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Henrique M. Gaspar

Handling Aspects of Complexity in Conceptual Ship Design

NTNU – Trondheim
Norwegian University of
Science and Technology

Doctoral Thesis

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Norwegian University of Science and Technology
Thesis for the degree of Philosophiae Doctor
Faculty of Engineering Science and Technology
Department of Marine Technology

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Skiriu savo žmonai

Design

I found a dimpled spider, fat and white,
On a white heal-all, holding up a moth
Like a white piece of rigid satin cloth –
Assorted characters of death and blight
Mixed ready to begin the morning right,
Like the ingredients of a witches' broth –
A snow-drop spider, a flower like a froth,
And dead wings carried like a paper kite.

What had that flower to do with being white,
The wayside blue and innocent heal-all?
What brought the kindred spider to that height,
Then steered the white moth thither in the night?
What but design of darkness to appall?–
If design govern in a thing so small.

— Robert Frost (1936)

Abstract

This research examines the handling complexity aspects of conceptual design. Contemporary consensus suggests vessel design must consider new market requirements such as greater emphasis on environmental performance, a larger degree of uncertainty in terms of contract horizon, and the need for reliability of multiple operations assessed during early stages. Consequently, the industry has experienced development on many levels of ship design, from advanced subsystems (e.g., a wide range of machinery configurations), to vessels with demanding operations (e.g., modern offshore support vessels), to incorporation of fleet assessment in early stages. Designers face a number of new technologies - usually representing greater investment - to obtain improved energy efficiency and flexibility regarding multi-faceted, future scenarios in which the vessel must operate. This large number of options results in an increase in the amount of information that should be considered to understand important aspects of the ship during the conceptual phase.

This thesis is based on a systems engineering perspective to approach these kinds of developments, especially recent theories combining complexity theory in engineering. This thesis reviews current methods and approaches that deal with conceptual ship design and its complexity aspects. Based on this review, three research questions are proposed. First, *which general complex systems theory premises can be used to define complexity in conceptual ship design?* Second, *what general principles for organizing and simplifying complexity fit the conceptual ship design task?* Third, *what methods efficiently handle primary complexity aspects during conceptual ship design?*

The results of this study are the identification of the general principle of handling complexity, based on decomposition and encapsulation, as a strategy to manage relevant information during conceptual design, and proposing a five-aspect taxonomy to characterize and classify complexity in conceptual ship design. The taxonomy categorizes five aspects of conceptual ship design. The structural aspect relates to arrangement and interrelationships of the physical parts in the ship. The behavioral aspect derives from form-function mapping. The external circumstances to which the ship is subjected are captured in the contextual aspect. Uncertainties in future scenarios and expected/unexpected changes over time relate to the temporal aspect. The perceptual aspect relates to how various stakeholders perceive the value they receive from a design through the operational life cycle of the vessel.

A discussion of both traditional and novel techniques to handle each of the aspects is presented. Focus is given to methods able to handle the three extended aspects (i.e., contextual, temporal, and perceptual). The goal of the study is to designate ship design as a complex system problem, developing and improving methods capable of handling primary complexity aspects during the conceptual phase.

The primary contribution is characterization of conceptual ship design as a complex systems engineering task. Decomposition and encapsulation is presented as a general principle to handle complexity during the conceptual phase of ship design. More importantly, it identifies the intelligent encapsulation allowed by the five-aspect taxonomy, with implementation and development of methods to handle each aspect. Structural and behavioral aspects are investigated, merging traditional and novel techniques. Epoch-era analysis and a ship design deployment problem are used to tackle contextual and temporal aspects. The perceptual aspect is discussed through complex value robustness, and integration and concurrent assessment of all five aspects is handled theoretically through the responsive systems comparison method.

This thesis consists of two parts. The first contains an introductory chapter presenting the background, the research questions, state-of-the-art conceptual ship design, ship as a complex system, information growth in ship design and complexity in a systems engineering framework, the research approach, a timeline of the research, initial results of a study of complexity aspects, results relevant to answering the three research questions, discussion of contributions, concluding remarks, and future research. The second part contains the five papers, in which individual results and contributions are discussed in more detail.

Preface

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for partial fulfillment of the requirements for the degree of philosophiae doctor. The work was performed at the Department of Marine Technology, Marine Systems Group, NTNU, Trondheim, with Professor Stein Ove Erikstad as the main supervisor.

The research was supported by the project Sustainable Design of Ships for the Future (Ship4C) at NTNU, funded by the Norwegian Research Council and industry partners (STX Europe and DNV). Part of this research was undertaken at the Systems Engineering Advancement Research Initiative (SEAri), at the Massachusetts Institute of Technology (MIT). The research stay was funded by the Ship4C project and Janson "Legat" fellowship.

This thesis is divided into two parts: an introductory chapter, comprised of six sections, and a compilation of papers. While writing the thesis, the intention was that each of the two parts should read independently. There might be some redundancy, though this was minimized while still introducing important parts of the research.

Acknowledgements

This work would not have been possible without the help of many competent and dedicated professionals, nor without the unconditional support from my family and close friends. During the entire process, there were so many interesting experiences encountered, so much learned and developed, as in every great step that we decide to give in our lives, and when it is done, we are able to look back and think *veni, vidi, vixi*[1].

NTNU

I am grateful to my supervisor, Professor Stein Ove Erikstad. In the fall of 2007, he trusted me to be part of his project, develop this thesis, and contribute to the maritime system group at NTNU. He gave me constant support and guidance during the entire process, never denying the opportunity to discuss an idea, suggest improvements, and criticize - or compliment - a piece of work. I cannot deny similar compliments to Professor Arnulf Hagen, my co-supervisor, with whom I had many interesting discussions and feedback in the last year of the work, while writing the journal papers. Outside the maritime environment, I offer my deepest gratitude to Professor Cecilia Haskins, from the Department of Production and Quality, for her constant willingness to provide good advice and motivating talks about systems engineering.

At NTNU, I was expecting to be surrounded by Norwegians, but fate provided me, as office mates and Ship4C partners over all the PhD years, two French people, quite different in their personalities and at the same time so friendly, interesting, and lovely. *Monsieur* Emmanuel Querrec and *Mademoiselle* Océane Balland, working on the Ship4C project would have been much less interesting without you. Thanks for the crucial discussions, excellent work environment, and friendship over all the years. On the Norwegian side, as descendants of the Normans, they had my loyalty and friendship as soon as I learned the meaning of the word *skål*! Erlend Meland, thanks for the constant friendship, willingness to help, and daily *trøndersk* classes. Thanks to Siri Solem, who managed to be a Ship4C industrial partner, PhD colleague, and neighbor at the same time. Thanks to Øyvind Berle for the sailing lessons and for help with applying for studies abroad.

Many thanks are owed to my other colleagues at NTNU, for the daily contributions and friendship, and to the administration staff and the librarians, for always being glad to talk, help, and facilitate the work.

MIT

At MIT, my research would not have been possible without all the competency, support, guidance, and stimulus from Drs. Donna Rhodes and Adam Ross. My time at SEAri was one of the most important experiences of my life. When I look at my research and find it to be relevant and of quality, I owe much of it to them.

---

[1] *I came, I saw, I lived* - Victor Marie Hugo (France, 1843)

Many thanks are also owed to my other colleagues at MIT, for the professional work environment and valuable discussions.

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Part I

1 Introduction

1.1 Background

A competitive maritime industry must be able to *develop and deliver complex, customized ships with high quality and short lead times to the global market* [44]. Achieving this objective brings many challenges to the design task. The adjectives "complex," "customized," "high-quality," and "short lead" encompass a particular aspect of the challenge. To describe the common understanding:

1. *Complex*: A ship is a large, highly integrated, self-contained system comprised of many subsystems and parts that interact nonlinearly.
2. *Customized*: A ship must be adapted to fit individual specifications in a manner that improves mission performance in comparison to standard design.
3. *High quality*: A ship should operate above required expectations.
4. *Short lead time*: A short lead time is such that it allows a ship to be constructed and delivered in a sufficiently short time to represent a competitive investment.

Deconstructing the meaning of these adjectives offers designers many interesting research questions. Not only are proper definitions of what is meant by *complex, customized, high quality*, and *short lead time* required, but most interestingly and relevant to the current project, it is also necessary to understand how they can be achieved. The two primary objectives of a merchant vessel are: i) mission performance and ii) profit [114]. These qualities are normally observed in terms of stepwise improvements, comparing the performance of the next design generation with previous; a new shape for a hull should perform better than the old one, or a new machinery configuration should be more efficient than the previous. These observations are thus based on empirical and analytical methods used daily in the industry. Competitive ships must be designed for a global value chain since contemporarily, the production line is distributed worldwide, with an increasing portion of ship value produced outside the shipyard. The high interactive process of design shifted from the traditional *shipyard as a hardware producer* toward management of a large amount of information from many stakeholders. Ship design must strengthen its ability to incorporate information exchange not only concerning the ship as product, but also current customer needs such as documentation of design performance during early stages with respect to lifecycle production, operation, safety, and risk.

Initial motivation for this thesis was to understand what type of information[2] it is necessary to gather, understand, and control in order to design a ship able to better perform its mission and satisfy the stakeholders' requirement to have a profitable investment.

Advancements in computational capacity led to rapid advancement of analysis tools during the preliminary stage of design in the last decade. A quick assessment of stability, seakeeping, maneuvering, and load consequence is possible at the beginning of the iterative process of design. Computer-aided engineering numerical techniques such as strength assessment through finite element method and hydrodynamic behavior predictions through computational fluid dynamics are broadly acceptable. However, technical measurements of a ship's structure alone are insufficient to perform proper evaluation of a design in the early stages, and non-static market drivers must be considered. These we can divide roughly into traditional and emergent trends that must be considered during conceptual design. Oil prices/demand and market fluctuations are examples of these traditional trends, which are difficult to predict. In the same category, we can include fleet ageing, second-hand value, and fuel efficiency during the lifecycle. A 2012 study on the offshore support vessel (OSV) market presents this type of *hard-to-predict* factors connected to the nature of the market. Asset values strengthened for new builds and modern five-year-old units, while a contrary trend was observed for 10- and 20-year-old vessels. These older vessels had their value either trend downwards or stay nearly flat, indicating reduced relative demand in this segment. Another example is disparity between markets. Data collected from the OSV fleet in Brazil between 2007 and 2012 showed gradual improvement in the averaged earned day rates, while keeping utilization at a high-value, constant rate. Neither Africa nor the Gulf of Mexico demonstrated the same phenomenon; utilization became a little lower for both locations, and the average earned day rate showed significant fluctuation. For the sake of example for these market variations, utilization data for anchor handling (AHTS) and supply vessels (PSV) for the Brazilian and Gulf of Mexico markets are compiled in Figure 1 [31].

Rather than pure technical and economical predictions, recent trends demand incorporation of other aspects of the ship during early stages. There is a necessity, for example, for proper assessment of lifecycle, considering environmental performance and operability under several operational profiles. However, current models and methods able to incorporate these analyses in the conceptual phase of design are less developed than most traditional methods of performance evaluation. One possible cause for this gap in development is limited understanding of the relationship between primary design parameters and their relationship with an unusual mission. A second and more generic possibility is a lack of knowledge inherent in design when dealing with future predictions - where abstract concepts play a greater role - such as information gathering and handing on experience. Management of this large amount of information does not follow a unique, common engineering standard.

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[2] I use the word information synonymously with knowledge, following Hagen [56]: *I will not distinguish between information and knowledge (...), since it would seem like a philosophical question that is beyond the scope to discuss at what point information becomes knowledge.*

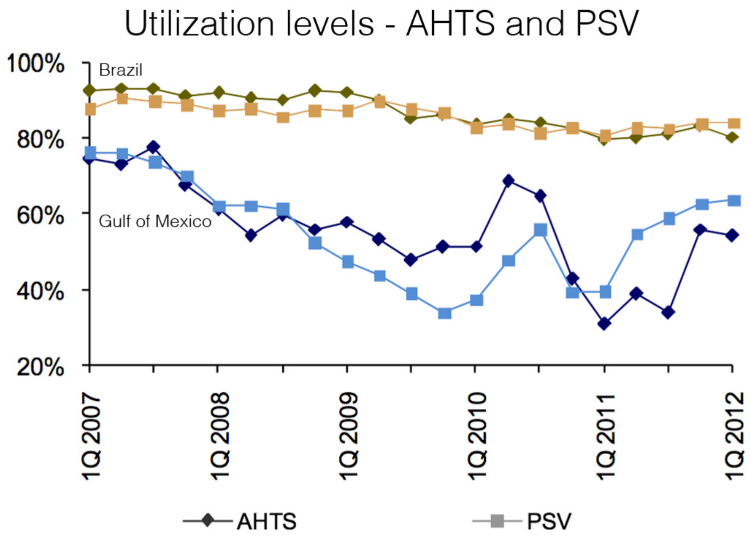


Figure 1: Utilization levels market dynamics for the AHTS and PSV segment (compiled from Clarkson, [31])

Regulatory changes also present challenges for designers, particularly in relation to how to comply with stricter environmental requirements. For example, the Baltic Sea has been an SOx controlled area (SECA) since 2005, the North Sea since 2007, and there is currently discussion to introduce similar legislation for the United States Coast and Mediterranean Sea. Norway imposed NOx taxes in 2007, and recently, the International Maritime Organization (IMO) mandated a CO_2 design index as a baseline for new designs (IMO 2008, 2009). In combination with enforcement of regulations appear responses from the market and academia, with development of new methods and technologies to diminish the environmental impact of shipping.

At first glance, one may assume that the usual *Design for X* techniques solve this problem, managing all important aspects, since the literature compiles many good general principles to tackle ship design problems ([4], [9], [7], [104], [89]). However, it is unclear when it comes to proper definition of X; *which type of information is relevant? Can we correctly characterize the primary factors and discover mapping between them?* The problem appears to connect to the large amount of information required to manage factors that should be considered during early stages, without a framework to organize them.

Based on this lack of consensus when dealing with less technical *Xs*, it is not wrong to assume that there is a need for better methods to manage and incorporate this information during conceptual phases of design. In other industries (e.g., aerospace) we have seen development of a number of approaches for handling early design effectively, based on simulation or large design sets, concept exploration models, robust methods, and large data-set analysis techniques. Similarly on the technology frontier, one can find integration of optimization and decision support techniques into analysis tools, both for parametric and shape optimization. Some of these developments have been applied in maritime, though the unique characteristics [42] require further research, such as the one presented in this thesis.

Figure 2 presents a summary of this idea within the conceptual ship design domain. On the left side are the structural objects, exemplified by the fleet, ship, and subsystems. The left side lists traditional and emergent factors that should be considered when analyzing and evaluating desired behaviors. The design task per se is the proper mapping between form and function, as expressed by Coyne *et al.* [33] and Suh [108]. The problem to be tackled in this thesis relies on understanding and proposing a framework that describes how to identify, incorporate, and quantify traditional and recent factors during conceptual ship design.

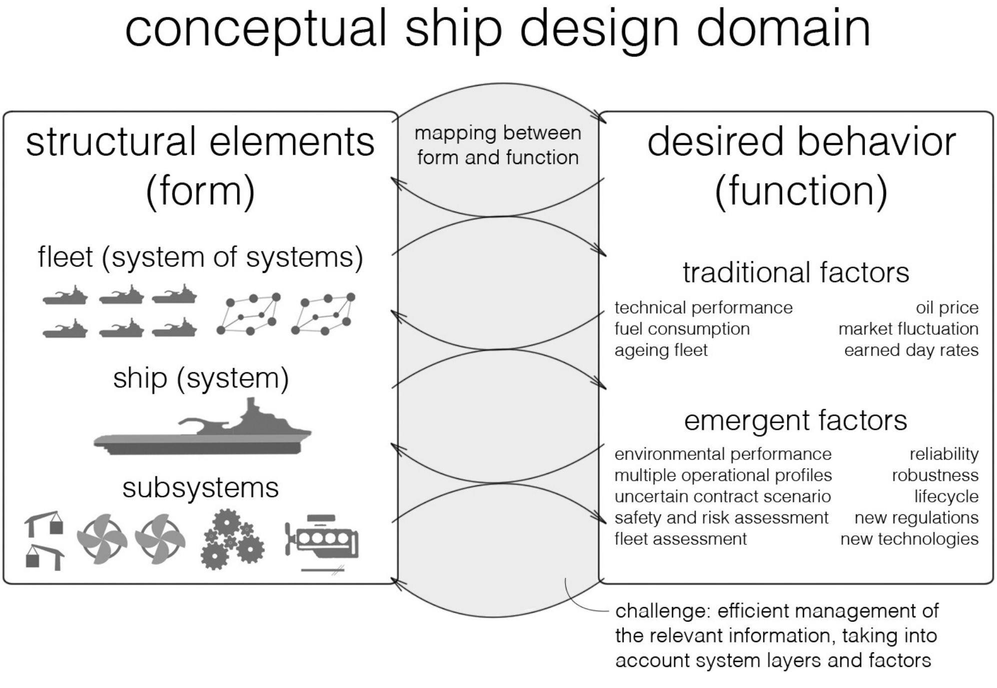


Figure 2: Conceptual ship design mapping domain

The current OSV market exemplifies this need for an extension in the factors well. For OSVs, the combined range of cargoes, operating engine/system loads, and other operating conditions forms an untold number of potential operating states, challenging designers who seek to understand how a ship will operate during its lifetime. The global OSV fleet remains dominated by smaller and older vessels [119], but the trend during the last decade has been toward a market with requirements for increasingly demanding operations, especially in deep water, in high-latitude operations, in cases of a higher degree of uncertainty in terms of contract horizon and predictability of future missions [31]. Larger and more specialized vessels are required to fulfill diverse needs and a general requirement of greater power, such as stronger bollard pulls, winches, remotely/autonomous operated underwater vehicles (ROV/AUV) capacity, and energy efficiency [53].

We have also observed increased interest in the study of custom operational profiles, justified by market demand for specialized vessels able to support operations in deepwater and harsh environments, showing a clear trend toward new opportunities for research. Onboard logging of engine and propulsion for vessels in operation indicates clearly that there are normally several groups of parameter combinations corresponding to typical missions or modes [52]. However, data also show that the operating patterns are often not as expected or predicted, and that ships often operate in ways and manage loads the designer never anticipated. This discrepancy places the impetus on the engineer to optimize design of a vessel while dealing with uncertainty. Similarly, installation of new capabilities will demand evaluation of new performance indicators for a broad range of operational scenarios since oil fields are deeper and further from shore, requiring large quantities and wide ranges of cargoes, and therefore a larger vessel.

Recent studies approach specificities of ship operations and deepwater handling, handling of buoyancy of neutral fiber ropes, trenching, installation of subsea systems, and ROV/AUV survey on the sea bottom. All of these examples trace to requirements imposed during ship design, that is, a capability that a new vessel should have, which was not considered in previous designs. They betray the necessity of understanding the operational profile of all these demanding missions [119], and the benefits of optimizing a vessel for the right operational profile such as fuel reduction and higher utilization level. The industry understood this call for new capabilities as an opportunity to invest in more specialized vessels, and it is common in recent literature to observe new vessels breaking records regarding some criteria such as the *the first jack windmill vessel of its type* or the *highest bollard pull value* [69]. Expectations of the design and performance, both from the service and equipment provided by a vessel, are also higher since an accident in a harsh environment leads to serious consequences.

These new trends and drivers are influencing shipowners' businesses a great deal, shifting perception from the delivery of goods by a ship with a *size X and power Y* to providing *service A and B* within safety, economic, and environmental constraints. As Gaël describes [22], a decade ago, a shipowner would sit with the client and discuss hull and propulsion. Today, the meetings are steered by factors such as safety, fuel consumption, capability, and reliability, necessitating documenting this kind of information as precisely as possible. The market does not agree on how this should be done, especially since this required knowledge is not easy to access due to the abstract (one may say humanistic) nature of these factors. There is a clear shift from purely technical to knowledge-oriented factors, with the conception of value including not only immediate economic return, but also robustness toward future uncertain scenarios.

