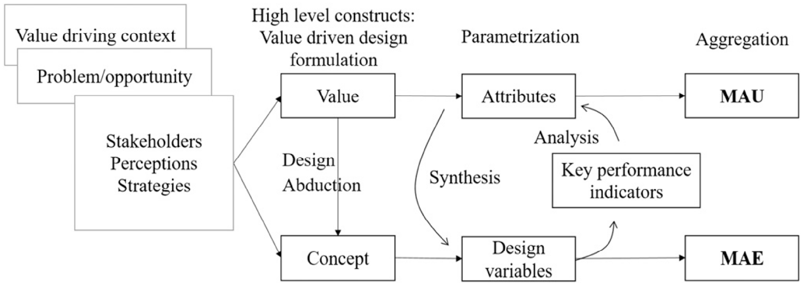

Fig. 2 Relating value and design concept to the tradespace

MAU refers to multi-attribute utility, while MAE refers to multi-attribute expense, a generalized cost representation.

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 nondominated solutions as the criteria of design goodness of fit (Keeney & 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 analyze 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 & 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 & 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 et al. 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 centers on the design of an OCV, 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 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 the gas industry. Increasing world population and economic growth is believed to lead to an increased demand for energy. Although 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 (GoM), 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 & Ross 2012). 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 GoM 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

Table 1 Stakeholder value attributes

Stakeholder	Value attribute	Level	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.

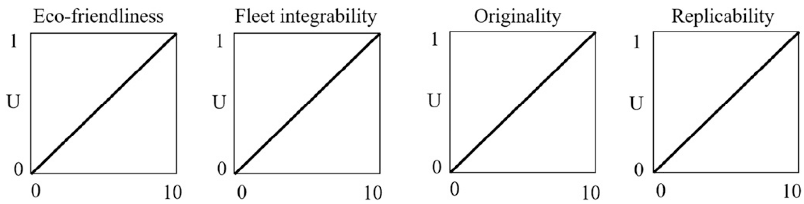

Fig. 3 Single-attribute utility functions

Table 2 Design variables

Design variable	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
LWI (tonnes)	0, 300, 600
Moonpool	No, yes
Fuel type	MGO, Dual fuel (DF)
Dynamic positioning	DP2, DP3
Remotely operated vehicle	No, yes

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 nonmonetary 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 nonmonetary 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 nonmonetary value attributes of each stakeholder are given in Fig. 3.

Originality represents the ability of being the first mover with advanced equipment into the 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 LWI 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 0–10 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 LWI 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.

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 Fig. 4.

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),

Fig. 4 Ship system boundaries and epoch variables

Table 3 Epoch variables representing important sources of exogenous uncertainty

	Epoch variable	Values
Contract	Contract rate (k$/day)	50, 70, 120, 170, 220
parameters	Operational area	1, 2, 3, 4
	LWI req. (tonnes)	0, 300, 600
	Module weight req. (tonnes)	0, 200, 400, 600
Technical	Accommodation req. (POB)	50, 150, 250, 350
requirements	ROV req.	0, 1
	Dynamic positioning req.	0, 1
	Deck area req. (m^2)	0, 1,000

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

Operational area	Epoch variable value	Depth (m)	Hs (m)
GoM	1	1,600	2.0
Brazil	2	2,500	2.5
North Sea	3	200	3.0
West Africa	4	1,800	1.0

as described in Table 4. Further, the possibility that the ship is in lay-up is also included.

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 modeling of physics and economics, via "key performance indicators". The outcome of Step 4 is a measure of MAU, and a cost measure, 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, and 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 modeling, 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 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.

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 nondominated 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.

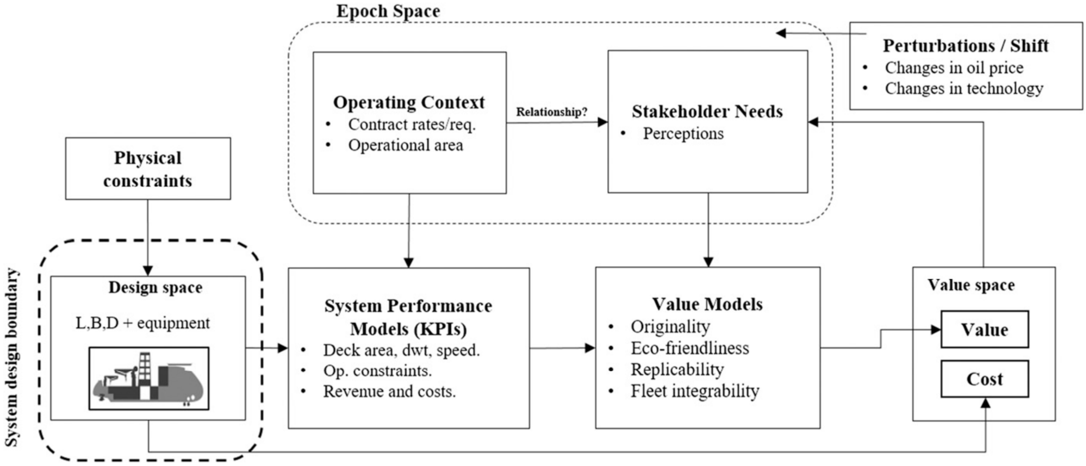

Fig. 5 Illustrating the design-value mapping model

Table 5 Sample designs for further assessment

Design name	I	II	III	IV	V	VI
Design ID	116,454	114,843	110,835	128,020	111,081	128,356
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
LWI (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)	1,200	2,000	1,000	1,300	1,000	1,000
Dwt (tonnes)	7,300	19,000	4,500	6,700	5,400	5,400
Max speed (knot)	18	20	18	18	17	18
Acquisition cost (m$)	164	210	215	236	223	247

Table 6 Three relevant example epochs for the GoM

	Low case	Base case	High case
Epoch ID	981	6813	6889
Contract rate	$70,000/day	$170,000/day	$220,000/day
Operational area	GoM	GoM	GoM
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	1,000	1,000
Tradespace yield	0.20	0.02	0.01

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.

The tradespace yield measures are in this case identical for the two stakeholders. Only the designs that have the technical

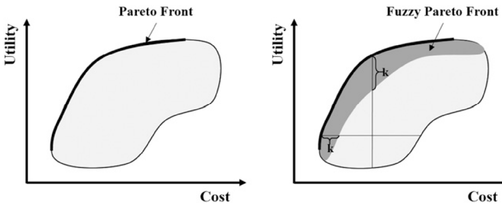

Fig. 6 Pareto optimality and Fuzzy Pareto optimality with k% fuzziness, for a tradespace defined by utility and cost

Table 7 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

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 become relatively low.

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 & 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, whereas FPN of 0 stands for Pareto optimality.

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 et al. 2008b):

- **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. The NPT, 10% fNPT, and 20% fNPT metrics are reported for the six designs in Table 8.

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. Although 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 the gas industry, and to include the possibility for shorter "accident-driven" missions. For the case, the following three eras