The remainder of this thesis discusses this conception of knowledge in relation to a complex systems engineering (SE) viewpoint. Complexity is the amount of information necessary to define a system, including components, interconnections, performance, and scenarios, among other required perspectives. This definition assumes every system carries an amount of information, and only the relevant information will be considered when defining it. Accordingly, understanding the type of complexities that exist in a ship during the early stages of design requires extension to current boundaries of maritime design ([57],[114]). This extension calls not only for more refined methods and calculations in the conceptual phase, but also a more flexible design methodology, which can include multi-stakeholder decision-making, considering new technologies, environmental concerns, regulations, operational profiles, and fleet interaction through the operational lifecycle of a ship. Traditional structural-behavioral aspects of ship design, focused on cost and technical performance, no longer encompass all information necessary to define the design of a ship as a *good one* during its early stages. Therefore, it is necessary to handle this complexity, and development of methods that offer other types of insights, in the preliminary stage, such as robustness toward uncertain scenarios and environmental performance.

For the OSV examples used in most of this thesis, addressing these new kinds of questions means, among other actions, correct identification of the type and range of missions the OSV will operate. At the same time, the shipowner must consider whether to install more capabilities than the minimum required for a standard contract, based on many uncertain criteria. It may not be possible, without exceeding the contract, to perform well according to some stakeholders' perception of value, and this requires a more complex operational profile. Based on these challenges, this thesis characterizes ship design as a complex systems problem, developing and improving methods to handle as much complexity as possible during the conceptual phase.

1.2 Scope

The scope of this thesis was defined by selecting what is in and out of the research, usually contrasting information based on a pair of opposite concepts in meaning. Accordingly, we can focus on the internal or external agents, local or global constraints, product or process, etc. The amount of information necessary to define a system connects strictly to its design scope. How complex the design of a system is depends, therefore, on what we are selecting to be included in the scope of the system. This idea is illustrated in Figure 3.

The scope of this thesis includes analysis of two fields: first, the types of factors that should be considered during the conceptual ship design phase, and second, the level of the system with which are we dealing. In particular, it comes from the idea that the

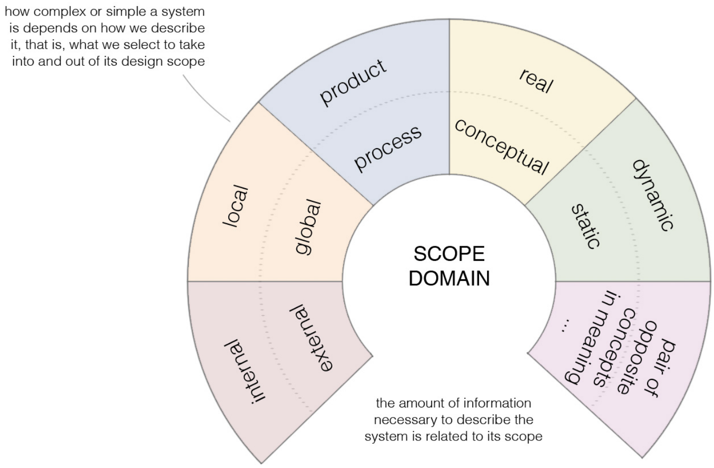
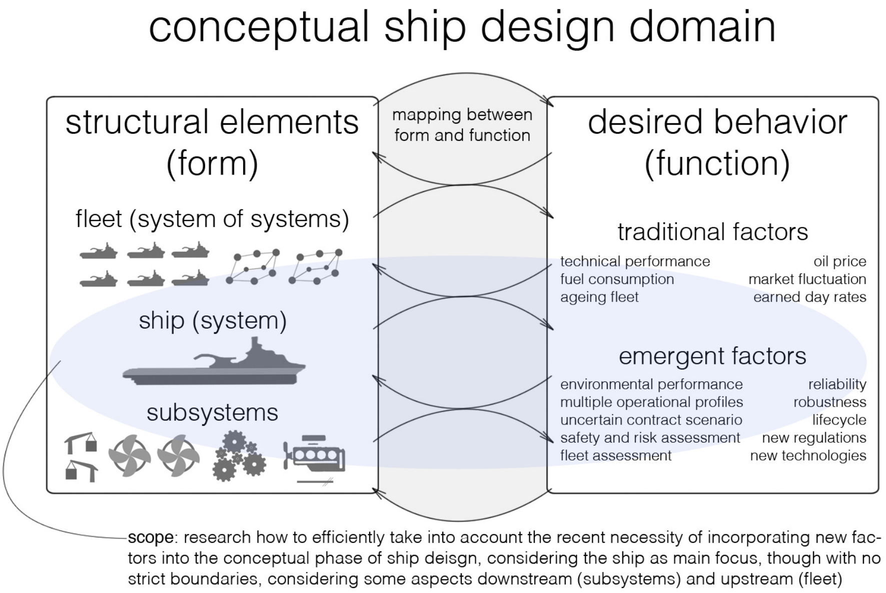


Figure 3: Type of information and the scope domain



scope: research how to efficiently take into account the recent necessity of incorporating new factors into the conceptual phase of ship deisgn, considering the ship as main focus, though with no strict boundaries, considering some aspects downstream (subsystems) and upstream (fleet)

Figure 4: Scope of the thesis

boundaries of what we mean by *complexity* during the early stages of ship design must extend beyond the structural and behavioral aspects of a ship. Since no formal taxonomy for handling the primary aspects of complexity is found in ship design literature, it takes as its taxonomy and framework recent advancements in *complex systems engineering* since the study of the literature led me to believe that this was the most appropriate path. This thesis focuses on the ship as the primary system of inquiry in ship conceptual design. However, due to non-rigid boundaries of any complex system, the thesis discusses some aspects downstream (e.g., efficient machinery) and upstream (e.g., value robust fleet planning) when necessary, as observed in Figure 4.

Since most of the current conceptual ship design literature relates to naval and transport ships, this thesis focuses on exemplifying the methodology through OSVs. As stated earlier, these vessels have a broad range of operational profiles, and missions easily change from one contract to another, leading to an instigating opportunity to be explored and providing a good deal of information on which to justify this research.

1.3 Research Questions

The objective of this study is to develop and improve methods to leverage the ability to consider a large amount of information during the early stages of ship design, especially considering factors beyond the traditional structural and behavioral aspects, allowing incorporation of less rigid requirements such as custom operational profiles, uncertainties related to future regulations and market expectations, and multiple stakeholders preferences. One of the core challenges is to assess the design performance when dealing with a large number of future scenarios, and consequently the uncertainty connected to this lack of information. Typically, a traditional design spiral method requires a finely defined set of requirements as a starting point, beginning the mapping between form and function from it. In the case of an uncertain mission - and consequently a non-precise set of requirements - it is necessary to use more elaborate methods, derived both from empirical data and first principles analysis models such as parametric design, and from lifecycle performance theories that consider models such as probabilistic scenarios and multi-stakeholder approaches.

A study should comprise efforts to quantify and document extension of design boundaries, with an appropriate mapping between design parameters and its performance under a range of future scenarios and based on implementation and domain-specific development of the complex systems thinking into ship design. The study, implementation combination, and development of methods able to tackle these *complexities* should also be considered as a research question. This thesis fits within three primary research questions: Which general complex systems theory premises can be used to define complexity in conceptual ship design? What general principles for organizing and simplifying complexity fit the conceptual ship design task? What methods efficiently handle primary complexity aspects during conceptual ship design? As shown in Figure 5, these questions are approached in a cascading way, with results of the first question leading to investigation of the second, whose results lead to investigation of the third.

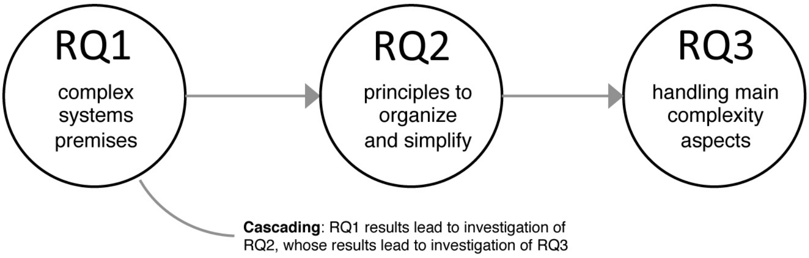


Figure 5: Thesis' research questions

The first research question connects to the idea that complexity theory is a broad field, combining research of biological organisms, behavioral economics, social sciences, artificial systems, and a number of other disciplines. For this reason, it was necessary to limit the scope of the study to systems engineering, extracting and sorting principles that offer insights from the definition of complexity. The question leads to not only a definition of complexity, but also a taxonomy that characterizes and considers new information that brings complexity into design. The study of general premises leads to the study of what would be the general principles for organizing and simplifying complexity that would be appropriate to tackle the conceptual ship design domain. Generally, the second research question investigates theoretically what can be presented as a general principle that handles the complexities defined in the first research question, opening space to selection and development of a framework that classifies aspects of complexity. The natural third research question - after the complex system premises and general principles have been identified - is what methods can handle the primary complexity aspects efficiently during conceptual ship design? This question tackles the handling of the primary complexity aspects and assumes that each aspect requires a specific study to be handled. This question is undoubtedly the most relevant to this thesis, and relies most on the results and contributions presented.

1.4 Papers

This thesis is presented as a primary body (Part I, Sections 1 - 6) and collection of papers (Part II and Appendix A). The connection between the papers, the research questions, and the contributions is presented in Section 5. The papers included in this thesis are:

Paper 1 (Journal)

Henrique M. Gaspar, Adam M. Ross and Stein Ove Erikstad: *Handling Temporal Complexity in the Design of Non-Transport Ships Using Epoch-Era Analysis.*

Transactions RINA, Vol 154, Part A3, International Journal Maritime Engineering, Jul-Sep 2012
Discussion published on Transactions RINA, Vol. 155, Part A3, Jul-Sep 2013

Paper 2 (Journal):

Henrique M. Gaspar, Adam Ross, Donna M. Rhodes and Steiv Ove Erikstad: *Addressing Complexity Aspects in Conceptual Ship Design - A Systems Engineering Approach.* Journal of Ship Production and Design, Vol. 28, No. 4, November 2012, pp. 1-15
Selected to be part of the *Transactions of SNAME*, Vol. 120, 2013 - with added discussion

Paper 3 (Journal)

Henrique M. Gaspar, Océane Balland, Dina M. Aspen, Adam M. Ross and Stein Ove Erikstad: *Assessing air emissions for uncertain lifecycle scenarios via responsive systems comparison method.* Submitted to an international peer-reviewed journal (June 2013)

Paper 4 (Journal)

Henrique M. Gaspar, Arnulf Hagen and Stein Ove Erikstad: *Perception of a Ship: Designing for Complex Value Robustness.* Submitted to an international peer-reviewed journal (June 2013)

Paper 5 (Peer Review Conference):

Henrique M. Gaspar, Donna H. Rhodes, Adam M. Ross and Stein Ove Erikstad: *Handling Complexity Aspects in Conceptual Ship Design*, Proc. 11th International Maritime Design Conference, Glasgow-UK, June 2012

1.5 Structure of the Thesis

This thesis is divided into two parts. The first is the main body of the thesis, providing background and context for the papers that follow. The second contains the five papers, in which individual results and contributions to the field are discussed in more detail.

The six sections that comprise the first part are the introduction, state of the art, research approach, results, discussion of contributions, and conclusion. The introduction provides a summary of the thesis. This section describes the background, the project's scope, the research questions, a list of papers, and the structure of the thesis. *State of the Art* focuses on complex ship design. It provides a literature review on conceptual ship design, a discussion of ships as complex systems, information about recent changes in conceptual ship design, a background on complex systems engineering, and an explication of the five-aspect taxonomy applied to recent ship design literature. The *Research Approach* provides a diachronic description of the study, presenting a timeline of the challenges this research faced and the tasks undertaken to complete it. Initial results are presented as justification for the study of complexity and the work developed abroad. The *Results* section provides a summary of theory developed during the thesis, presenting in logical order the six achievements of the thesis, and a brief self-evaluation of the papers used to document results. The *Discussion of Contributions* section discusses the thesis' role in contributing to extant literature, both as a whole and in terms related to each paper that appears in the second section. *Concluding Remarks and Future Work* concludes the thesis, touching on the initial objectives and raising topics for future research that follows from the thesis

The second part contains the papers published or submitted for publication during the research. These papers relate to complexity in conceptual ship design, and, combined, form an impression of the current state of ship design and the challenges engineers face - and strategies they employ to meet them.

2 State of the Art

2.1 An Overview of Conceptual Ship Design

The conceptual phase of ship design appears in the literature under many titles such as preliminary, feasibility, and precontract; even the term conceptual can have various meanings [98]. Typical outputs for this phase consist of a concept definition, usually the primary dimensions and capabilities (documented through an outline specification), simulations, analysis, engineering models, and mockups [85].

This study takes the conceptual phase under all of these titles as its subject and focuses on marine design methodology. The International Marine Design Conference (IMDC) state-of-the-art reports ([98], [27], [91], [7], [104]) present an advanced study on development of ship design. As concluded by Andrews in his 2012 review of these documents [8], while marine design methodology is a mature discipline, distinct and diverse, it has a disparate level of formalization from other fields of marine design such as marine structures and hydrodynamics. Marine design requires a dynamic and open aspect rather than a coherent and therefore rigid design methodology, which offers designers an opportunity for creativity and innovation not available in other fields.

Much has been published on the specificities of a comprehensive methodology for the design of ships, and the compilation work of Mistree *et al.* [82] and Andrews ([5], [13], [8]) receive special attention in this thesis. The state-of-the-art reports also operate as a valuable introduction to understanding development of the design methodologies over the years, specifically the place of ship design in a general design theory, pointing out common and specific points [98].

It is a well-established idea that the most significant decisions regarding the overall performance of a vessel are decided during the conceptual phase [42]. Even if only a small portion of the total costs is expended during these phases (usually 5% to 8%), it is not incorrect to affirm that between 60% and 80% of the total lifecycle cost is determined during this stage, since all later design decisions are constrained by these initial choices. A wrong decision in this phase can lead to serious economic consequences such as an inefficient or defective design, with a cost to extract this defect in the operating phase up to 1000 times more than the cost in the early stages. Figure 6, adapted from Dahl [35], illustrates these ideas as they apply to the primary design phases.

Even as the *freedom to change* the primary variables of the design decreases as a design progresses through phases, the engineer's *knowledge* of the problem and how the design could be adapted to the situation increases [42]. As one goes to a more detailed part of the process, the decisions narrow toward a certain space of solutions. Ontologically, to make a decision means giving up other options, thus decreasing the freedom to modify the design parameters in future stages of the process. The idea of conflict between design knowledge and freedom to change is presented in Figure 7.

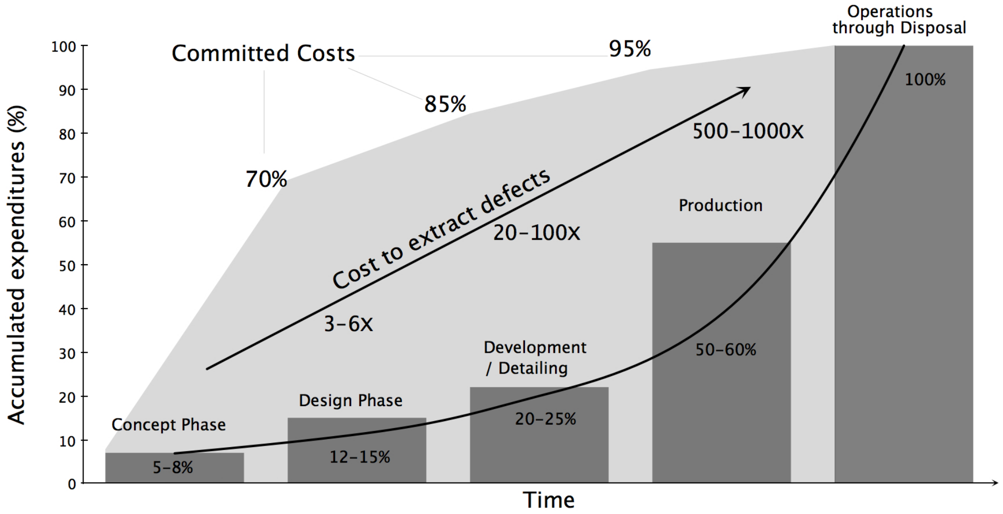


Figure 6: Accumulated expenditures, committed costs, and costs to extract defects in the main design phases (adapted from [35])

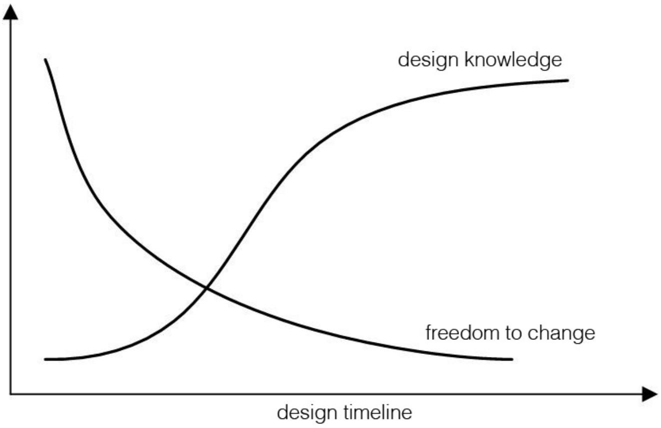


Figure 7: Tradeoff between the freedom to change and acquired knowledge [42]

Erikstad [42] offers reasons for this *limited availability of knowledge* early in the process, such as inherent uncertainty between the design space and the performance space, and the high ratio of qualitative to quantitative information. Seven characteristics characterize conceptual phase domain of ship design: complex mapping between form and function, multi-dimensional performance evaluation, high cost of error, strict time and resource constraints, a shallow knowledge structure, a strong domain tradition, and a predominance of one-of-a-kind and engineered-to-order solutions.

A number of other characteristics of the conceptual phase domain begin with the fact that unlike other engineering systems, the ship is a self-contained, highly-integrated structure, coupling tightly effects between the ship's subsystems. The physical necessity of moving a solid body at the boundary between two fluids, and the complexity and stochastic nature of the external environment, make the relationship between form and function particularly *complex*. Due in part to the uncertainty of the task, it is difficult to simplify performance assessment in the conceptual phase domain. Maximizing profit and minimizing risk alone, though relatively easy, do not provide a full picture of performance, and it is important to include non-monetary indicators. Total performance needs to be evaluated for many key performance indicators (KPIs).

High cost of error in the conceptual phase domain likewise relates to complexity, and amplifies the need for performance evaluation. A wrong decision in this phase can lead to an inefficient design, or to a serious problem in it. The cost to improve a design later may be as much as a thousand times more than the cost to approach it in the early stages, as Figure 6 suggests. In this uncertain environment, the fact that engineers hold shallow knowledge in the conceptual phase poses a particular challenge. Although first principles theory/analysis offers a deeper knowledge structure, information to assess ship performance is usually based on empirical studies and (outdated) data from previous designs. New ships may face different tasks and require different capabilities, and in the conceptual phase domain, the engineer has little opportunity to explore these needs. At the same time, a strong domain tradition means stakeholders usually hold preconceived anticipations of the result of the conceptual design domain. The designer needs to have experience and knowledge from past solutions, without allowing intrinsic inertia to prevent innovative solutions to the problems they anticipate.

Strict time and resource constraints also hamper development of innovation solutions. The designer faces pressure to find a design that meets the contractual requirements as fast and as cheaply as possible. For example, consideration of a new call, such as risk and environmental questions, can only be settled in the design process after fewer design generations. Consequently, engineers experience pressure to produce fast answers and achieve a new threshold of risk and energy efficiency in a short period for each design. A final challenge lies in the fact that each ship design presents its own challenges. Each requires a distinct solution to allow the ship to perform a mission, making it more difficult to save time and money by using traditional manufacturing techniques such as standardization and large-scale production.

In addition to these seven core challenges in the conceptual phase, designers must seek elucidation of the requirements proposed by Andrews ([11], [14]). Andrews contrasts fixed and straightforward approaches to a pre-established list of requirements, that is, purely systematic requirement engineering, with elucidation of the requirements collaboratively from the owner, operator, and designer. This multi-stakeholder dialogue in the early stages is an essential technique to verify and mature a reason to construct the ship, methods, and tools, and to select which conceptual solutions should be used. Andrews' analysis also elucidates the sequential and iterative process of the design as a recurrent theme, captured by Erikstad as four steps: generate, analyze, evaluate, and decide (Figure 8, [42]), and observed in Andrews' processes from Figure 9.