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

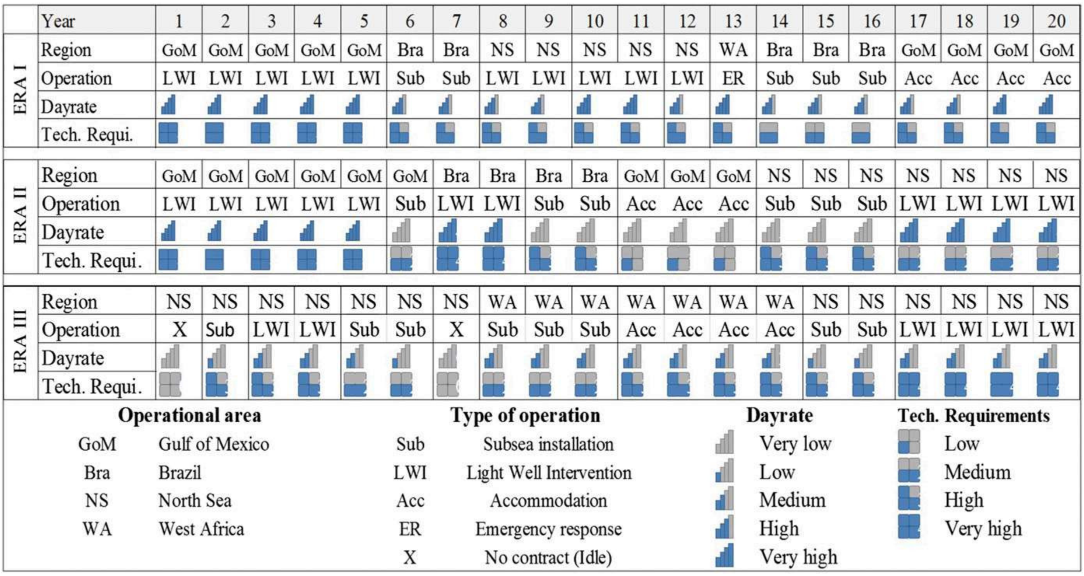

Fig. 7 Description of three narrative eras

are specified for a 20-year system lifecycle, encapsulating stakeholder beliefs. The three eras are presented in Fig. 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.

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

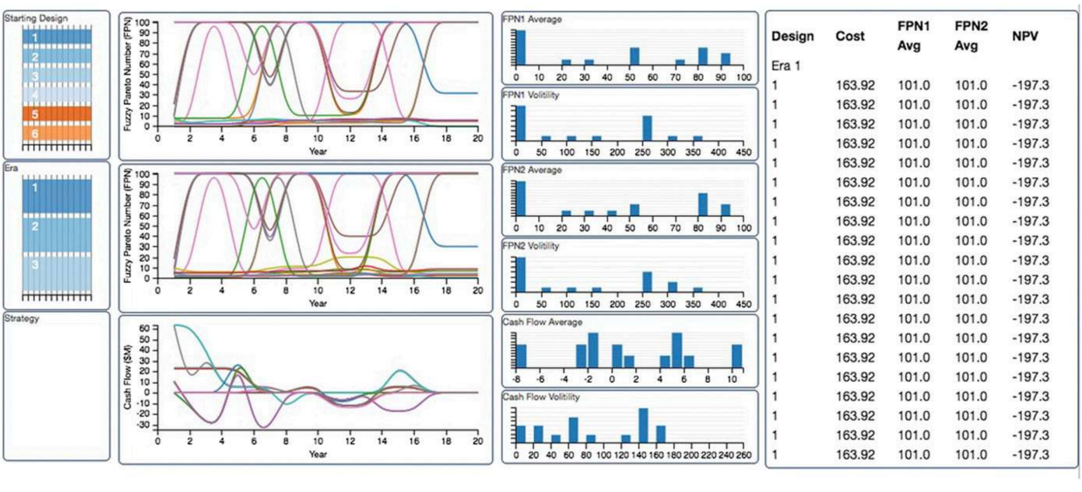

Fig. 8 Illustration of candidate designs over different single eras with supporting metrics (adapted from Curry et al. [2017])

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.

Tracking of monetary performance metrics such as NPV and return on investment (ROI) through each scenario, are particularly interesting to commercial system stakeholders. Monetary and nonmonetary performance metrics can be concurrently illustrated in a lifecycle performance plot, as shown in Fig. 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. Although 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 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 Fig. 9.

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 an MAU 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 MAU theory are violated when attempting to incorporate profitability as an epoch-level value attribute, namely nonredundancy and operationalization (Keeney & Raiffa 1993).

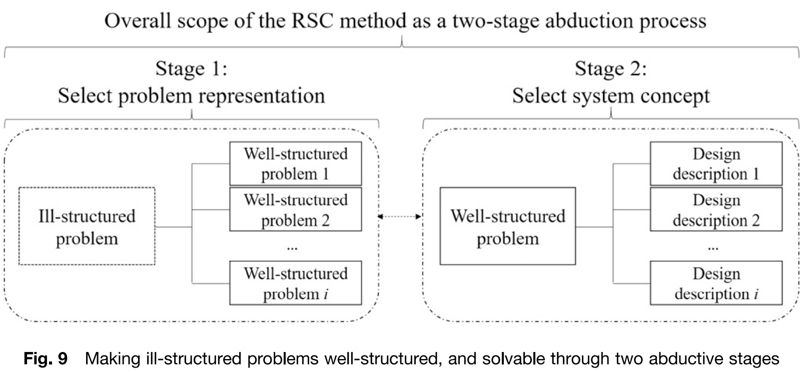

Fig. 9 Making ill-structured problems well-structured, and solvable through two abductive stages

What generates value and what demands resources, or costs, should be kept separate according to the nonredundancy 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 Fig. 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 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 modeled 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 MAU theory to commercial engineering systems design is that the profit cannot be rationally modeled 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 RSC 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 OCV, we show that commercial systems performance models can be integrated within the framework.

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Ulstein, T. and Brett, P. O. 2015 What is a better ship?–It all depends, *Proceedings*, IMDC 2015, May 11–14, Tokyo, Japan, 49–69.

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Main Article 2

Exploiting latent functional capabilities for resilience in design of engineering systems
Pettersen, S. S., Erikstad, S. O., & Asbjørnslett, B. E.
Research in Engineering Design, Vol. 29, No. 4, 2018, pp. 605-619.

Is not included due to copyright

Main Article 3

Latent capabilities in support of maritime emergency response
Pettersen, S. S., Garcia, J. J., Rehn, C. F., Asbjørnslett, B. E., Brett, P. O., & Erikstad, S. O.
Submitted to Maritime Policy and Management.

This article is awaiting publication and is not included

Main Article 4

Evaluating fleet effectiveness in tactical emergency response missions using a maximal covering formulation

Pettersen, S. S., Fagerholt, K., & Asbjørnslett, B. E.

Resubmitted after revision to the Naval Engineers Journal.

This article is awaiting publication and is not included

Appendix D: Previous PhD theses at the Department of Marine Technology

Previous PhD theses published at the Department of Marine Technology

(earlier: Faculty of Marine Technology)

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY

Report No.	Author	Title
	Kavlie, Dag	Optimization of Plane Elastic Grillages, 1967
	Hansen, Hans R.	Man-Machine Communication and Data-Storage Methods in Ship Structural Design, 1971
	Gisvold, Kaare M.	A Method for non-linear mixed -integer programming and its Application to Design Problems, 1971
	Lund, Sverre	Tanker Frame Optimalization by means of SUMT-Transformation and Behaviour Models, 1971
	Vinje, Tor	On Vibration of Spherical Shells Interacting with Fluid, 1972
	Lorentz, Jan D.	Tank Arrangement for Crude Oil Carriers in Accordance with the new Anti-Pollution Regulations, 1975
	Carlsen, Carl A.	Computer-Aided Design of Tanker Structures, 1975
	Larsen, Carl M.	Static and Dynamic Analysis of Offshore Pipelines during Installation, 1976
UR-79-01	Brigt Hatlestad, MK	The finite element method used in a fatigue evaluation of fixed offshore platforms. (Dr.Ing. Thesis)
UR-79-02	Erik Pettersen, MK	Analysis and design of cellular structures. (Dr.Ing. Thesis)
UR-79-03	Sverre Valsgård, MK	Finite difference and finite element methods applied to nonlinear analysis of plated structures. (Dr.Ing. Thesis)
UR-79-04	Nils T. Nordsve, MK	Finite element collapse analysis of structural members considering imperfections and stresses due to fabrication. (Dr.Ing. Thesis)