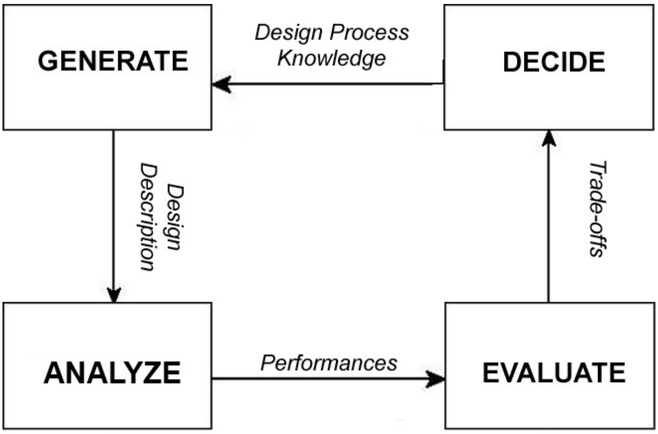


Figure 8: Basic design process (adapted from [42])

Andrews divides the conceptual phase into three stages ([3], [14]). *Concept Exploration* deals with the possible design space solution at an abstract level, gathering information about the limits of a search. *Concept Studies* examines the subset of solutions, helping inform trade off investigations of typically ship-related issues such as speed, powering, and seakeeping. Development of a description based on conclusions from the previous stages is documented and extended in the *Concept Design* stage, with creation of a baseline design, exploring the tradeoffs and cost benefits relevant to the customer. McDonald [80] exemplifies this conceptual synthesis through Andrews' architecturally integrated ship design [2], discussing advantages of the model in comparison to the classic design process and allowing both a simpler and broader synthesis in the same process, with evaluation of innovative configurations. Both processes are presented in Figure 9.

For a simplified example of the process and as a guide to this state-of-the-art section, one can use Gaspar and Balland's [51] call to include assessment of environmental performance during the early stages. This is based on a similar process, the meta-model presented by Smith [107] for exploration of a ship in the early stages of frigate design, as shown in Figure 10.

The authors suggest five actions that should be performed in each of the design steps to address environmental performance in the conceptual phase (adapted from [51]). Firstly, to gather methods, data, and techniques, that is, knowledge to evaluate the concept, measuring relevant KPIs during the early stages. For example, how to estimate speed,

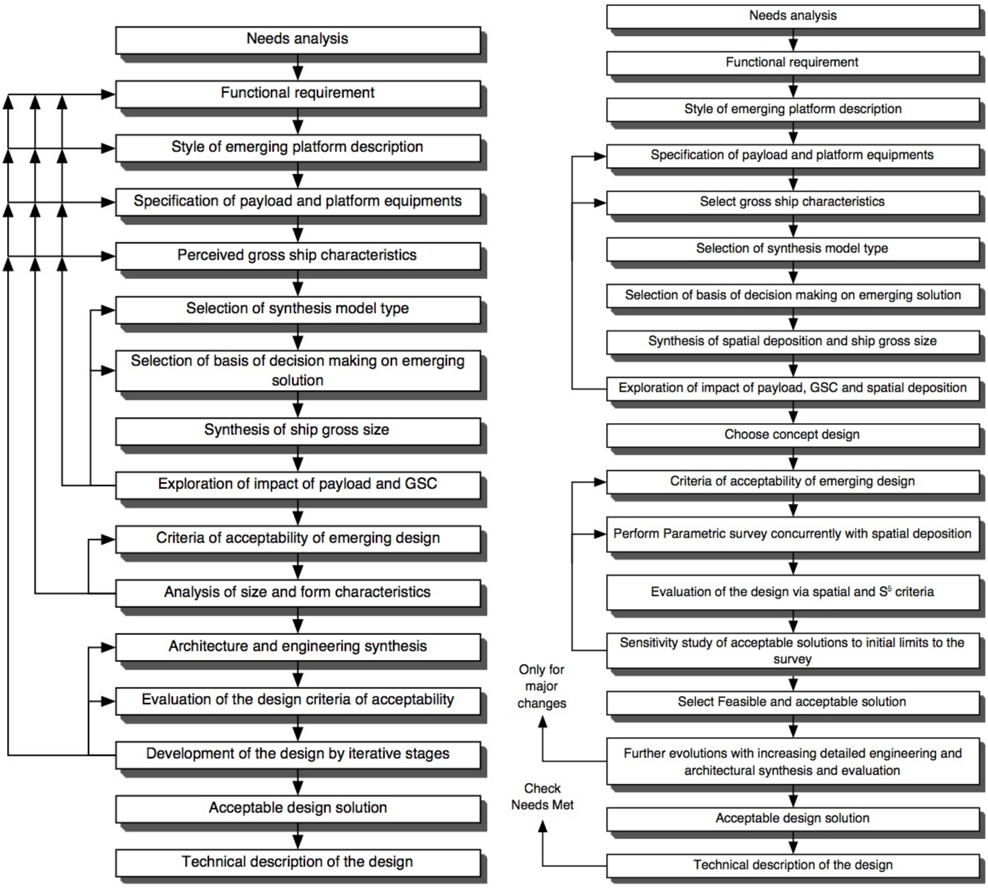


Figure 9: Classical (left) and Architecturally Integrated Ship Design (right) Processes (from [80], [2])

powering, fuel consumption, and air emissions given a ship's operational profile, when the characteristics of the ship are not defined well. Special focus should be given to the role of the operational profile of the ship, for example, using data from the operational profile of similar vessels, derived from the onboard log. The following step consists of identify and narrow design variables that have a strong impact on or relevance to the environmental performance, such as speed, specific fuel consumption and capacity. The integration of the methods into the traditional design process is the third step, in order to calculate environmental KPIs - emphasizing the pertinent subsystems (e.g., propulsion system and its influence on air emissions) and new technologies to diminish impact (e.g., NOx and

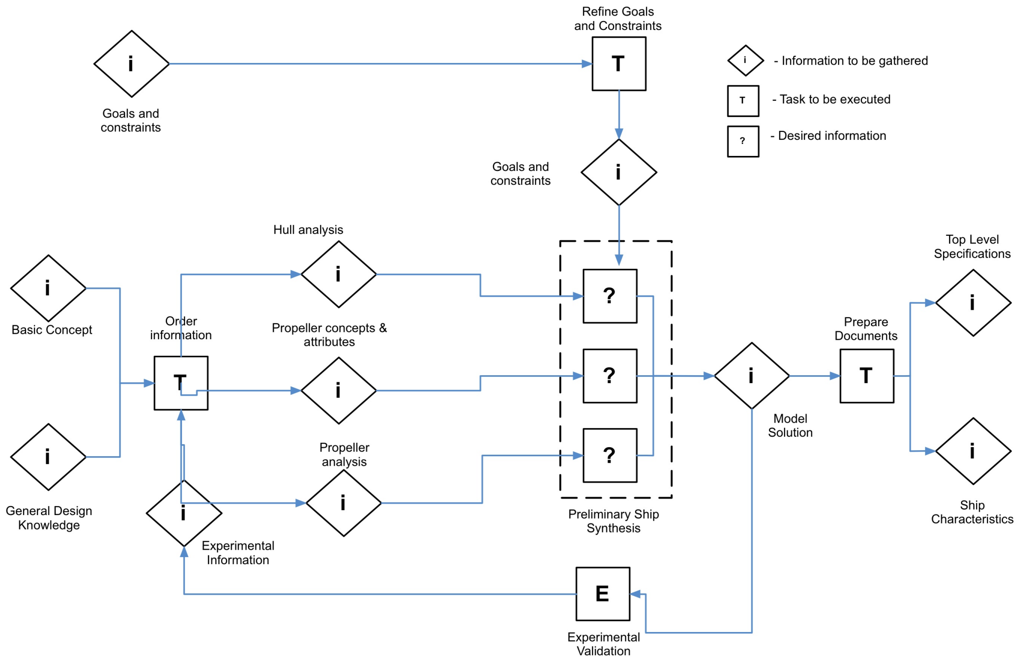


Figure 10: Meta-model for the preliminary design event for a frigate [107]

SOx control methods). Later, quantification and normalization of the environmental KPIs, combined with traditional ones, is necessary, as well as creation of tradeoffs such as marginal cost of X, Pareto frontiers, and response surfaces. Lastly, the task of document tradeoffs and determine how much the value of the environmental KPIs will influence the final decision (i.e., answer questions such as *Is the actual environmental performance sufficient?* and *Does it satisfy the criteria?*

Figure 11 presents a general conceptual ship design methodology that considers division of the proposed actions [51]. The explanation of the process according to the five steps numerated in the methodology, exemplified by assessment of environmental performance, is made.

Gathering Knowledge refers to efficient exploration of existing knowledge, which is necessary to derive a good design description, as recommended by Andrews [14]. Erichsen proposes the study of the market and its interrelations that influence supply and demand of the ship service as one of the primary points to clarify the design objective [41]. In his opinion, the designer should be familiar with market reactions toward developments in technology, business, and organizational arrangements, and other conditions that might affect the solution. An example of the interrelations that influence the bulk market is presented in Figure 12.

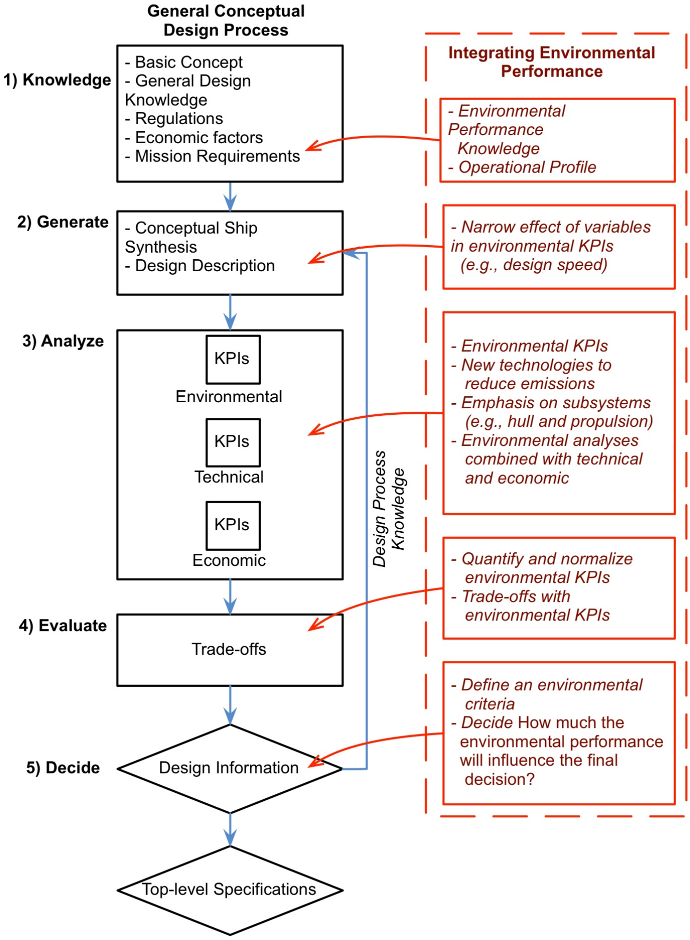


Figure 11: Generic conceptual design methodology with the inclusion of environmental performance [51]

Erikstad [43] discusses acquisition of syntactic and interpretative knowledge, and suggests five common knowledge element groups in the conceptual ship design domain: previous design cases and existing vessel data, generalized design cases and templates, syntactic knowledge (vocabulary), rules and facts, and solution methods, strategies, and tactics. As part of addressing each element group, designers must consider data, methods, regulations, and economic factors of the environmental measures. In this context, the current literature reinforces the important role of acquiring correct data from the operational profile. Levander [75] affirms that the starting point for ship design is to define its mission and related functions well. The design should focus on a ship that performs its

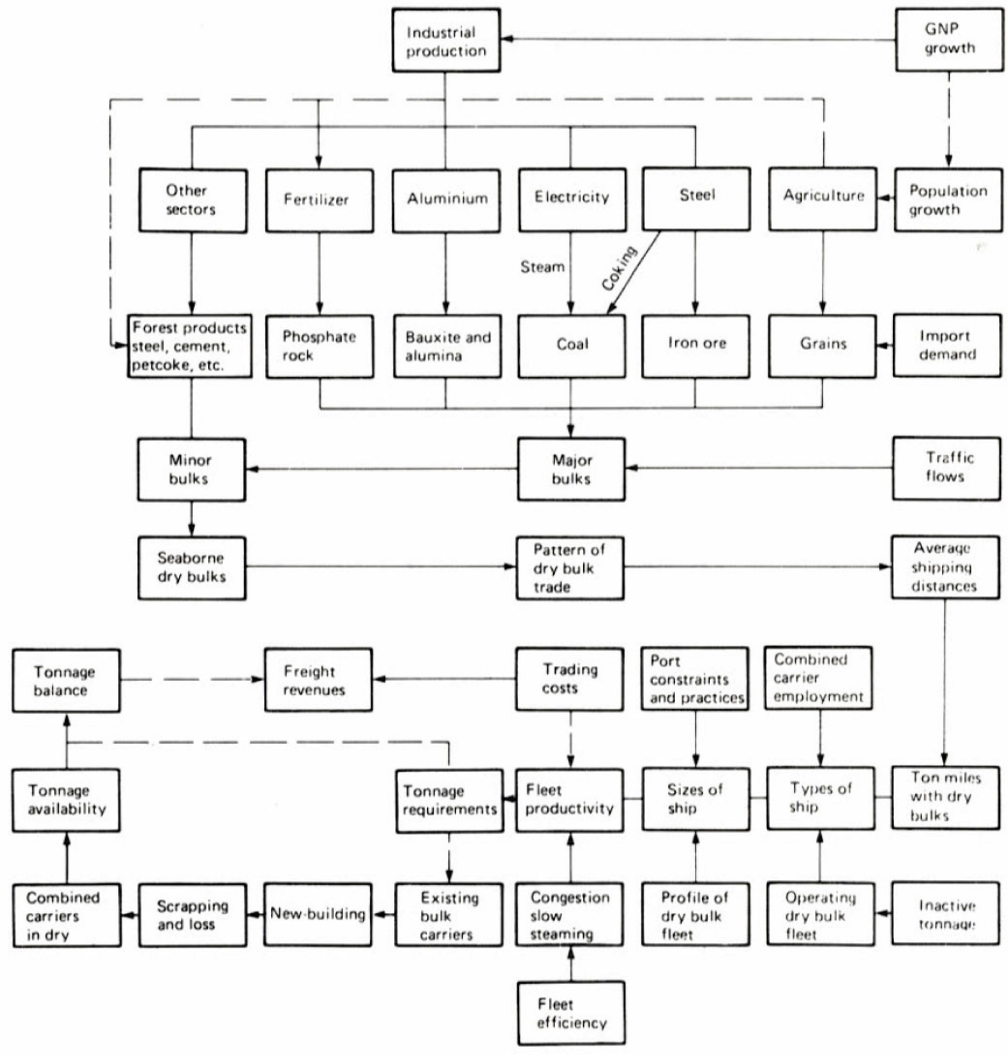


Figure 12: Scheme for the interrelations that influence supply and demand in the bulk market [41]

mission according to the plan. This concept is the basis of his *System Based Ship Design*, exemplified by the process shown in Figure 13.

There is, however, a gap between the real operational profile of a vessel and the one for which it has been designed. Values such as speed, draft, and power demand - optimized at the design stage - can vary substantially in real scenarios, diminishing the efficiency of

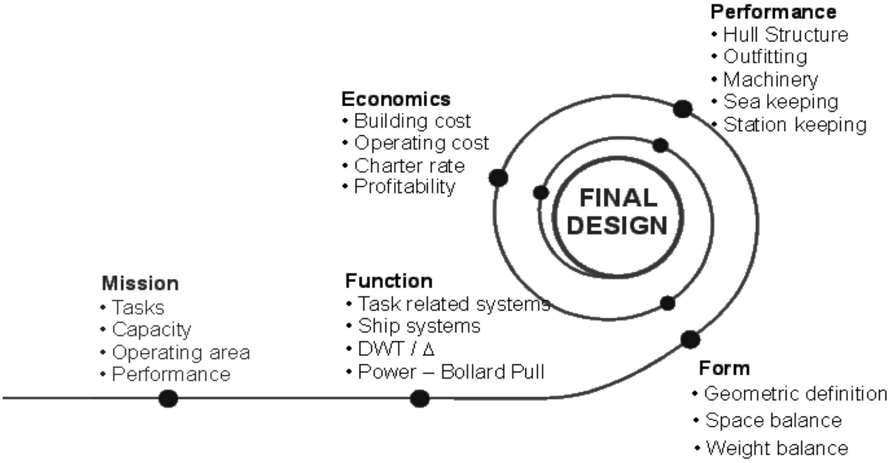


Figure 13: System based ship design process [75]

a ship and increasing costs. Seeking to address this problem, Hagen and Grimstad [57] propose extension of system boundaries during conceptual ship design. This consists of inserting the design task into the broader scope of the transportation system, iterating the process from the bottom end (e.g., emissions) to transport chain requirements (e.g., transport demand). For example, it connects the subsystem of a ship, such as the machinery, with logistic aspects. Figure 14 reproduces the authors' simplified model, combining the mission perspective with a ship perspective.

Hagen and Grimstad also present an overview of the current changes in the ship design domain: technology (i.e., shipping business, design tools, propulsion efficiency, and new materials), operational/logistics, and new ship design requirements. They also call attention to the current importance of correctly assessing the emissions of a fleet, observing that environmental performance must rank much higher as an evaluation/decision parameter. To avoid discrepancies, the designer must thus study the possibilities of the variations in the operational profiles. Cuesta *et al.* [34] present a model in which the operational profile is an essential input to assessment of cost and environmental performance of a ship, leading to considerations in the fleet and transport chain effects. Gaspar and Erikstad [52] also require detailed documentation of the operational profiles to calculate an index applied to transport and non-transport vessels.

After knowledge gathering, it becomes possible for an engineer to generate a design description, which should contain the most important variables corresponding to the ship's primary aspect [42]. The hull form, essential equipment, or functionalities can be included. Established design books present a good compilation of what kind of information should be contained in a good design description: Erichsen's management approach [41], Watson's practical ship design, [115], Lamb's version of SNAME's ship design and con-

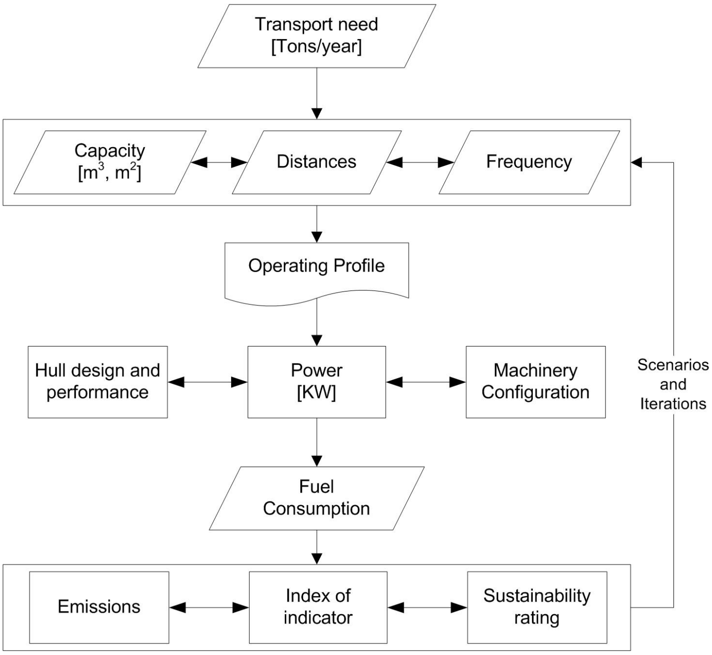


Figure 14: Simplified conceptual design process, combining mission perspective with a ship perspective [57]

struction [74], Parsons' parametric ship design [90], Schneekluth and Bertram design for efficiency [97], and Levander's system based ship design [75]. The next phase, performance analysis, involves combining the design description with data, models, and theories to calculate ship attributes and KPIs. These processes evolved rapidly with use of computers, but the classic design spiral from Evans still demonstrates the basic process. Early in the 1950s, for example, conceptual design already demanded analysis of technical disciplines such as machinery, stability, resistance, and structure (Figure 15, [48]).