UR-79-05	Ivar J. Fylling, MK	Analysis of towline forces in ocean towing systems. (Dr.Ing. Thesis)
UR-80-06	Nils Sandsmark, MM	Analysis of Stationary and Transient Heat Conduction by the Use of the Finite Element Method. (Dr.Ing. Thesis)
UR-80-09	Sverre Haver, MK	Analysis of uncertainties related to the stochastic modeling of ocean waves. (Dr.Ing. Thesis)
UR-81-15	Odland, Jonas	On the Strength of welded Ring stiffened cylindrical Shells primarily subjected to axial Compression
UR-82-17	Engesvik, Knut	Analysis of Uncertainties in the fatigue Capacity of Welded Joints
UR-82-18	Rye, Henrik	Ocean wave groups
UR-83-30	Eide, Oddvar Inge	On Cumulative Fatigue Damage in Steel Welded Joints
UR-83-33	Mo, Olav	Stochastic Time Domain Analysis of Slender Offshore Structures
UR-83-34	Amdahl, Jørgen	Energy absorption in Ship-platform impacts
UR-84-37	Mørch, Morten	Motions and mooring forces of semi submersibles as determined by full-scale measurements and theoretical analysis
UR-84-38	Soares, C. Guedes	Probabilistic models for load effects in ship structures
UR-84-39	Aarsnes, Jan V.	Current forces on ships
UR-84-40	Czujko, Jerzy	Collapse Analysis of Plates subjected to Biaxial Compression and Lateral Load
UR-85-46	Alf G. Engseth, MK	Finite element collapse analysis of tubular steel offshore structures. (Dr.Ing. Thesis)
UR-86-47	Dengody Sheshappa, MP	A Computer Design Model for Optimizing Fishing Vessel Designs Based on Techno-Economic Analysis. (Dr.Ing. Thesis)
UR-86-48	Vidar Aanesland, MH	A Theoretical and Numerical Study of Ship Wave Resistance. (Dr.Ing. Thesis)
UR-86-49	Heinz-Joachim Wessel, MK	Fracture Mechanics Analysis of Crack Growth in Plate Girders. (Dr.Ing. Thesis)
UR-86-50	Jon Taby, MK	Ultimate and Post-ultimate Strength of Dented Tubular Members. (Dr.Ing. Thesis)

UR-86-51	Walter Lian, MH	A Numerical Study of Two-Dimensional Separated Flow Past Bluff Bodies at Moderate KC-Numbers. (Dr.Ing. Thesis)
UR-86-52	Bjørn Sortland, MH	Force Measurements in Oscillating Flow on Ship Sections and Circular Cylinders in a U-Tube Water Tank. (Dr.Ing. Thesis)
UR-86-53	Kurt Strand, MM	A System Dynamic Approach to One-dimensional Fluid Flow. (Dr.Ing. Thesis)
UR-86-54	Arne Edvin Løken, MH	Three Dimensional Second Order Hydrodynamic Effects on Ocean Structures in Waves. (Dr.Ing. Thesis)
UR-86-55	Sigurd Falch, MH	A Numerical Study of Slamming of Two-Dimensional Bodies. (Dr.Ing. Thesis)
UR-87-56	Arne Braathen, MH	Application of a Vortex Tracking Method to the Prediction of Roll Damping of a Two-Dimension Floating Body. (Dr.Ing. Thesis)
UR-87-57	Bernt Leira, MK	Gaussian Vector Processes for Reliability Analysis involving Wave-Induced Load Effects. (Dr.Ing. Thesis)
UR-87-58	Magnus Småvik, MM	Thermal Load and Process Characteristics in a Two-Stroke Diesel Engine with Thermal Barriers (in Norwegian). (Dr.Ing. Thesis)
MTA-88-59	Bernt Arild Bremdal, MP	An Investigation of Marine Installation Processes – A Knowledge - Based Planning Approach. (Dr.Ing. Thesis)
MTA-88-60	Xu Jun, MK	Non-linear Dynamic Analysis of Space-framed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-61	Gang Miao, MH	Hydrodynamic Forces and Dynamic Responses of Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
MTA-89-62	Martin Greenhow, MH	Linear and Non-Linear Studies of Waves and Floating Bodies. Part I and Part II. (Dr.Techn. Thesis)
MTA-89-63	Chang Li, MH	Force Coefficients of Spheres and Cubes in Oscillatory Flow with and without Current. (Dr.Ing. Thesis
MTA-89-64	Hu Ying, MP	A Study of Marketing and Design in Development of Marine Transport Systems. (Dr.Ing. Thesis)
MTA-89-65	Arild Jæger, MH	Seakeeping, Dynamic Stability and Performance of a Wedge Shaped Planing Hull. (Dr.Ing. Thesis)

MTA-89-66	Chan Siu Hung, MM	The dynamic characteristics of tilting-pad bearings
MTA-89-67	Kim Wikstrøm, MP	Analysis av projekteringen for ett offshore projekt. (Licenciat-avhandling)
MTA-89-68	Jiao Guoyang, MK	Reliability Analysis of Crack Growth under Random Loading, considering Model Updating. (Dr.Ing. Thesis)
MTA-89-69	Arnt Olufsen, MK	Uncertainty and Reliability Analysis of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-89-70	Wu Yu-Lin, MR	System Reliability Analyses of Offshore Structures using improved Truss and Beam Models. (Dr.Ing. Thesis)
MTA-90-71	Jan Roger Hoff, MH	Three-dimensional Green function of a vessel with forward speed in waves. (Dr.Ing. Thesis)
MTA-90-72	Rong Zhao, MH	Slow-Drift Motions of a Moored Two-Dimensional Body in Irregular Waves. (Dr.Ing. Thesis)
MTA-90-73	Atle Minsaas, MP	Economical Risk Analysis. (Dr.Ing. Thesis)
MTA-90-74	Knut-Aril Farnes, MK	Long-term Statistics of Response in Non-linear Marine Structures. (Dr.Ing. Thesis)
MTA-90-75	Torbjørn Sotberg, MK	Application of Reliability Methods for Safety Assessment of Submarine Pipelines. (Dr.Ing. Thesis)
MTA-90-76	Zeuthen, Steffen, MP	SEAMAID. A computational model of the design process in a constraint-based logic programming environment. An example from the offshore domain. (Dr.Ing. Thesis)
MTA-91-77	Haagensen, Sven, MM	Fuel Dependant Cyclic Variability in a Spark Ignition Engine - An Optical Approach. (Dr.Ing. Thesis)
MTA-91-78	Løland, Geir, MH	Current forces on and flow through fish farms. (Dr.Ing. Thesis)
MTA-91-79	Hoen, Christopher, MK	System Identification of Structures Excited by Stochastic Load Processes. (Dr.Ing. Thesis)
MTA-91-80	Haugen, Stein, MK	Probabilistic Evaluation of Frequency of Collision between Ships and Offshore Platforms. (Dr.Ing. Thesis)
MTA-91-81	Sødahl, Nils, MK	Methods for Design and Analysis of Flexible Risers. (Dr.Ing. Thesis)