Continuous advancement of computational capacity and methods allowed more reliable simulations to guide ship design (Sharma *et al.*, [100]). This allows engineers to apply simulations to structures, fluid dynamics, discrete events (e.g., oil-spill dispersion, cargo handling, and ship evacuation) and economic efficiency [21]. Analysis of environmental performance, focusing on air emissions in shipping activity (ENTEC [40]; Corbett [32]; IMO [65], [64], [63]), oil spills, and energy efficiency (Eide *et al.* [38]; DNV [37]) represents a recent area of inquiry that improved simulations made possible at the conceptual stage. Several technical and economic measures lead to changes in environmental factors, such as hull optimization (Hochkirch and Bertram [60], Bertram *et al.* [20]). Balland *et al.* [16], [15] present a decision-support framework for the study and selection of air emission controls, i.e., measures to diminish the impact on the atmosphere.

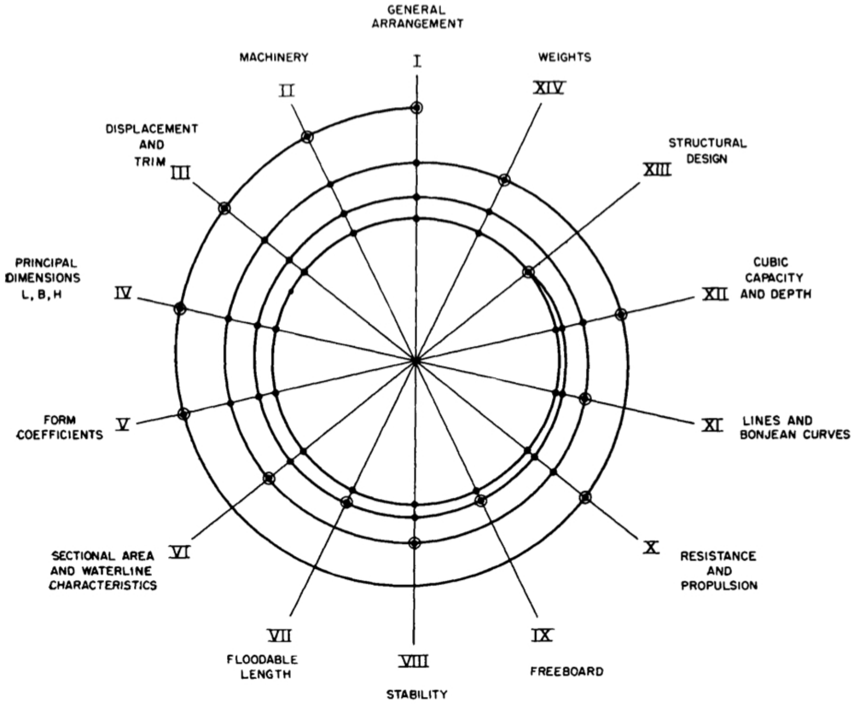


Figure 15: Evans' classic design spiral, exemplifying main technical analysis [48]

The analysis phase yields a set of KPIs for installed power, hull resistance, fuel consumption, air emissions, natural periods, etc. These KPIs allow a designer to evaluate a design by analyzing tradeoffs each of these decisions involve. This is conducted by assigning their marginal costs (in terms of environmental impact and money) and comparing those to other options. Insensee and Bertram [67] provide a method to quantify emissions by shipping operation, placing monetary values on environmental impacts and transforming them into a single indicator.

Winnes and Ulfvarson [117] also provide guidance to evaluate a design, applying systems engineering and lifecycle assessment methods to define a hierarchy of requirements in the ship design task and using scoring functions to quantify various domain indicators. The method resembles the value analysis process [60], consisting of selection of relevant figures of merit and assigning a weight factor to them (Figure 16). Use of scoring functions normalizes various KPIs in the range zero to 1 to allow comparisons. The best design is the one with the highest sum of all parts.

Winnes and Ulfvarson's method, however, might obscure the study of a design's sensitivity, uncertainty, and robustness; a blurred line exists between criteria that go beyond the technical/rational and criteria that are humanist/abstract. As Buxton notes, [26]

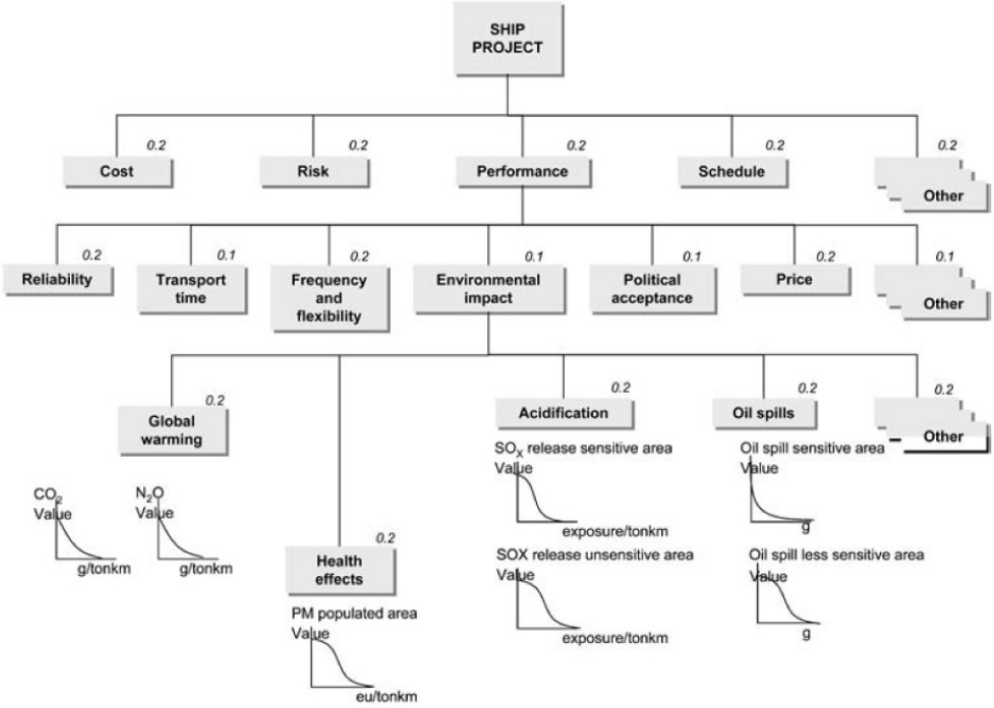


Figure 16: Scoring functions in ship design for the evaluation of environmental impact [117]

It may well be that relative values are more important than absolute values (...) with the go/no-go decision being taken externally as a semi-political judgment. Buxton [26] and Erichsen [41] provide a correction to excessively technical analysis in their presentation of traditional tradeoffs in ship design. They base their analysis on the variation of initial data (knowledge) and their effects on technical and economic KPIs. Three ways to analyze these tradeoffs include the marginal cost of each decision, Pareto frontiers, and multi-objective criteria. Comparing two conflicting performance measures such as air emissions and cost of abatement complicates investigation of the marginal cost of each vessel parameter. Multi-objective criteria provide a resolution to conflicts that arise therein, enabling the designer to, for example, find minimal emissions and cost while maximizing powering or bollard pull. Ultimately, a ship's designer must use evaluation data gathered to make decisions that finalize the design by selecting a set of KPIs or tradeoffs to rank and select designs. Ulstein and Brett [114] state that the desires of stakeholders in the design, their general level of accord, and the information they have and expect influence decision-making in a new shipbuilding development. They note that poor decisions in the early stages create more conflicts and problems later.

2.2 Ship as a Complex System

The idea of a ship as a complex structure is so established in the field that even in classic works such as Evans [48] and Benford [19] it is possible to find a reference to the word (my emphasis):

> Evans (1959): Ships and aircraft are examples of such extremely *complex problems*. Not only are they structures, but vehicles as well. Furthermore, they are vehicles whose efficiency or, in fact, whose very ability to perform at all, is strongly dependent upon weight economy.
>
> Benford (1967): The selection of ship size has in the past been rather arbitrary simply because the *complexities* of the problem precluded any sort of rational approach.

Evans and Benford focus on determining the correct value of the technical performance of a design. The classic approach, of which Evans and Benford are both examples, uses the decomposition of hierarchical systems, serving as a strategy to handle the information necessary to describe the boundaries of a ship. Figure 17 exemplifies a ship as a hierarchical system, made up of subsystems and components, and as an element of a large maritime transportation system.

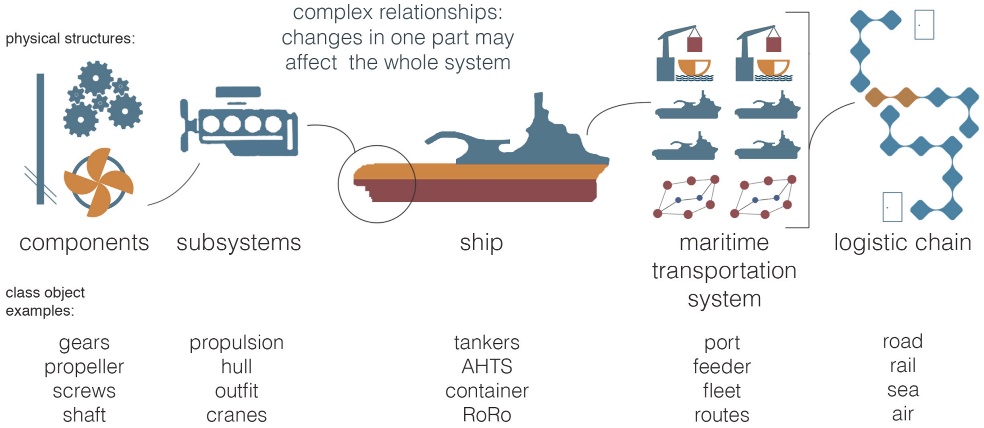


Figure 17: Ship as a hierarchic system

Division of a ship into subsystems (e.g., propulsion and hull) allows better comprehension of the effects of each part on the system as a whole, and relationships to other subsystems. Traditional ship design considers this division and accommodates for high interaction effects the subsystems may have. Any preliminary design methodology, such as the Evans-Buxton-Andrews spiral [82] or Levander's System Based Ship Design ([75], [46]), uses this principle of approaching design via hierarchization of each subsystem and, through interactions, a ship.

The corresponding tradeoff between technical and economic objectives is still the core of the design task, and is captured with the Evans-Buxton-Andrews spiral. Mistree *et al.* [82] discussed extension of this traditional view toward an SE approach in the early 1990s with their proposal to embrace stronger systems thinking, concurrent engineering, and lifecycle perspectives during the conceptual phase. More recently, Gualeni and Dazzy [55], Hagen and Grimstad [57] and Ulstein and Brett [114] call for extended boundaries in systematic design, focusing on current challenges such as new technologies and environmental concerns. Andrews also discusses SE thinking as a rational way to approach ship design, and states that both U.K. and U.S. defense acquisitions often use this approach. Some aspects of the approach are criticized as constraining the fundamentally creative elements of design [5]. Consequently, Andrews formulates a comprehensive methodology for ship design [5] and a creative approach to ship architecture [6] as an extension of pure SE thinking to enable creativity. Andrews proposes, for example, the building block approach as a method to handle the structural aspect, producing a more informed and information-rich preliminary design.

Singer *et al.* [105] corroborate the increase in complexity during the preliminary design, but differ from Andrews' in that they propose the set-based design as a means of handling increased information content during conceptual design. The method goes beyond the traditional point-based design, concurrently identifying multiple design alternatives within the feasible design space as opposed to iterating from a single instance as with the design spiral. An approach more industrial than Andrews' or Singer *et al.*'s to address complexity in ship design is presented by Ulstein and Brett [113]. They classify shipping market segment complexity versus market volume and size. The classification serves to illustrate that engineered-to-order ships are usually considered more complex than standardized-to-order ships, even if the former have a lower share of the market (Figure 18). The authors support an extended approach during the design phase, arguing for critical systems thinking as an extension of the rational-analytical approach used traditionally [113]. They exemplify the call for a broader framework by classifying primary ship design approaches by systemic model attributes. Considering commercial, technical, and operational attributes, the authors conclude that there exists a lack of capability among ship designers and researchers to expand the core idea of ship design and fleet development. By their evaluation, of 29 postwar ship design models, only two reflect the invention/creation of new ideas. Only five include the business proposition formulation as an important aspect. About half begin with some type of closed stakeholder requirements, constraining better elucidation of the real requirements. Only three are concerned with managing marine and ship design processes.

Ulstein and Brett endorse a critical systems framework to offer unity to the multidisciplinary aspect of the design task, combining systems thinking and participatory methods to address the challenges of problems characterized by large scale, complexity, uncertainty, importance and imperfection [113]. This thesis argues that industry calls for a design methodology that includes new elements during the early stages such as multi-stakeholder decision-making, innovation, new technologies, environmental concerns, op-

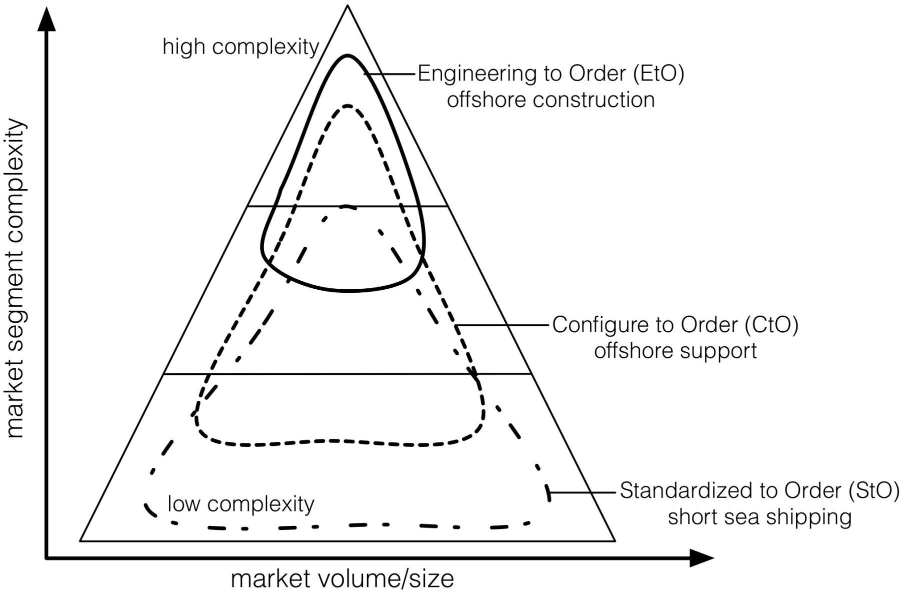


Figure 18: Market and product pyramid in terms of segment complexity (adapted from [113])

erational profiles, and fleet interaction, but none have done so. Traditional structural-behavioral aspects no longer cover all information necessary to define a design as good during early stages. Today, a ship is more complex because so many additional factors go into evaluating it. This new amount of information thus increases the complexity of new designs.

2.3 Information Growth in Ship Design

Diachronic analysis of the references highlights important questions. Besides Ulstein and Brett's analyses of postwar approaches, another useful example is research from Yang in 2004 [118], who created a timeline with primary design ship design references (Figure 19). The author uses it as an example to position his axiomatic design case and later to propose a call for new types of design methodologies [14].

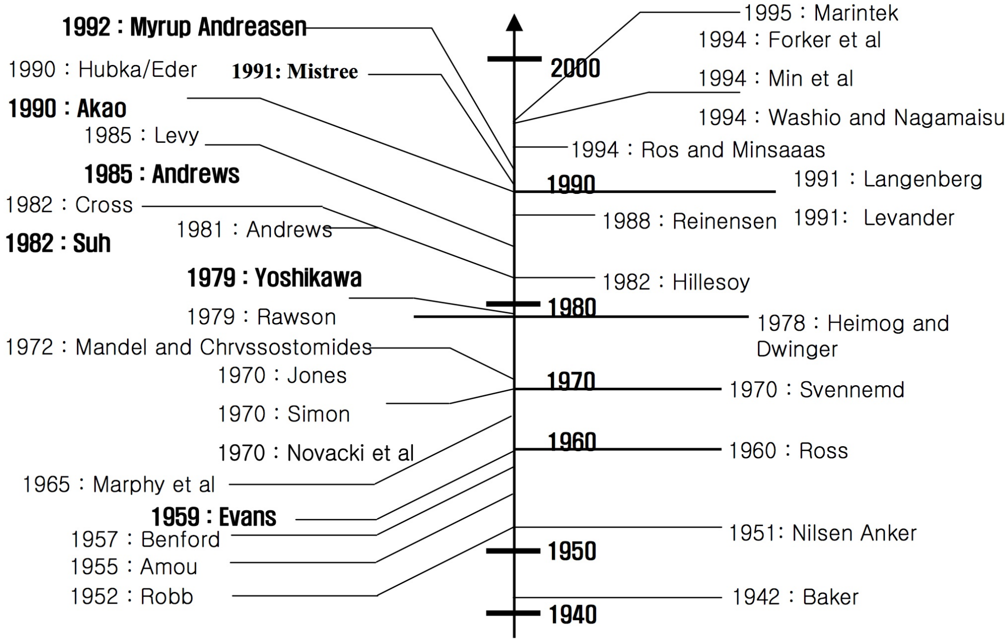


Figure 19: Yang's 2004 timeline for ship design methodologies [118]

A critical challenge is determination of which type of information is necessary to establish whether a design specification is good enough, a central question in the ship design community [10]. However, the amount of information required has increased over the years - as this thesis demonstrates - even while the design is controversial or unclear in how to manage this information. Lack of focus on information related to design analysis makes it difficult to track the history of that information. It is possible, however, to affirm that some type of information appeared relevant just after a certain base was developed. For example, the optimization algorithm for calculating hull resistance is valid because of development of the first estimations based on the hull shape. The trigger for focus on environmental performance, nearly absent in ship design references more than 20 years old, was primarily strengthening of environmental regulations and a need for fuel efficiency given fuel price increases.

Figure 20 shows a timeline of information growth for each decade. Far from being a definitive proposal, this simplification illustrates some information advancements in ship design over time through examples of one reference for each significant type of growth. The purpose of this illustration is to introduce the idea that information in ship design grows continuously in the direction of high interactions and less rigid boundaries. Rather than a complete list, the references are examples since it is impossible to compile all of the branches ship design had and has in a small figure. Advanced study of the development of the ship design task is presented in the IMDC state-of-the-art reports ([98], [27], [91], [7], [104]). These and previous reports make it possible to grasp an overview of the last six decades.

The information growth is summarized as:

1950s - Overall design methodology
1960s - Rational selection of main dimensions
1970s - Economic balance
1980s - Computer-aided design
1990s - Systems engineering approach
2000s - Simulation in preliminary design
2010s - Extension of system boundaries

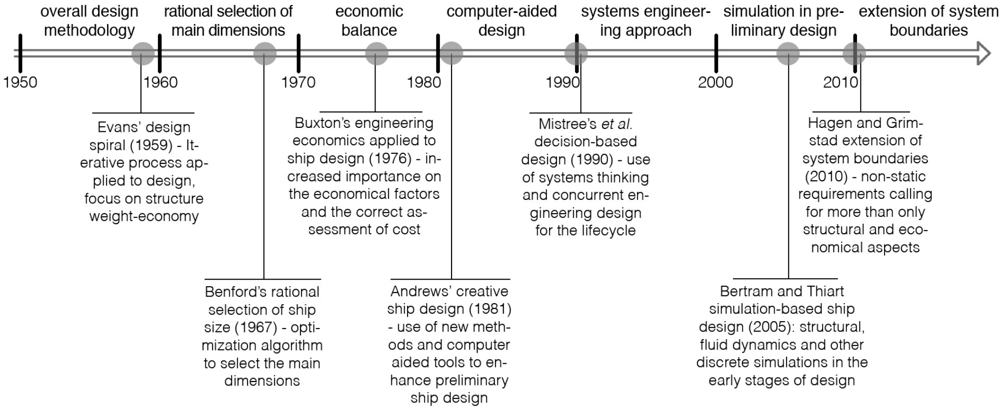


Figure 20: Simplified timeline for information growth in ship design through the decades 1950s-2010s

A brief explanation of the timeline is made in the following paragraphs. In 1959, Evans [48] introduced an overall structured design methodology in his design spiral. This single-point procedure made possible a series of technical advancements in following years. Eight years later in 1967, Benford [19] exemplifies the rational selection of the primary dimensions and capabilities with one of the first algorithms to explore the iterative nature of design toward a more efficient vessel. Lamb [73] presents the first rational procedures using regression analysis and empirical formulas. The increase in shipping activity during the 1970s and oil issues drove some research to the right assessment of the cost of shipping activity, exemplified by Buxton (1976, [25]).

By 1980s, with the advent of the personal computer, it became clear that engineering was changing a great deal, affecting ship design as well. Andrews raises a more serious discussion of creativity in design, defending new methods and computer-aided tools in early stages since computational capacity became more accessible in the 1980s. Establishment of SE methods such as concurrent engineering brought ship design a broader systems thinking, extending the single-point overall methodology, exemplified in 1990 by Mistree's *et al.* decision-based design review of the paradigm (1990, [82]). The new century offered high computational power, stimulating many types of simulations during early stages to offer support to traditional empirical methods. We observe refinement of procedures previously presented by Lamb, with a comprehensive methodology from Andrews [5], a practical approach from Watson [115], and the fully parametric approach presented by Parsons [90].

In the last two decades ship design focused greatly on computational capacity and the power of simulation. Bertram exemplifies this by using simulation toward efficiency and economy ([97], [60], [20]). Bertram and Thiart (2005, [21]) show advancement of computational methods in the last few decades, enabling more reliable simulation-based ship design. They argue design behavior is evolving from experience-based (exemplified by regression analysis tools) to simulation-based (exemplified by discrete tools) methods, allowing application in structures, fluid dynamics, discrete events (e.g., oil-spill dispersion, cargo handling, and ship evacuation), and economic efficiency. These advancements permit increased information to be handled during the conceptual phase, necessitating a discussion of the impact of simulation in ship design such as that offered by Andrews and Pawling [10].

Extending to today, ship design reflects the necessity to consider other types of information in design, rather than purely technical or economic information, since new elements are now gaining importance such as environmental performance and risk. Hagen and Grimstad (2010, [57]) offer a discussion of these new elements, proposing an extension to boundaries of design. This extension is not only concerned with refined methods and calculations, but also includes a call for other aspects during early stages. By extension of the boundaries, the authors require a design that includes new technologies, environmental concerns, operational profiles, and fleet interactions during early stages. Traditional structural-behavioral aspects no longer cover all information necessary to define a design in early stages. This need to understand how complexity and information is handled led me to review literature on complex systems theory and complexity using a systems engineering framework.

2.4 Complexity in a Systems Engineering Framework

Complexity Theory evolved rapidly in recent decades, spreading complexity thinking to social, biological, and technical sciences, from corporation management [110] to the evolution of biological organisms [23]. There were even institutions created such as the New England Complexity Systems Institute (NECSI) and the Santa Fe Institute (SFI) that are devoted to developing complexity theory in diverse areas of knowledge. Mitchel compiles many meanings the word can take [83], pointing out the difficulties of defining it:

> In 2004 I organized a panel discussion on complexity at the Santa Fe Institute's annual Complex Systems Summer School (...) The panel consisted of some of the most prominent members of the SFI faculty (...) The students at the school - young scientists at the graduate or postdoctoral level - were given the opportunity to ask any question of the panel. The first question was, *How do you define complexity?* Everyone on the panel laughed, because the question was at once so straightforward, so expected, and yet so difficult to answer. Each panel member then proceeded to give a different definition of the term. A few arguments even broke out between members of the faculty over their respective definitions. The students were a bit shocked and frustrated. If the faculty (...) could not agree on what was meant by complexity, then how can there even begin to be a science of complexity?

Mitchel later presents the most common definitions, explaining the reasoning on which they are based. Complexity as *size*, as a natural choice, is to count the number of elements in a system. The definition is criticized, however, for not considering the number of interactions and consequences. Complexity as *entropy*, measured as the amount of information in terms of Shannon entropy, defines it according to how objects are ordered and information can be predicted. Kolmogorov's definition, defined in terms of how much relevant information is necessary to define an object, relates to complexity as *algorithmic information content*. Complexity as *logical depth* relates to how difficult an object is to construct; it is not about the description, but that more complex objects are harder to construct. Similarly, complexity as *thermodynamic depth* is based on the sequence of events that leads to construction of a system, measuring total thermodynamic and information resources required during construction. Complexity as *computational capacity* is measured in terms of the sophistication of what a system can compute. Statistical complexity relates to the minimum information regarding a system's past behavior needed to optimally predict the statistical behavior of the system. Complexity as *fractal dimension* quantifies how much interesting detail is observed at all scales as an observer digs deeper into the infinite cascade of self-similarity. Complexity as *degree of hierarchy*, based on Simon's definition that the complexity of a system can be defined in terms of its degree of hierarchy, suggests the complex system being composed of subsystems that, in turn, have their own subsystems, and so on [101].

This thesis uses three seminal works to choose among the most relevant to ship design, connected strongly to Mitchel's algorithm information content and degree of hierarchy definitions. Herbert Simon ([101], [103]) proposes that how complex or simple a structure is depends critically on the way we describe it. Simon proposes a hierarchical approach to complexity, decomposing the system until it can be understood:

> If you ask a person to draw a complex object e.g., a human face, he will almost always proceed in a hierarchic fashion. First he will outline the face. Then he will add or insert features: eyes, nose, mouth, ears, hair. If asked to elaborate, he will begin to develop details for each of the features - pupils, eyelids, lashes for the eyes, and so on - until he reaches the limits of his anatomical knowledge. His information about the object is arranged hierarchically in memory, like a topical outline. When information is put in outline form, it is easy to include information about the relations among the major parts and information about the internal relations of parts in each of the sub-outlines. Detailed information about the relations of subparts belonging to different parts has no place in the outline and is likely to be lost. The loss of such information and the preservation mainly of information about hierarchic order is a salient characteristic that distinguishes the drawings of a child or someone untrained in representation from the drawing of a trained artist.

It is always difficult to describe a structure; by selecting words, we are also defining the abstract boundaries in the meaning of the term and, by exclusion, all the infinite characteristics that the term does not contain. A simple example is a ship. *Is it a structure that floats? Does it have its own propulsion? Are barges, canoes, and ships vessels? Are vessel and ship synonymous?*

The second seminal work clarifies Simon's insights. Algorithm information theory as described in Kolmogorov's definition of complexity [71] refines Simon's approach. If any object is simply constructed, then a small quantity of information is sufficient for its description, but if it is complicated, then its description must contain much information. According to some arguments, it is convenient to call the quantity thus introduced as complexity. Kolmogorov argues that the more information an object has, the more information is needed to describe it, and therefore the more complex the object is. Our object is thus the system. It includes other objects that interact with the system since the specification task of an object is easier when another object to which this object relates is already specified. Suh also developed the idea of information connected to design complexity, proposing that violation of the information axiom - to minimize information content of a design maximizes probability of success - will result in complexity in the system ([108], [109]). More information creates complexity, applying common sense that is easier to design and evaluate a system that requires less information to be defined than a system that requires more information.

In summary, the idea of complexity used in this thesis contains elements from these three authors, approached from an SE viewpoint. Summarized by Magee and de Weck [76], complexity is thus defined as the amount of information necessary to define a system, including components, interconnections, performance, and scenarios among other perspectives that may be required. This definition assumes every system carries an amount of information, and only relevant information will be considered when defining it. It is clear that information related to structural strength or welding properties are more pertinent than taste or color when designing in the maritime sector. The same assumption, however, cannot be true when dealing with food engineering or dentistry.

The SE approach already incorporates the word complex in the definition of a system. Defined by Oliver et al., a system is a complex unity formed by many, often diverse, parts subject to a common plan or serving a common purpose [74]. Complex thus means a system that requires much information in several perspectives to be defined. As another example, there is the definition proposed by NASA: *a system is a construction or collection of different elements that together produce results not obtained by the elements alone* [85]. Other definitions such as those published by INCOSE [66] also consider the non-triviality of interactions among between parts.

Norman and Curas [23] present an interesting discussion about complexity and intricacy. Although the term complexity has been used more to define natural evolutionary and self-organized systems (e.g., world economies and telecommunication), intricacy relates to complex arranged elements (i.e., an intricate system is made from pieces designed carefully to fit into a previous structure), which establishes conditions for the subsequent structure. The shape of intricate systems is unaffected by the environment as much as evolutionary systems. It was my decision, however, to adopt the SE idea of complexity, based strongly on the design of artificial systems [103].

The traditional engineering process (i.e., functional specification, design, testing, and validation [23]) creates artificially designed systems in which the idea of control is stronger in comparison to natural systems; there is higher knowledge in the process, leading to a designed object that performs some function. In this context, more complex systems lead to lower control when designed since the mapping between form and function is not salient. The definition of complexity related to the amount of information aligns with the SE approach of defining complexity. Hubka and Eder [62] propose a four-level degree to measure complexity (Table 1). Although classification is limited to the aforementioned focus on the structural/behavioral viewpoint, it serves as a rough measure to affirm the commonsense idea that a system such as a ship is more complex than a propeller.

Most advanced engineered systems are even more complex than the level IV presented in Table 1 since a large ship, aircraft, or building lies in the limit between a system and a system of systems. SE is, therefore, a discipline that accords with this attempt to understand problems such as highly complex designs. Magee and de Weck [76] developed a definition to distinguish complex engineered systems from other complex systems such as natural systems. They define all complex engineered systems as real, open, artificial, dynamic, hybrid (i.e., system states are both continuous and discrete), and having mixed control (i.e., both autonomous and human-in-the-loop elements or subsystems). Most advanced engineered systems are complex, such as a ship, aircraft, computer, etc. Several

Table 1: Technical Systems Classified by Degree of Complexity [62]

Degree of Complexity	**Technical System**	**Characteristics**	**Examples**
I (simplest)	part, component	elementary system produced without assembly operations	bolt, bearing sleeve, spring, washer
II	group, mechanism, subassembly	simple system that can fulfill some higher functions	gear box, hydraulic drive, spindle head, brake unit, shaft coupling
III	machine, apparatus, device	system that consists of sub-assembles and parts that perform a closed function	lathe, motor vehicle, electric motor
IV	plant, equipment, complex machine unit	complicated system that fulfills a number of functions and that consists of machines, groups and parts that constitute a functional and spatial unity	hardening plant, machining transfer line, factory equipment

works define and characterize this system of systems, and Hastings and McManus even present a framework to understand and mitigate uncertainty in complex systems [58].

Another challenge consists of assigning numbers to complexity to evaluate it. In other words, *how does one measure it?* The information theory approach provides some answers. Kolmogorov relates complexity to the amount of information necessary to define an object (or in this case, a system) [71]. Simpler systems require less information than complicated ones. In engineered systems, the information necessary to define an object is obtained not only from the system itself, but also from interactions of one system with others. Dynamic systems have many more interactions among parts than static ones. This increase in interactions can also be understood as an increase in information regarding the system, and consequently as an increase in complexity, as presented by Norman and Curas [23]. The well-known division in the maritime field increases complexity because the number of possible interactions (or necessary information to define the system) is higher.

As *interactions* implies, a physical object (e.g., component of a ship) is not the only focus. Interactions among stakeholders, design task, components, and other inherent aspects of design gain importance and add complexity during the conceptual phase. Simon defines hierarchy as a primary scheme to understand a complex system [101]. This hierarchization consists of observing a system as a unit comprised of a *large number of parts that interact* *in a non-simple way*, meaning that it can be divided into a finite number of subsystems, each of which may be divided further. Therefore, decomposition is the way to handle the ability of a system to be separated into basic elements (i.e., decomposability), making it more comprehensible. Simon realizes the difficulty of decomposing a complex system into independent parts due to the high level of interaction that some systems may have, and he proposes that a system with many interactions among parts and with other systems can be nearly decomposable. This near-decomposability is a major facilitating factor in the understanding of the system.

Good decomposition leads to rational encapsulation of parts, a construct that facilitates the bounding of information according to one function/process, constraining the part into a common ideal rationality/to-do purpose. Information encapsulation is a way of accomplishing a bounding strategy, as observed by McClamrock [79]. By encapsulating the parts of a system within a criterion, normally functional, one can focus on the overall behavior of the subsystem as a black box - with respect only to its inputs and outputs - and later compare this result according to the big picture of the system's behavior. Encapsulation also establishes an interface for each part (i.e., modules), allowing some sort of interaction (e.g., information trading or physical connection). Decomposing and encapsulating information aligns with Suh's axiomatic design theory [108], in which he defines a good design as an independent one (i.e., independency axiom), with the minimum information necessary to define the part (i.e., information axiom). Suh's methods, however, are rarely used in maritime design problems due to strong dependence among parts of a system, leading to violation of the independency axiom.

Traditional design methods link strongly to the mapping between form and function the design task requires, as explained by Coyne *et al.* [33]. Design relies on model-based engineering approaches to derive a behavior (i.e., technical/economic) from a physical structure. As discussed in the introduction, this traditional division does not fully consider the new kind of information necessary to define and design a ship today. New elements such as environmental performance, risk, and future uncertainties can no longer be ignored/constrained, requiring taxonomy to be incorporated during early stages.

According to Rhodes and Ross ([92], [93]), *the evolutionary path of engineering is threefold: (1) initial constructs and conceptual approaches emerge; (2) quantitative approaches are then formulated and formal methods are developed; and (3) methods are then made executable through computer-based implementation.* Although a ship is not purely an evolutionary system, design that directs conceptualization of contemporary, highly advanced ships have a number of evolutionary aspects. Rhodes and Ross thus propose the equivalent of classification for the engineering of complex systems, based on five essential aspects. The benefit of this decomposition is inclusion of the current model-based systems engineering approach, which embraces the behavioral and structural current state of practice, and the addition of three aspects: contextual, temporal, and perceptual. These aspects extend system boundaries, giving attention to a system's environment with unprecedented levels of information. Table 2 provides a brief definition of the five aspects

Table 2: Five aspects' definition [92]

Traditional	**Structural:** related to the form of system components and their interrelationships **Behavioral:** related to performance, operations, and reactions to stimuli	*State of the practice* systems architecting and design, and emerging model-based systems engineering approaches
Extended aspects	**Contextual:** related to circumstances in which the system exists **Temporal:** related to dimensions and properties of systems over time **Perceptual:** related to stakeholder preferences, perceptions and cognitive biases	New constructs and methods seek to advance *state of the art*, for example: Set Based Design, Ship Design and Deployment Problem, Epoch Modeling, Epoch-Era Analysis, Multi-stakeholder negotiations, visualization of large data sets

that characterize this decomposition, and Table 3 summarizes the literature review of complexity and complex systems engineering discussed in the papers.

Table 3: Summary of literature review in complexity and complex systems engineering

Reference	**Topic**	**Relevance for this thesis**
Alexiou et al., 2010 [1]	Complexity and Design	Definition of complexity and application of complex design thinking to social and technical systems
Ben-Ari and Chao, 2009 [18]	Systems engineering applied to defense systems	Complex systems engineering approach applied to the government defense systems and the industry that supports it
Braha et al., 2006 [23]	Complex theory applied to engineered systems	Use of complex theory applied to biological and artificial systems, focusing on definitions, design and general applications
Eisner, 2005 [39]	Creative thinking applied to large-scale systems	System engineering approach to complex systems, using functional *decomposition* to explore problem-solving strategies
Gama et al., 1994 [50]	Design patterns	Describing design patterns on object-oriented software, such as interface and encapsulation
Hubka and Eder, [62]	Theory of technical systems: a total concept theory for engineering design	Traditional systems engineering approach, with a definition of complexity based on the number of physical components
Kolmogorov, 1983 [71]	Information theory and the calculus of probabilities	Definition of complexity based on Komolgorov and the classification of complex systems
Magee and de Weck, 2004 [76]	A classification of complex system	Definition of complexity based on Komolgorov and complex systems classification
March, 1994 [78]	Decision making under uncertainty	Decision making theory, applied to uncertain situations, and the guess about the future scenarios and futures preferences given a scenario
McClamrock, 1995 [79]	Information theory and artificial systems	Use of *encapsulation* as a general principle to deal with complex systems
Oliver et al., 1997 [86]	Engineering complex systems with models and objects	Traditional systems engineering approach, with incipient complex systems theory thinking
Pahl and Beitz, 1998 [87]	Systematic approach to engineering design	Traditional systematic approach applied to systems design
Rhodes and Ross, 2010 [92], [93]	Five aspects taxonomy	A taxonomy extending the traditional structural and behavioral aspects of complex systems, adding contextual, temporal and perceptual
Simon, 1962, 1996 ([101], [103])	Architecture of complex systems	Seminal work on theory of complexity, proposing *hierarchization* as a main principle to understand and handle complex systems (1962) and theories of design and decision making applied to artificial systems
Suh, 1990, 2005 ([108], [109])	Principles of axiomatic design (1990) and applications to complexity (2005)	Axiomatic design, introducing the independence axiom and information axiom (1990) and extension, linking the two axioms with complexity (2005)

2.5 Summarizing the State of the Art

This section presents a critical summary of the state of the art, that is, important research used as a basis for this thesis' proposal that an essential way to understand complexity in ship design is to relate it to a five-aspect taxonomy. The first three subsections lie within the ship design domain, specifically conceptual ship design methods, the tackling of the ship as a complex system design and the idea that information in ship design is growing. It provides an overview of scholarly engineering literature concerning conceptual ship design, including literature related to the fundamentals of the conceptual phase, characteristics of ship design, and the most traditional design methodologies. In the sequence, the idea of ships as complex systems, summarizing the common approach to understanding the complexity of ship design by decomposing its structure in an hierarchy of systems, was discussed. Literature in this category explores the idea that some ships are more complex than others, and customization drives this complexity. The third subsection, information growth in ship design, encapsulates the explosion of information influencing contemporary ship design. A timeline of the primary advances in conceptual ship design, divided by decades, summarizes a situation in which engineers face an increasing field of information they have to consider in ship design.

The contemporary call to extend system boundaries led to the study of complexity theory, more specifically within a systems engineering framework, providing a brief introduction to complexity theory and how the five-aspect taxonomy makes it possible for systems engineering to tackle the issue. The critical analysis of the state of the art summarized above yields a number of conclusions. The first is that maritime design is a mature field; it encompasses many well-established procedures designers can follow to produce an effective design for the concept of a ship. Some of the methodologies presented such as set-based and systems-based ship design explore the design space toward a specification of a ship able to perform its mission. The unclear part is how to decompose, analyze, and evaluate each of the emergent, contemporary factors required (Figure 2).

In spite of the advantages of working in an established design area, this issue relates to the fact that ship designers can handle only a limited amount of information, meaning a simplification in some aspects of the methodology such as a more rigid idea of mission or use of standard solutions rather than highly customized designs, which are more complex since they require more information to be evaluated. Growth in information, which designers must consider, continues to expand, exacerbates the complexity problem. Use of CAE and, more recently, the need to extend the boundaries outside the structural/behavioral, including important contextual and perceptual aspects, typifies this problem. Given that there are many views and understandings of the idea of complexity, the complex systems engineering approach appears to fit well with this growth of required information, or increased complexity, in the course of the conceptual ship design problem because we are dealing with design of artificial systems. To handle this increased complexity is not merely the same as designing more advanced ships or increases in size; it means an efficient design process, able to produce a ship that will efficiently perform its mission, and provide value to in the face of many future scenarios.

My conclusion from the literature review is that the five-aspect taxonomy presents a framework for extension of the system boundaries as they relate to conceptual ship design. The structural and behavioral aspect approach, traditional and essential to any engineered design, is incomplete in relation to the increasing needs of a contemporary ship designer. For this reason, the taxonomy's ability to consider contextual, temporal, and perceptual aspects in addition to traditional structural and behavioral aspects opens space to study and develop other techniques that address this new information.