MTA-91-82	Ormberg, Harald, MK	Non-linear Response Analysis of Floating Fish Farm Systems. (Dr.Ing. Thesis)
MTA-91-83	Marley, Mark J., MK	Time Variant Reliability under Fatigue Degradation. (Dr.Ing. Thesis)
MTA-91-84	Krokstad, Jørgen R., MH	Second-order Loads in Multidirectional Seas. (Dr.Ing. Thesis)
MTA-91-85	Molteberg, Gunnar A., MM	The Application of System Identification Techniques to Performance Monitoring of Four Stroke Turbocharged Diesel Engines. (Dr.Ing. Thesis)
MTA-92-86	Mørch, Hans Jørgen Bjelke, MH	Aspects of Hydrofoil Design: with Emphasis on Hydrofoil Interaction in Calm Water. (Dr.Ing. Thesis)
MTA-92-87	Chan Siu Hung, MM	Nonlinear Analysis of Rotordynamic Instabilities in Highspeed Turbomachinery. (Dr.Ing. Thesis)
MTA-92-88	Bessason, Bjarni, MK	Assessment of Earthquake Loading and Response of Seismically Isolated Bridges. (Dr.Ing. Thesis)
MTA-92-89	Langli, Geir, MP	Improving Operational Safety through exploitation of Design Knowledge - an investigation of offshore platform safety. (Dr.Ing. Thesis)
MTA-92-90	Sævik, Svein, MK	On Stresses and Fatigue in Flexible Pipes. (Dr.Ing. Thesis)
MTA-92-91	Ask, Tor Ø., MM	Ignition and Flame Growth in Lean Gas-Air Mixtures. An Experimental Study with a Schlieren System. (Dr.Ing. Thesis)
MTA-86-92	Hessen, Gunnar, MK	Fracture Mechanics Analysis of Stiffened Tubular Members. (Dr.Ing. Thesis)
MTA-93-93	Steinebach, Christian, MM	Knowledge Based Systems for Diagnosis of Rotating Machinery. (Dr.Ing. Thesis)
MTA-93-94	Dalane, Jan Inge, MK	System Reliability in Design and Maintenance of Fixed Offshore Structures. (Dr.Ing. Thesis)
MTA-93-95	Steen, Sverre, MH	Cobblestone Effect on SES. (Dr.Ing. Thesis)
MTA-93-96	Karunakaran, Daniel, MK	Nonlinear Dynamic Response and Reliability Analysis of Drag-dominated Offshore Platforms. (Dr.Ing. Thesis)
MTA-93-97	Hagen, Arnulf, MP	The Framework of a Design Process Language. (Dr.Ing. Thesis)

MTA-93-98	Nordrik, Rune, MM	Investigation of Spark Ignition and Autoignition in Methane and Air Using Computational Fluid Dynamics and Chemical Reaction Kinetics. A Numerical Study of Ignition Processes in Internal Combustion Engines. (Dr.Ing. Thesis)
MTA-94-99	Passano, Elizabeth, MK	Efficient Analysis of Nonlinear Slender Marine Structures. (Dr.Ing. Thesis)
MTA-94-100	Kvålsvold, Jan, MH	Hydroelastic Modelling of Wetdeck Slamming on Multihull Vessels. (Dr.Ing. Thesis)
MTA-94-102	Bech, Sidsel M., MK	Experimental and Numerical Determination of Stiffness and Strength of GRP/PVC Sandwich Structures. (Dr.Ing. Thesis)
MTA-95-103	Paulsen, Hallvard, MM	A Study of Transient Jet and Spray using a Schlieren Method and Digital Image Processing. (Dr.Ing. Thesis)
MTA-95-104	Hovde, Geir Olav, MK	Fatigue and Overload Reliability of Offshore Structural Systems, Considering the Effect of Inspection and Repair. (Dr.Ing. Thesis)
MTA-95-105	Wang, Xiaozhi, MK	Reliability Analysis of Production Ships with Emphasis on Load Combination and Ultimate Strength. (Dr.Ing. Thesis)
MTA-95-106	Ulstein, Tore, MH	Nonlinear Effects of a Flexible Stern Seal Bag on Cobblestone Oscillations of an SES. (Dr.Ing. Thesis)
MTA-95-107	Solaas, Frøydis, MH	Analytical and Numerical Studies of Sloshing in Tanks. (Dr.Ing. Thesis)
MTA-95-108	Hellan, Øyvind, MK	Nonlinear Pushover and Cyclic Analyses in Ultimate Limit State Design and Reassessment of Tubular Steel Offshore Structures. (Dr.Ing. Thesis)
MTA-95-109	Hermundstad, Ole A., MK	Theoretical and Experimental Hydroelastic Analysis of High Speed Vessels. (Dr.Ing. Thesis)
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)
MTA-96-112	Æsøy, Vilmar, MM	Hot Surface Assisted Compression Ignition in a Direct Injection Natural Gas Engine. (Dr.Ing. Thesis)
MTA-96-113	Eknes, Monika L., MK	Escalation Scenarios Initiated by Gas Explosions on Offshore Installations. (Dr.Ing. Thesis)