3 Research Approach and Initial Results

3.1 Research Timeline

This study was conducted in three stages. The first identified a challenging theme while I collaborated on the project that funded the research, *Competence Project for Conceptual Design Methods for Complex, Customized Ship* (Ship4C)[3]. The objective was to systematically develop new knowledge, competence, and methods to be used in the conceptual and early design of complex, customized ships [38]. The second stage was receiving feedback at conferences concerning conceptual ship design such as the *International Marine Design Conference* (IMDC), *International Conference on Computer Applications and Information Technology in the Maritime Industries* (COMPIT), *International Symposium on Ship Design & Construction* (ISSDC), *International Symposium on Practical Design of Ships & Other Floating Structures* (PRADS) and workshops with industrial participation, such as the *Co-operation between Nordic Maritime Universities and DNV* (NORDIC). The entire process, including co-supervision of master's theses and projects with industrial partners, became essential to explain that some topics did not comfortably fit the traditional model-based approach, and there are open research questions on how to handle it.

Having established the research questions, the third stage consisted of developing and applying complex systems theory to conceptual ship design, studying the problem of how to extend analysis of conceptual ship design beyond the traditional categories of structural and behavioral aspects. It yielded the question of whether the five-aspect taxonomy provided a framework better suited to contemporary ship design. Part of this research was conducted in collaboration with the Massachusetts Institute of Technology (MIT). Figure 21 presents an overview of the primary activities during development of the study. Details, and how those details led to the study, follow.

Figure 21 demonstrates that theoretical research like this involves many complementary tasks in which the problem relies on understanding design knowledge in its abstract sense. This humanistic science requires a different approach in comparison to the study of purely technical performance, for example, a qualitative experiment able to measure *the efficiency of a new type of propeller, or the economic gain of considering fleet time-window in the allocation of a ship into a contract.* Design relies on the abstract idea that an object (i.e., form) executes a function, and this abductive reasoning [33] is far from fitting an exact cause-consequence framework.

The diachronic approach observed in Figure 21 compiles the primary milestones of the study. The first year focused on a literature review connected to the objectives of the SHIP4C project. Five sub-goals were developed to support the primary objective. The first addresses a need to develop new methods for analysis and optimization of conceptual

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[3] URL: www.ivt.ntnu.no/imt/ship4c

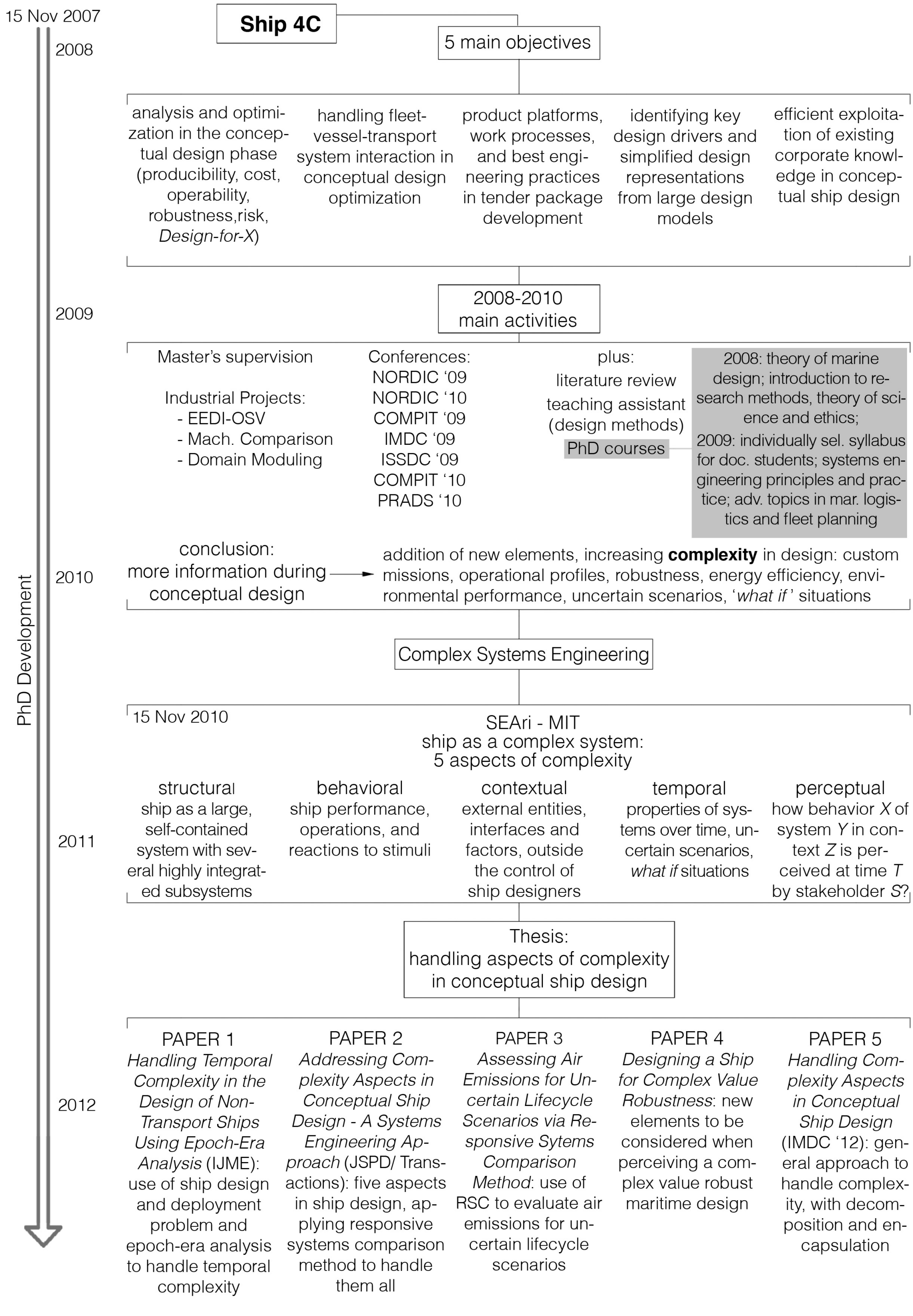

Figure 21: Research timeline

design. This process emphasizes early assessment of producibility, cost, operability, robustness, and risk. The second calls for developing and documenting methods and models for ship conceptual design optimization. The context of a fleet and/or transport system, emphasizing availability, ease of use, and robustness under seasonal route variations (e.g., due to ice) and continuous production, prompted this sub-goal. The third is to develop and document product platforms, work processes, and best engineering practices that will reduce time and effort spent in tender design package development from request to delivery. The fourth involves developing methods to identify essential design drivers and simplified design representations from large design models, with focus on assessing performance differentials (i.e., *What-If* situations) rather than absolute performance levels. The fifth calls for developing competencies and methods for exploitation of data embedded in existing databases to support design decisions and provide input to tendering documentation.

To pursue topics connected to these five sub-goals, the first stage of the research included co-supervision of master's students, projects in partnership with industry, and participation in the project *Applying an Environmental Design Index to Offshore Support Vessels* (EEDI-OSV). This project was in cooperation between NTNU and Det Norske Veritas (DNV), with the objective of developing and testing alternative design indexes to assess overall environmental performance of OSVs [52]. This project directed the focus of this thesis toward an environmental viewpoint, producing an extensive literature review on ship design and environmental performance.

The summer of 2009 offered the opportunity to undertake another project in cooperation with industry, a project titled Ship Machinery Configuration Comparison, focused on ship machinery configuration performance. The objective was to investigate the possibilities of developing a decision-support tool to enhance the machinery configuration process in an early vessel design phase, including defining a methodology to evaluate ship machinery configuration performance based on a given vessel operation. The scope also included development of a simplified tool for comparing ship machinery configurations based on the proposed methodology. Besides a technical report, another outcome was publication at COMPIT '10 [53]. This paper was important to understanding that no established mode of considering multiple operational profiles during conceptual ship design could be found clearly.

The last Ship4C project of 2009 in which I participated was the domain-modeling workshop, in cooperation with DNV and MARINTEK. The objective was to develop a system domain model within the maritime field of research, defining and linking essential concepts to facilitate communication in the research community [68]. This led to the realization that a more general taxonomy was possible that was able to embrace many aspects of one system. A compilation of the research produced until 2010, which is relevant to this thesis, is discussed in the next subsection. The abstract of the paper published during this period are presented in Appendix A.

3.2 Initial Research Stage: A demand for methods to deal with multiple operational profiles and environmental performance

For simplicity, let us say that the primary motives for improving a vessel design are cost reduction, efficiency (which often is merely a variety of cost), and competitiveness (making sure that you secure the desired or at least a sufficient amount of business) - or some variety thereof. If we extend this line of reasoning, we would realize that whereas operating cost reductions and efficiency improvements often require significant initial investments (i.e., increased construction costs) and/or use of new and unproven technology, resulting savings will mainly be on the fuel bill, and therefore the owner will not see this directly. The only real motivation for the owner to invest in improving vessel designs or operations is to make certain the vessels are as good as or slightly better than the competition. The importance of this is chiefly that the vessel is increasingly viewed as a part of a bigger, integrated system, implying performance of the vessel should also be assessed based on the operating profile (i.e., mission profile) defined by the total supply chain. A central point that influenced this research is the fact that highly specialized ships, like many OSVs, may face many different missions during its lifetime. Data collected from vessels in operation show that the operating patterns are often not as expected during the design phase (Figure 22).

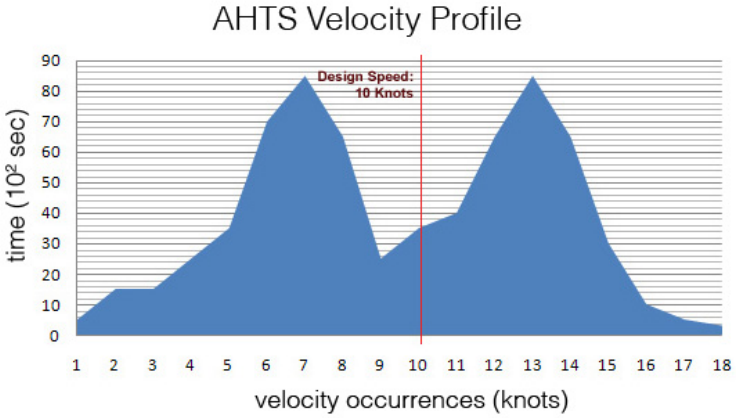

Figure 22: Example of data (velocity) collected from an AHTS operation

This led to the study of a ship's mission, operational profiles, and operational states. Each mission was classified as *Standard* or *Customized*. A mission thus was defined as a set of operational profiles. The operational profiles performed by a ship relate to its services and capabilities installed on board. By definition and at each moment, the ship has to be performing one and only one operational profile. The total time of the mission is thus the sum of the time spent in each operational profile. Each operational profile has its own set of operational states, which can be changed for each operation that the ship is performing. By definition and at each moment, the ship must be performing one and only one operational profile. The total time of the operational profile is thus a sum of the time spent in each operational state. Each of the operational states links to a performance indicator such as fuel consumption data or operability. Figure 23 exemplifies this result, linking the mission with the operational profiles, operational states, and performance.

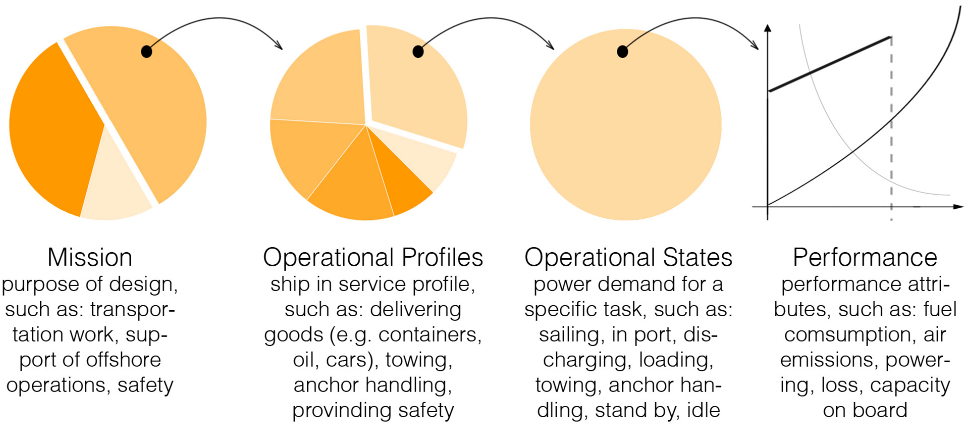

Figure 23: Representation of the relation between mission, operational profiles, operational states and performance.

A standard mission was assumed to be the one the vessel was *designed for*. Although this might be a rational approach for designers in terms of providing a simple, transparent, and manageable set of tasks, it may be oversimplified when looking into highly advanced vessels. This is not to say that standardized missions are not useful. If the intended application is to compare the vessel with an industry standard, or to document the energy efficiency of a vessel without assuming any contracts or service, a standard mission is preferable. A standardized mission also allows comparison of a large set of ships, analogue in the way that IMO does with regression curves (IMO, [64]). However, this standard mission will need to be directed toward the service profiles of ship type.

Figure 24 presents an example for a tanker, with a less complex set of demands than an AHTS, and one Operational Profile and four Operational States: port, sailing laden, sailing ballast, and charging/discharging.

A Custom Mission was defined as a set of Operational Profiles that reflects the actual or intended mission of the vessel, based on a contract or a client-specific case. A Custom Mission is useful, for example, when comparing alternative offers in a tendering process. It is also the appropriate approach to calculate the performance of the vessels for a specific mission. This approach, however, limits benchmarking of a small group of vessels to a

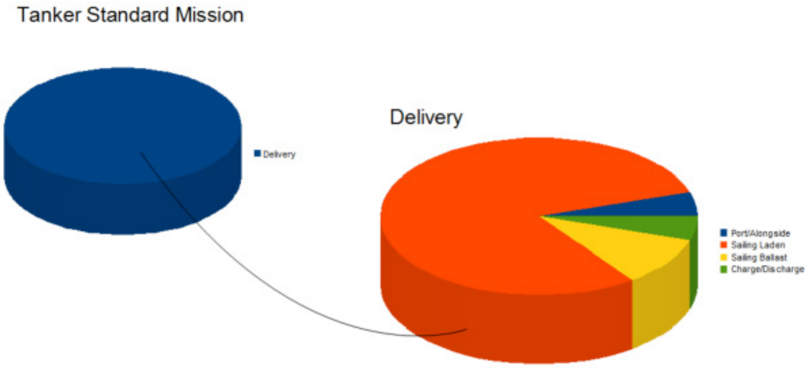

Figure 24: Example of a tanker standard mission.

function such as an AHTS operating in North Sea or Transport of oil from Iraq to Europe. Figure 25 illustrates this type of more customized mission for an AHTS.

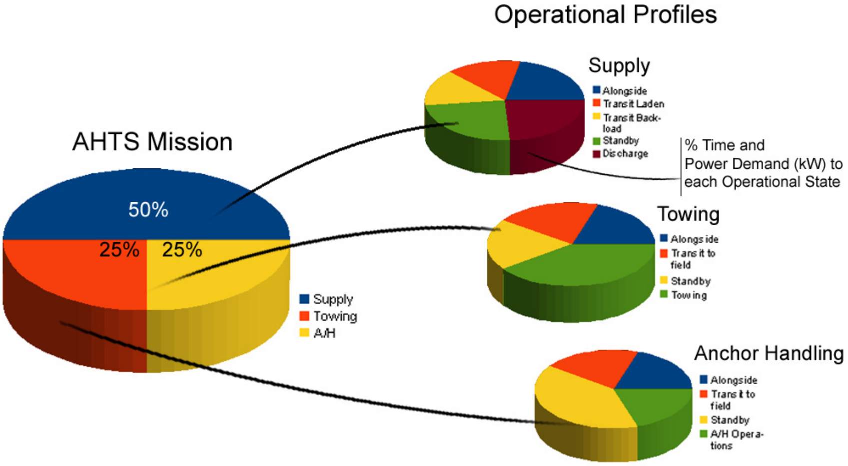

Figure 25: Example of an AHTS custom mission.

A broad range of operational profiles led the study toward advanced machinery systems that operate efficiently under various loads. In the OSV case, this machinery typically includes diesel-electric or diesel-hybrid engine configurations, combined with azimuth and podded propulsion. Although representing a significantly higher investment, these machinery solutions experienced increased market share based on improved energy efficiency and a higher degree of flexibility toward the complex, demanding, and multi-faceted operational profiles these vessels meet.

This research allowed the study and development of a methodology that analyzes and evaluates vessel propulsion performance given a machinery configuration. This was published in [53] and is summarized in Figure 26. In short, the methodology begins with a given mission, which leads to a set of operational profiles, and a vessel, which leads to the primary design variables. Mapping between both is made, leading to a power demand, which enters as input for the machinery configuration. Propulsion performance is evaluated after the proper load distributions and loss estimations are made.

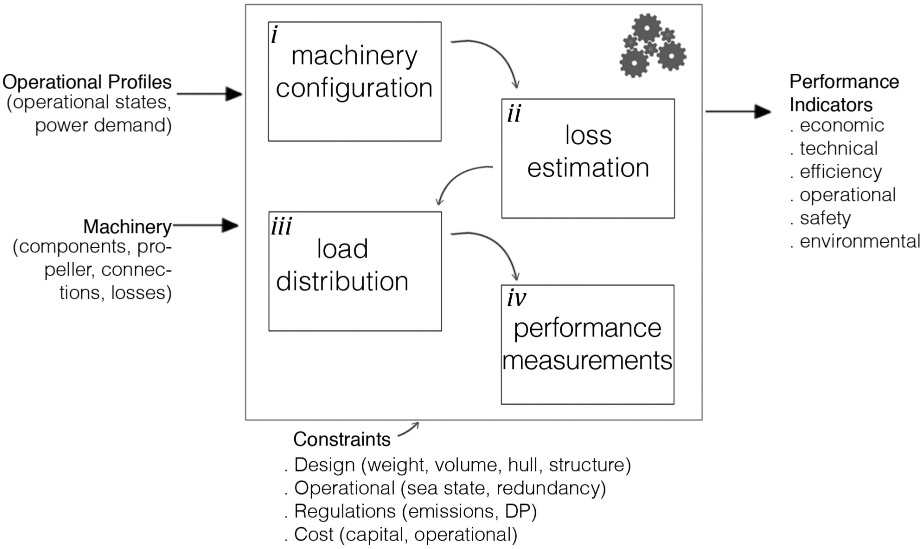

Figure 26: Vessel propulsion performance evaluation via machinery configuration point of view.

Appendix A compiles the abstracts of five secondary dissertations, developed within the Ship4C project in the initial stage of the research. These dissertations were the first studies of the new concerns of conceptual design, and represent research that was published during the PhD.

Related to this development, two issues instigate interesting research questions. First, how can we efficiently design these advanced subsystems in the early phases of project development, based on the expected operating profile of the vessel? Second, how can system performance in terms of cost, energy efficiency, emissions, flexibility, and availability be documented for the customer to increase the likelihood of winning the contract? This motivated the sketch of what would become the research questions presented in this thesis, connected to complexity theory and ship design. Receiving the Janson "Legat" fellowship stimulated international cooperation.

3.3 Complexity Aspects in Conceptual Ship Design

At the conclusion of 2010, it was clear that a ship's design is a task that not only embraces complex mapping between form and function, but also considers the ship both a whole, organized structure, composed of several subsystems (e.g., propulsion, hull, equipment, etc.), and as a part of a wider organization such as a fleet and the entire transportation system. The same logic connects this logistical chain to the economic and social systems of the world, transforming ship design task in a highly complex activity.

The Norwegian University of Science and Technology (NTNU) has broad expertise in the maritime sector, but the study of how to handle complexity in intricately engineered systems such as a ship is a challenge that has not been tackled extensively. The work of Drs. Donna Rhodes and Adam Ross concerning complexity systems led to collaboration as a visiting researcher working on the SEAri at MIT in the Fall of 2010. The mission of the group matched the new focus of the research, stated as: *to advance the theories, methods, and effective practice of systems engineering applied to complex socio-technical systems through collaborative research*[4]. The group also has extensive publications related to systems engineering and uncertainty, with many topics common to both Ship4C interests and mine.