MTA-96-114	Erikstad, Stein O., MP	A Decision Support Model for Preliminary Ship Design. (Dr.Ing. Thesis)
MTA-96-115	Pedersen, Egil, MH	A Nautical Study of Towed Marine Seismic Streamer Cable Configurations. (Dr.Ing. Thesis)
MTA-97-116	Moksnes, Paul O., MM	Modelling Two-Phase Thermo-Fluid Systems Using Bond Graphs. (Dr.Ing. Thesis)
MTA-97-117	Halse, Karl H., MK	On Vortex Shedding and Prediction of Vortex-Induced Vibrations of Circular Cylinders. (Dr.Ing. Thesis)
MTA-97-118	Igland, Ragnar T., MK	Reliability Analysis of Pipelines during Laying, considering Ultimate Strength under Combined Loads. (Dr.Ing. Thesis)
MTA-97-119	Pedersen, Hans-P., MP	Levendefiskteknologi for fiskefartøy. (Dr.Ing. Thesis)
MTA-98-120	Vikestad, Kyrre, MK	Multi-Frequency Response of a Cylinder Subjected to Vortex Shedding and Support Motions. (Dr.Ing. Thesis)
MTA-98-121	Azadi, Mohammad R. E., MK	Analysis of Static and Dynamic Pile-Soil-Jacket Behaviour. (Dr.Ing. Thesis)
MTA-98-122	Ulltang, Terje, MP	A Communication Model for Product Information. (Dr.Ing. Thesis)
MTA-98-123	Torbergsen, Erik, MM	Impeller/Diffuser Interaction Forces in Centrifugal Pumps. (Dr.Ing. Thesis)
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)
MTA-99-132	Søreide, Fredrik, MP	Applications of underwater technology in deep water archaeology. Principles and practice. (Dr.Ing. Thesis)
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)
MTA-99-134	Elvekrok, Dag R., MP	Engineering Integration in Field Development Projects in the Norwegian Oil and Gas Industry. The Supplier Management of Norne. (Dr.Ing. Thesis)
MTA-99-135	Fagerholt, Kjetil, MP	Optimeringsbaserte Metoder for Ruteplanlegging innen skipsfart. (Dr.Ing. Thesis)
MTA-99-136	Bysveen, Marie, MM	Visualization in Two Directions on a Dynamic Combustion Rig for Studies of Fuel Quality. (Dr.Ing. Thesis)
MTA-2000-137	Storteig, Eskild, MM	Dynamic characteristics and leakage performance of liquid annular seals in centrifugal pumps. (Dr.Ing. Thesis)
MTA-2000-138	Sagli, Gro, MK	Model uncertainty and simplified estimates of long term extremes of hull girder loads in ships. (Dr.Ing. Thesis)
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)
MTA-2001-142	Samdal, Ole Johan, MM	Modelling of Degradation Mechanisms and Stressor Interaction on Static Mechanical Equipment Residual Lifetime. (Dr.Ing. Thesis)
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)
IMT-2005-12	Fredheim, Arne	Current Forces on Net-Structures. (Dr.Ing. Thesis)
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)
IMT-2008-38	Harlem, Alf	An Age-Based Replacement Model for Repairable Systems with Attention to High-Speed Marine Diesel Engines. (PhD-Thesis, IMT)
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
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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
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IMT-11-2017	Martin Hassel	Risk Analysis and Modelling of Allisions between Passing Vessels and Offshore Installations
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IMT-21-2018	Sigurd Solheim Pettersen	Resilience by Latent Capabilities in Marine Systems