The SEAri group has contributed importantly to the understanding of complex engineered systems, specifically within multi-attribute exploration methods and design under uncertainties. Two recent papers published by SEAri in 2010 - *Five Aspects of Engineering Complex Systems: Emerging Constructs and Methods* [92] and *Shaping Socio-technical System Innovation Strategies using a Five Aspects Taxonomy* [93] - introduced an opportunity to apply advanced complex systems engineering to ship design. They presented innovative classifications to organize system information using the five-aspect taxonomy to identify new elements such as environmental performance and uncertain scenarios, without constraining them to a purely structural or behavioral viewpoint. The paper also introduced many SEAri techniques for handling uncertainty such as epoch-era analysis (EEA) and responsive systems comparison method (RSC). The taxonomy, however, has not been applied to a practical engineering domain, which led to an opportunity to implement and develop such methods in maritime design field.

Two topics related closely to SEAri research are worthy of exploration. The first is understanding the complexity of the ship design task using aspects proposed by Rhodes and Ross ([92], [93]) and paradigm change discussed by Minai *et al.* [23]. It consists of studying classic ship design from the perspective of complex systems. I believed it was possible to offer new insights to the field by applying the logic of complex systems, for example, developing the five-aspect framework for ship design thinking. Another important aspect I planned to study was how to handle complexity - design robustness and scenario uncertainties - during the conceptual design phase. This was an approach to two problems:

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[4] URL: http://seari.mit.edu

1. Given an operational scenario, how should the robustness of a ship's design be estimated? For example, in the practical case of a vessel that needs to perform a mission consisting of diverse tasks *A, B,* and *C* to each of which a different time percentage is allocated. How much can these time percentages be changed while the design still fulfills the criteria? How can we understand such a simple case to achieve a robust-by-structure design?

2. Given uncertainty in the external environment (i.e., the type of mission that a ship will perform), how can uncertainty leading a design to perform better in scenarios *X, Y,* or *Z* regarding criteria (e.g., low environment impact) be estimated? How should novel/unexpected circumstances be handled in the early stages of design? The works of Hastings and McManus [58] and Magee and de Weck [76]can be used as a starting point to clarify this question.

In summary, my initial proposal for my time at MIT was to incorporate the Complex Engineered Systems concepts into conceptual ship design, studying how to handle complexity in the early stages of design, with focus on estimation of robustness toward changes in operational profiles (A, B, and C) and uncertainties toward various (unexpected) scenarios (X, Y, or Z), developing a framework suited to handle complexity in the conceptual ship design case and, with an understandable study case, able to present a framework able to handle aspects of complexity that I have been studying.

The first approach at SEAri consisted of trying to answer questions such as: *what does research in maritime systems and systems engineering have in common?* Much of SEAri's research focused on systems engineering theory, with applications primarily toward aircraft and aerospace systems. *Which of these techniques had similarities with ship design? How should we bring innovation and insights into conceptual ship design based on these new tools? Much of the initial work consisted of reading a paper with an innovative technique such as the EEA, and raising questions such as: Is there any equivalency in ship design, and how can it be developed and applied to ship design?* At this time, linked to answer these questions, an outline of what would become Paper 2 and Paper 5 of this thesis was sketched.

I faced this work both as a challenge and opportunity. It posed a challenge because even if there were a taxonomy, it was very recent research, with no proper implementation of it applied in a practical engineering field. Much needed to be researched and developed to apply these principles to conceptual ship design. It offered an opportunity to find an instigating and competent research team that had already published relevant research that could provide me with a starting point for my research, and to be accepted to develop this research in collaboration with them.

In April 2011, the plan started to take shape, resulting in the outline of what would become paper 1 of this thesis. The proposal was to develop and apply more directly the five-aspect taxonomy and a SEAri-developed method in a marine systems case. At that time, the Ship4C project had just published a paper on ship design and deployment problems [96], and this opened a door to explore how such a technique merges with epoch-era to handle contextually temporal complexity. A paper on this subject was completed in September of that year and was accepted for publication three months later (Paper 1).

The third paper presented in this thesis binds the research in energy efficiency developed in 2009/2010, from the complexity perspective. It applies the RSC method for operational lifecycle assessment of air emissions during the early stages, based on machinery configuration, operational profiles, and air emission control methods.

The final months of the research focused on the perceptual aspect and the incorporation of residual information, which cannot always be handled precisely. Professor Arnulf Hagen influenced this thinking, and a paper linking the idea of value robustness with this perceptual aspect was developed based on this discussion (Paper 4), finalized at the same time this thesis was written.

4 Results

4.1 Main Papers

This section presents the results of the research, organized as a main body (Sections 1 through 6) and collection of main papers (Part II), which underlie the core of the work toward answers to the research questions. I am first author on the five selected papers and two discussions, contributing the major intellectual input, implementation, and writing. An explanation of the relevance of each paper to this thesis, and my contribution to each, is:

Paper 1 (Journal):

Henrique M. Gaspar, Adam M. Ross and Stein Ove Erikstad: *Handling Temporal Complexity in the Design of Non-Transport Ships Using Epoch-Era Analysis.* Transactions RINA, Vol 154, Part A3, International Journal Maritime Engineering, Jul-Sep 2012
Discussion published on Transactions RINA, Vol 155, Part A3, Jul-Sep 2013
DOI No: 10.3940/rina.ijme.2012.a3.230

Relevance to this thesis: This paper explores uncertainty in future scenarios through EEA and ship design deployment problem (SDDP). The combined techniques handle contextual and temporal aspects since contextual elements are decomposed into epoch variables and temporal elements into epochs and eras. The SDDP provides an optimum solution for each *chunk* of time.

My contribution: I am first author and I wrote most of the paper, including development of a mathematical model for EEA applied to a ship design case. Co-authors contributed with guidance, revisions, and discussions. This paper was sketched in April 2010 when Stein Ove Erikstad was visiting SEAri, and he wrote part of the SDDP introduction and discussion. Adam Ross developed the EEA, and Stein Ove Erikstad developed the SDDP. Both contributed with a discussion of the text and critical review of the mathematical model.

Paper 2 (Journal):

Henrique M. Gaspar, Donna M. Rhodes, Adam M. Ross and Stein Ove Erikstad: *Addressing Complexity Aspects in Conceptual Ship Design - A Systems Engineering Approach.* Journal of Ship Production and Design, Vol. 28, No. 4, November 2012, pp. 1-15
DOI: http://dx.doi.org/10.5957/JSPD.28.4.120015
Selected to be part of the *Transactions of SNAME*, Vol. 120, 2013 - with added discussions

Relevance to this thesis: This paper defines *complexity* used in this research and presents ship design as a complex system problem. It introduces the five-aspect taxonomy, dividing the aspects into structural, behavioral, contextual, temporal, and perceptual. It applies each to the ship as a system. The RSC method is used as a general approach to handle the five aspects in the early stages of design, with a case example.

My contribution: I am first author and I wrote most of the paper, including the mathematical model for the RSC case. Co-authors contributed with guidance, revisions, and discussions. This paper was the first one sketched at SEAri, and it took more than a year to complete since it defines the basis for understanding the complexity aspects in conceptual ship design. Donna Rhodes and Adam Ross developed the five-aspect taxonomy and the RSC method, which I use in the paper. Stein Ove Erikstad contributed with a discussion when applying general theory to the ship design case.

Paper 3 (Journal):

Henrique M. Gaspar, Océane Balland, Dina M. Aspen, Adam M. Ross and Stein Ove Erikstad: *Assessing air emissions for uncertain lifecycle scenarios via responsive systems comparison method*, Submitted to an international peer-reviewed journal (June 2013).

Relevance to this thesis: This paper applies the responsive systems comparison method as a design tool for machinery configuration and assessment of air emission for uncertain operational lifecycle scenarios during early stages of design. The initial motivation of this work was to combine research developed for environmental assessment, machinery configuration, and operational profile (discussed in Section 3.2) with complex systems engineering theory through the responsive systems comparison method.

My contribution: I was first author and I wrote most of the paper. Co-authors contributed with writing, guidance, revisions, and discussions. Océane Balland focused on the literature review of energy efficiency, air emission control methods, and data for the RSC model, and Dina Aspen did the same for the lifecycle topic. Adam Ross and Stein Ove Erikstad contributed critical discussions of the text and the mathematical model.

Paper 4 (Journal):

Henrique M. Gaspar, Arnulf Hagen and Stein Ove Erikstad: *Designing a Ship for Complex Value Robustness*, Submitted to an international peer-reviewed journal (June 2013).

Relevance to this thesis: This paper discusses the elements important when perceiving the *goodness of a ship*, linking the perception of a value robust design with a rational decision. An extended definition of mission concept is presented to handle the perception of value robustness in the early stages of maritime design.

My contribution: I am first author and I wrote most of the paper. Co-authors contributed guidance, revisions, and discussions. Most of the ideas in this paper surfaced while discussing perceptual complexity with Arnulf Hagen, and both he and Stein Ove Erikstad contributed some writing and a strong critical review of the structure of the paper.

Paper 5 (Peer Review Conference):

Henrique M, Gaspar, Donna H. Rhodes, Adam M. Ross and Stein Ove Erikstad: *Handling Complexity Aspects in Conceptual Ship Design*, Proc. 11th International Maritime Design Conference, Glasgow-UK, June 2012

Relevance to this thesis: This paper discusses a general approach to handling complexity based on decomposition and encapsulation. It lists the primary techniques that apply this general approach to each of the five aspects, with a final example of an offshore support vessel.

My contribution: I am first author and I wrote most of the paper. Co-authors contributed with guidance, revisions, and discussions. I developed this general approach after a discussion with Stein Ove Erikstad. Donna Rhodes and Adam Ross developed the five-aspect taxonomy, which I use in the paper.

4.2 Decomposition and Encapsulation as fundamental premises when dealing with complexity

The result of the thesis connects fundamentally to the first research question: which general complex systems theory premises can be used to define complexity in conceptual ship design? The most self-evident solution would be that *To handle complexity we need simplicity.* Yet, why is so difficult to keep the design of engineering systems simple? A reason, proposed by Sha [99], is that a better design involves pursuit of features and performance; to achieve higher performance, to include advanced functionalities and improve capabilities, means we should stretch the limits of our understanding, exemplified by technologies and scientific advancements. Avoiding what we would call *complex methodologies* is impractical in most cases. What is required is an approach that allows us to exploit safely future scenarios and equivalent features available that will respond better to each.

Among many known patterns of dealing with information, this research converged into two strategies for simplifying complex engineered systems. Decomposition traces to 1962 and Simon's principles [101], and 1983 and Kolmogorov's *bit* [71], based on hierarchizing and dividing the system into parts to a size small enough where the amount of information necessary to define, and therefore understand, that part of the system is known and manageable. Encapsulation consists of organizing each part based on a common bounding strategy to conceal this internal complexity behind a simple and functional, well-defined interface. The approach is based on decomposition and encapsulation, discussed in Papers 4 and 5. Decomposition simplifies the handling of a complex system by breaking core aspects into smaller chunks or parts (or assemblies, subsystems, classes) for better understanding of them and their mutual interactions, reducing information required to sufficiently (for the purpose) understand performance of the overall system. Encapsulation simplifies connection of parts with other parts, defining clear inputs/outputs. This process combines smaller parts into larger subsystems or assemblies, with predefined interfaces, thus reducing the number of interactions and the need for detailed information (Figure 27).

Statement of a fundamental premise should be able to summarize into two patterns the essence of handling complexity, that is, decomposition of the information necessary to define the system into *pieces* small enough that one can understand (and therefore manage), and encapsulate these *pieces* in its main categories. This general principle connects to the desired outcome of dealing with any kind of complex systems, which is to simplify it.

Computers are a current example of these principles in use. Decades ago, one would be trained to handle computation of a simple algorithm, whether through punch cards or, at a different time, floppy disks. Today, a much broader range of people carries powerful computers in their pocket such as smartphones and use them daily. This advancement was only possible due to handling of the large amount of information necessary to design

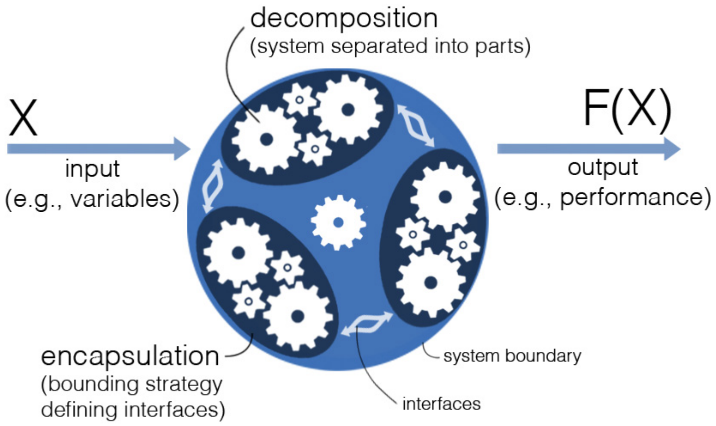

Figure 27: Decomposition and encapsulation as a general approach to handle complexity in systems.

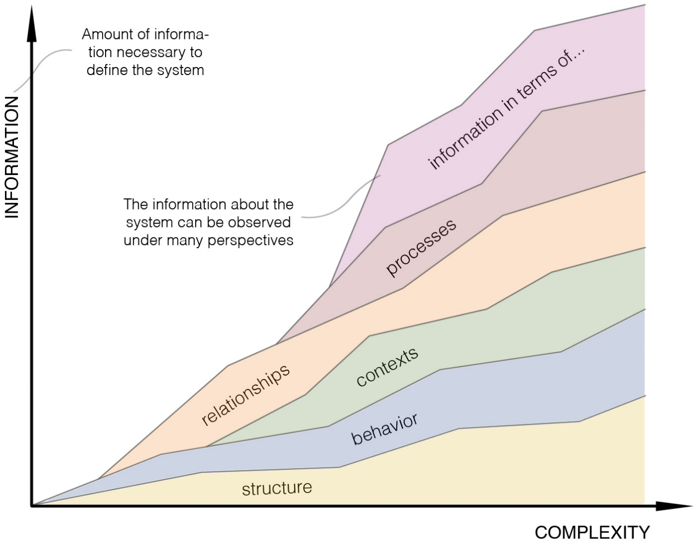

Figure 28: Complexity related to the amount of information necessary to define the system.

these objects. A modern microchip contains many more single parts and connections than a computer from the 1960s. However, it presents a well-defined boundary of inputs and outputs, with pre-defined interfaces. This encapsulation occurs not only in the structural part, but also in the perceptual, with an interaction that the user is much more friendly on a level that allows even a child to use the object.

No one argues that the design of merchant ships should focus on operability by a child. It is, however, possible to realize how these basic principles are also used currently in maritime praxis. Modularity exemplifies decomposition of parts of a ship by their functions, and an encapsulation constrained by technical or economic situations. For example, a 100-ton crane capacity at the shipyard will constrain the size and weight of the largest block that can be transported. The next step is to understand how these basic strategies apply to the conceptual ship design case.

Figure 28 represents the link between complexity and information, with two essential principles. First, when a system requires more information to be defined, it is more complex. Second, this information can be observed under many perspectives, and a good system definition considers only those germane. In the remainder of this section, we propose that the structural and behavioral aspects dominate when defining and evaluating a complex system. These two aspects are essential in engineering, but used alone, they exclude important information.

4.3 Five aspects taxonomy applied to Conceptual Ship Design

Selection of decomposition and encapsulation as driver patterns to handle complexity led to use of the five-aspect taxonomy, decomposing what should be considered important information when conceptually designing a ship, that is, the kind of knowledge that can be extracted from the factors discussed in the background presented in Section 2.4 and illustrated in Figure 28, including physical structure, performance expectations, and market demand, among other factors. The next step was categorization of the current literature on conceptual ship design in light of the taxonomy. All papers in this thesis relate to this connection. The sections below summarize each of the five aspects - structural, behavioral, contextual, temporal, and perceptual - of the taxonomy's relationship to conceptual ship design.

Structural Aspect: The structure/behavior pair aggregates information covered extensively in traditional model-based techniques. The structure is decomposed and encapsulated in subsystems and components (Figure 14). Modern approaches transform classic subsystem into modules. Andrews ([5], [12]) also uses systemic thinking and complex systems terminology when justifying his comprehensive methodology for ship design and a creative approach to ship architecture [6]. For example, the author uses the building block approach as a design method; once applied, it produces an informed and information-rich preliminary design. The method presents a functional breakdown of the system into semi-independent building blocks as a design technique. This strategy is a means of handling structural complexity. An extensive study on this and other modularization techniques is discussed by [45], presenting an overview of modularization related to shipbuilding and emphasizing the modularization task, platform technologies during product development, and tendering phase.

McDonald [80] uses Lamb's number of unique parts in a product [74] to exemplify the complexity of ships in structural terms. Caprace and Rigo [29] present an approach that is an introduction to complexity thinking in the conceptual phase, suggesting a metric to compare ships based on structural complexity. The formulation proposed is based on the type and configuration of the ship. The metric is, however, focused strongly on the structure and general configuration, leaving out aspects that should be addressed when discussing complexity.

Behavioral Aspect: The behavioral aspect is approached in conceptual design by the analytical tools used to evaluate each subsystem decomposed by the functional breakdown. The system-based ship design assumes that the *design should start from the mission specified for the ship; the mission statement settles tasks, capacity and performance (...) as consequence the design task structure to "define systems and functions - estimate size and weight - select dimensions - check performance"* [46] (Figure 13).

Decomposing the behavioral aspect commonly means decomposing expected performance of the ship into KPIs by using model-based tools. New approaches to estimate the behavior not only consider empirical data, but also rely on system simulation. As presented by Bertram and Thiart [21], advancement of computational methods in recent decades has developed, enabling more reliable simulation-based ship design. As observed by the authors, design behavior is evolving from experience-based (e.g., regression analysis tools) to simulation (e.g., discrete tools). These advancements permit increased information to be handled during the conceptual phase, necessitating a discussion on the influence of the simulation in ship design, such as Andrews and Pawling [10].

Some optimization techniques develop the behavioral aspect to handle uncertainty in the input data, such as fuzzy logic modeling [54], and identification of an optimum design, such as the ship design and deployment problem [47]. A compilation of the main advancements and challenges in computer applications for ship design and analysis is discussed by Sharma *et al.* [100], looking at computer-aided design, geometric representation, hydrodynamics, structure, production, and experimental testing.

Contextual Aspect: The challenge for handling the contextual aspect is the transition between constraint context parameters, usually technical and economic, toward a more extensive and flexible decomposition that incorporates new social elements in early phases (e.g., environmental performance and risk assessment). Uncertainties in the context parameter and shifts/changes must also be considered. As noted previously, Andrews defends more open observation of the initial requirements [14], proposing an elucidation rather than “pure engineering,” while Hagen and Grimstad [57] defend this broader scope, calling for a context that includes the transportation system, iterating the process from the bottom (e.g., air emissions) to transport chain requirements (e.g., transport demand).

Environmental issues gained importance during the last decade ([51], [38]). The idea of how a ship should be designed, to be environmentally friendly for example, is not yet clear to the community. It can include several areas such as energy efficiency, low emissions, biohazards, and being toxin free. Several studies are being developed primarily with the objective of addressing energy efficiency and air emissions. Examples include hull optimization [97], design of machinery configuration considering environmental KPIs [53], and air emission controls optimization [15]. Risk is another important context factor to be incorporated in the early stages. Risk-based design is a methodology that supports and nurtures a safety culture paradigm during ship design by treating safety as design objective rather than constraint [72]. Papanikolau [88] presents a compilation of recent methods, tools, and applications during risk-based ship design.

Temporal Aspect: One common approach to handling the temporal aspect is lifecycle assessment (LCA). The technique relates strongly to sustainability in that it quantifies a parameter’s performance (e.g., environmental load or economic performance) through the entire lifespan of the system. Cabezas-Basurko *et al.* [28] present a study to encapsulate environmental, economic, and social sustainability during preliminary ship design, proposing a holistic approach to maintaining sustainability. Fet [49] uses LCA to discuss sustainability in shipping.

A limitation of the traditional methods is simplification of various contexts through time. This limitation is justified by an increase in design complexity when designing under a large number of shifts/uncertainties in the context of the system's lifespan. The epoch-era method [96] represents a decomposition-based approach to handling temporal complexity, as exemplified in Paper 1 of this thesis. It captures alternative expectations about the future by formulating distinct epochs (i.e., sets of contextual parameters) with a fixed operating context, from which performance of each alternative design can be analyzed. These epochs can then be combined into many possible eras, each representing a possible lifecycle scenario for the vessel. This idea is explained in Section 4.5.

Perceptual Aspect: The perceptual aspect addresses *satisfying the diversity of stakeholder stylistic preferences* [92]. It requires critical systems thinking [114] and elucidation of requirements [14]. Later in the process, the ability to evaluate whether design A is value robust or whether design A is more efficient than design B requires formal construction of system KPIs, customized to each stakeholder's preferences. However, the possibility of analyzing a large design space toward a large number of possible scenarios results in a huge amount of information to be handled. To handle this data implies, for example, study of sensitivity analysis, uncertainty, and robustness of the design ([41], [97], [115], [75]). Another common way to approach a multi-criteria study is decomposition of stakeholder preferences in factors and the weighting of factors in an Analytical Hierarchy Process (AHP) ([84], [24]) and/or through scoring functions.

Table 4 summarizes a selection of the literature review discussed in this section, organized by the five aspects and its topic.

Understanding that a good taxonomy is crucial to decomposition and encapsulation was one of the reasons to adopt the five-aspect taxonomy in the ship design case as a central part of my research. The five aspects of a complex system, proposed by Rhodes and Ross ([92], [93]), keep the current model-based systems engineering approach, which embraces behavioral and structural complexity aspects, and adds three other aspects: contextual, temporal, and perceptual. The latter three extend design problem boundaries while leading to a systems environment that is continuing to grow in terms of information. All five papers presented as part of this thesis applies these five aspects into conceptual ship design, with varying details. The fact that the concepts introduced in this taxonomy are novel makes it necessary to provide overlapping explanations of these aspects; this particular taxonomy has not been applied in the maritime field prior to this research.

Table 4: Summary of recent conceptual ship design literature under the light of the five-aspects taxonomy

Paper	**Aspect**	**Topic**
Andrews, 2003 [6]	Structural	Efficient Building block division - Building block based design
Andrews, 2011 [14]	Perceptual	Requirement elucidation - Perception of requirement elucidation rather than requirement engineering
Andrews, 2006, 2009 [12], [10]	Behavioral	Simulation on Preliminary Ship Design - The impact of simulation in design, with building block approach case
Bertram and Thiart, 2005 [21]	Behavioral	Simulation application during early stages of design - Simulation-based ship design
Cabezas-Basurko, et al., 2008 [28]	Temporal	Lifecycle assessment - A holistic approach for guiding shipping and stakeholders towards sustainability using economically viable, less polluting and more human-friendly operating models
Caprace and Rigo, 2010 [30]	Structural	Complexity assessment during early stages of design - Measurement of ship complexity based on structural arrangement
Erikstad, 2009 [45]	Structural	Modularization - Modularization in shipbuilding and modular production
Erikstad et al., 2011 [47]	Contextual	Ship design and deployment model - Optimization model when designing for several contexts
Erikstad and Levander, 2012 [46]	Structural, Behavioral	System based design - System based design applied for offshore vessels
Hagen and Grimstad, [57]	Contextual	The extension of system boundaries in ship design to include more context elements, from the fleet and subsystems
Levander, 2006 [75]	Structural, Behavioral	System based ship design, emphasizing structural and functional breakdown
Singer et al., 2010 [105]	Structural, Behavioral	Set based ship design, establishing of feasibility before commitment, keeping good solutions to evolve in parallel
Sharma et al., 2012 [100]	Behavioral	Computer applications for evaluating performance during early stages via simulation and discrete methods
Winnes and Ulfvarson, 2006 [117]	Perceptual	Use of scoring functions to evaluate environmental improvements
Whitfield et al., 1999 [116]	Behavioral, Perceptual	Multi-objective robust design methods in ship design, with a robust framework containing optimization tools and response surface methods
Ulstein and Brett, 2012 [114]	Perceptual	Value Robustness - Critical systems thinking to aid decision making and perception of value

This work's contribution consists of applying and categorizing the ship design task into the taxonomy. In short, the *structural* aspect relates to the arrangement and interrelationship of the physical objects in the ship. The *behavioral* complexity derives from the form-to-function mapping. Technical performance analysis such as resistance and propulsion, seakeeping, maneuvering, stability, and strength is both mathematically complex and computationally intensive. The *contextual* aspect defines external operating circumstances to which the ship is subjected. It consists of the external entities, interfaces, and factors that influence the behavior of the ship and should be considered when designing it. The *temporal* aspect of complexity refers to changes over time during a ship's operational lifecycle. Shifts and uncertainties in this context such as a diverse operational profile are also handled in this aspect. The *perceptual* aspect relates to how the ship is interpreted from the perspective of system stakeholders through its lifespan. It not only considers individual stakeholder expectations and preferences, but also how they vary across stakeholders. Figure 29 illustrates these aspects.

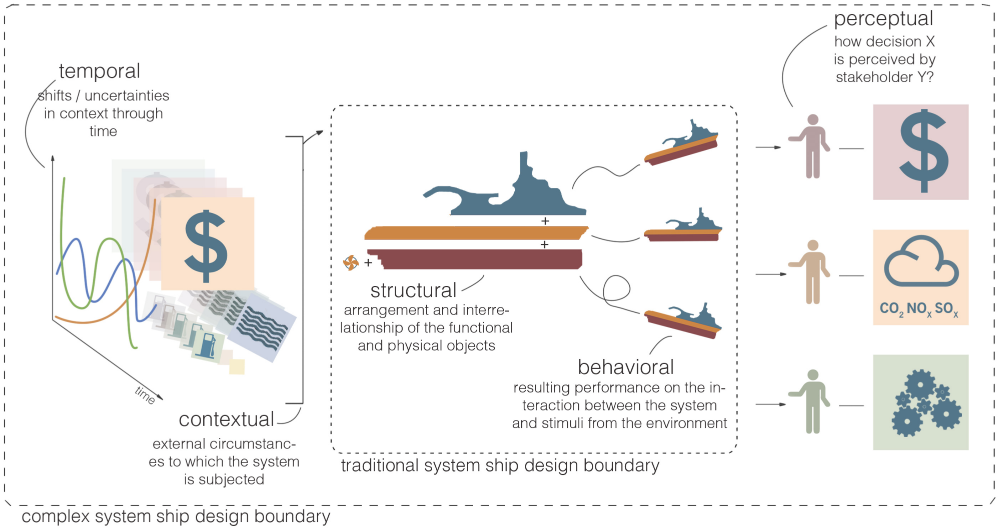

Figure 29: Five aspects of complexity applied for conceptual ship design

Table 5 presents a compilation of methods to approach ship design through decomposition and encapsulation of each aspect.

Table 5: Decomposition and encapsulation of the five aspects applied to conceptual ship design

Aspect	**Decomposition**	**Encapsulation**
Structural	Modularization, identifying near independent modules and defining criteria to create modules; decomposition of the structural aspects via a discretization of the design variables, with a given range max-min, creating a design space. The evaluation and refinement of the design space through a unified process, such as RSC, leading to a flexible group of choices.	Defining inputs and outputs of each module, in order to grasp the scope of what belongs to the inside and outside of each module; defining interface criteria to connect one module to another, enabling an efficient *communication* among them.
Behavioral	Functional breakdown, dividing the system into subsystems according to a task to be performed, then evaluating the behavior of each subsystem, for instance, via simulation or regression analysis; performance attributes in a concurrent engineering process, with the design space being evaluated for all the contexts in the same phase.	Methods to reduce the size and number of dimensions of the search space, such as analysis of variance; Response Surface and other similar methods to encapsulate data from simulation; Pareto sets and tradeoffs analysis to select a subset of designs.
Contextual	Decomposing context factors, taking into account multiple scenarios, with different operational profiles and context parameters (market, technology, and policy/regulations). For instance, via epoch variables where context factors are decomposed during the epoch characterization process.	Use of standard and customized operational profiles, that is, a set of context parameters with a fixed period of time encapsulated in a mission/scenario/epoch.
Temporal	Decomposition of the operational life-cycle into *chunks*, such as in epoch-era analysis. First, dividing the life span of the system via a vector of context parameters (epoch variables), with each epoch representing a snapshot of a certain period of time.	Lifecycle path analysis is a powerful way to evaluate the behavior of a given design set under many alternative future scenarios. EEA offers the concept of an era to encapsulate scenario changes and uncertainties into a time-sequenced set of epochs.
Perceptual	Complex value robustness decomposition, taking into account multiple stakeholders' expectations, perceptions, and preferences. Decomposition of what is considered to be valuable, proposing a utility range in the attributes able to grade designs according to a certain performance attribute value. Study of the residual information	Multi-objective methods e.g., Pareto plots/trace/sets, response surface and AHP); attributes normalized under a common utility metric, facilitating the solutions comparison and tradeoffs. It allows a customized selection of the design set towards specific decision-maker's preferences.

4.4 Dealing with Structural and Behavioral aspects

The results on structural and behavioral aspects connect to the structure of the basic *generate, analyze, evaluate, decide* design process (Figure 8, from [42]). As observed in the previous subsection, the structural aspect relates to the form in the basic form-function mapping of the design. It includes the physical objects of the ship, as observed by Levander in his system based ship design methodology ([75], [46]). As noted, this aspect relates to the ship as a large, self-contained system with several highly integrated subsystems such as: propulsion, hull, outfit, etc. Each subsystem contains many components, which also consists of a physical structure, and interacts with other components, similar to the classification presented in Table 1 from [62]. For the ship as a main system, all subsystems must be provided by the vessel itself within a limited volume, in which changes to one part might influence other parts through highly interactive relationships. This large structure, the ship, also interacts with other structural components from the maritime system (transport, service and/or naval), a system of systems in which it is included. An overview of the structural aspect of the ship is presented in Figure 17 (Section 2.2).

The structural aspect of the subsystem follows similar logic. For the machinery case, it includes the usual physical objects of the machinery system such as the propeller, main engine, gear, transmission, generators, and shafts. All components must be within volume and weight constraints, creating a highly interactive environment. This aspect also relates to interaction of the propulsion subsystem with other subsystems. Figure 30 exemplifies the type of subsystem used in this research. It contains the overall arrangement, with parts and interconnections of the machinery such as number and type of components, main powering capacity information, and a set of fuels compatible with the engines.

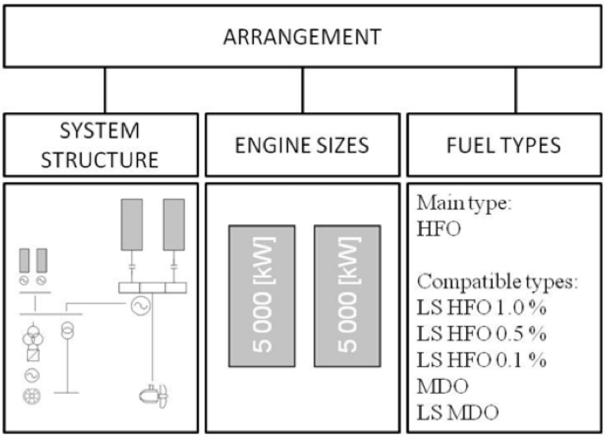

Figure 30: Machinery arrangement as example of structural subsystem (adapted from [17]).

The behavioral aspect derives function from form, and it handled by technical analysis performed during design, for example, resistance, propulsion, seakeeping, maneuverability, and stability. It is also the interaction between the system and a stimulus, either internal stimuli from a subsystem (such as the propulsion engine) or external stimuli from the environment (such as the waves). During conceptual design, the type of analyses required to estimate ship behavior relies to a large degree on empirical formulation and advanced engineering tools such as regression analysis models, finite element methods, and computational fluid dynamics. Traditional performance is thus estimated by mapping between form and function to ensure in the conceptual phase that a ship X will perform task Y. Over the past few decades, model-based approaches have been developed to handle the structural/behavioral aspect, and are now at a mature level of practice [92]. In addition to traditional, technical/economical tradeoffs, ship conceptual design today requires estimation of the behavior across a broad number of areas, including, for instance, risk, safety, and environmental performance, resulting in a more complex and multi-objective evaluation function. Figure 31 illustrates the behavioral aspects.

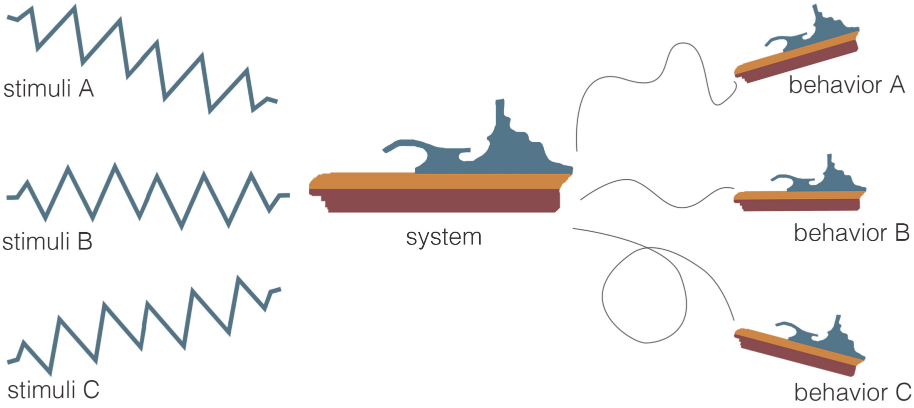

Figure 31: Behavioral aspect.

Subsystem behavior is approached similarly. A purpose of this study was to evaluate machinery behavior under multiple operational profiles. The process included the one discussed in Section 3.2 (Figure 23). A mission was decomposed as a set of operational profiles performed by a ship. Each operational profile had its own set of operational states depending on ship function. Each operational state linked to a KPI [15], and behavior was evaluated based on the process explained in Section 3.2, Figure 26. This process was combined with ship design and used to evaluate the environmental performance of the ship on two levels: 1) as design variables, similar to a parametric evaluation, by mapping design variables into attributes, are explained in the RSC, Section 4.7 and 2) as behavior in terms of its installed capabilities and consequently the ability to meet a contract. No formal assessment of the fleet was conducted; however, the study of a vessel in terms of its capabilities enabled the same type.

Structural and behavioral aspects dominate when determining the primary design specifications of a ship. Clearly, these two aspects are the basis of each design, essential in the *soul* of the engineering process. Used alone, they exclude important information, discussed in subsequent subsections.

4.5 Dealing with Contextual and Temporal aspects via Epoch-Era Analysis

The contextual aspect consists of external entities, interfaces, and factors, outside of the control of ship designers, which may influence system behavior and should be considered while designing it. Traditional contextual aspects are usually fixed and predetermined during the requirements elucidation phase. It usually includes a scenario, with a fixed set of market variables and regulations (Figure 32).

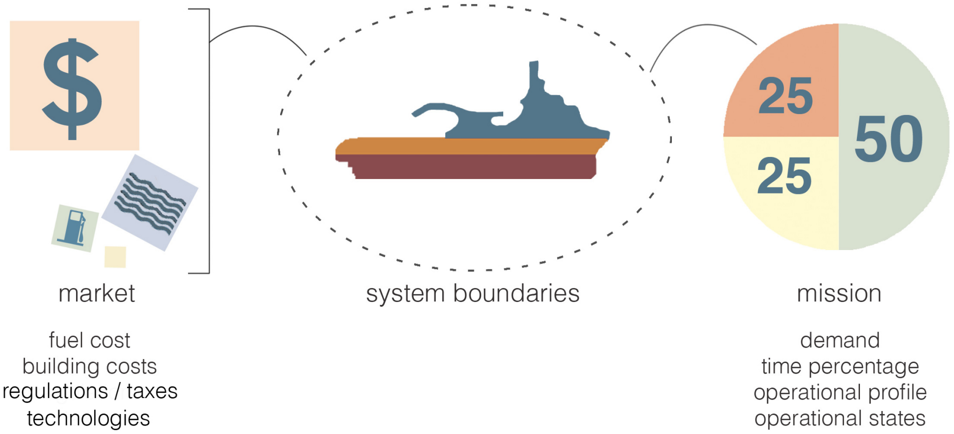

Figure 32: Contextual aspect.

The dynamic properties of the context lead to changes in external entities that might influence the system over time. The temporal aspect characterizes those shifts of the context during system lifespan. Uncertainties concerning how contexts might unfold are also incorporated as part of this aspect, for example, uncertainty related to the operational profile of the ship or due to estimation of future contract scenarios (Figure 33).

An important component of this research was decomposition of contextual and temporal aspects, with the intention of implementing these factors into ship design. Traditional system-based design methodology normally considers a rigid set of pre-defined context variables, usually static in time. By decomposing these variables regarding maximum and minimum and quantifying what type of behavior is expected from them in the future, we are able to apply the established design process exemplified in the previous section to evaluate the behavior of a design set (e.g., structure) under a large set of various future scenarios.

A result of the need for multi-scenario evaluation was introduction, development, and implementation of Epoch-Era Analysis (EEA) as a tool to handle the contextual and temporal complexities that arose. The EEA method proposes a useful representation of

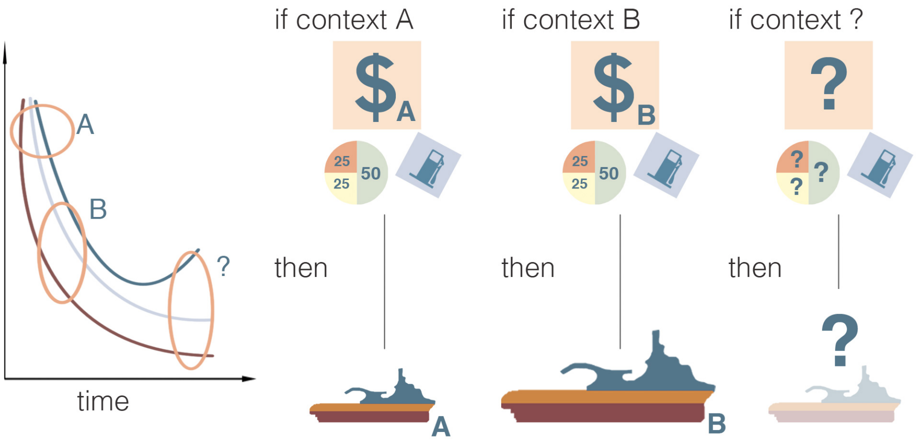

Figure 33: Temporal aspect.

the context as an interval of time with a static set of contextual factors forming an epoch - from the Greek *epokhé*, which means a fixed period. Several epochs create a dynamic interval of time, a time-ordered set of contexts defined as an *era*.

EEA apply premises discussed in Section 4.1 to the problem, decomposing context factors into epoch variables, which are presented within a range of values, connected to future expectations. The encapsulation provided by analysis of each epoch provides a simple interface of inputs - a design set analyzed for each epoch - and its consequent output - vessel performance for each epoch - concealing performance evaluation behind a simplified interface.

EEA handles the temporal aspect by dividing system lifespan into a series of epochs. Significant changes in contextual factors trigger the start of a new epoch, and changes include various context parameter values, which can be certain or uncertain. In the case of the design of non-transport vessels, these parameters relate to four categories. *Field Development* relates to opening of a new market, which might require different technology to be on board such as ice class for an oil and gas field in the Arctic or ultra deepwater equipment for operation in the Brazilian, pre-salt, offshore market. *Technology Development* is when a new technology appears on the market (e.g., new machinery), requiring a different type of fuel, or strengthened steel foundations on the hull and main deck, altering the capabilities of a vessel. *Policy and Regulations* relate to the regulatory aspects of the context such as creation of a new emission control area (ECA), limiting SOx or NOx levels (SECA/NECA). New rules relate to dynamic positioning or fire-fighting and even a mandatory air control method to prevent environmentally harmful emissions. The last category connects to the *Market Trends*, considering shifts in the market, with alterations in the fuel and freight price, high or low demand condition, and potential spot market options (Figure 34).

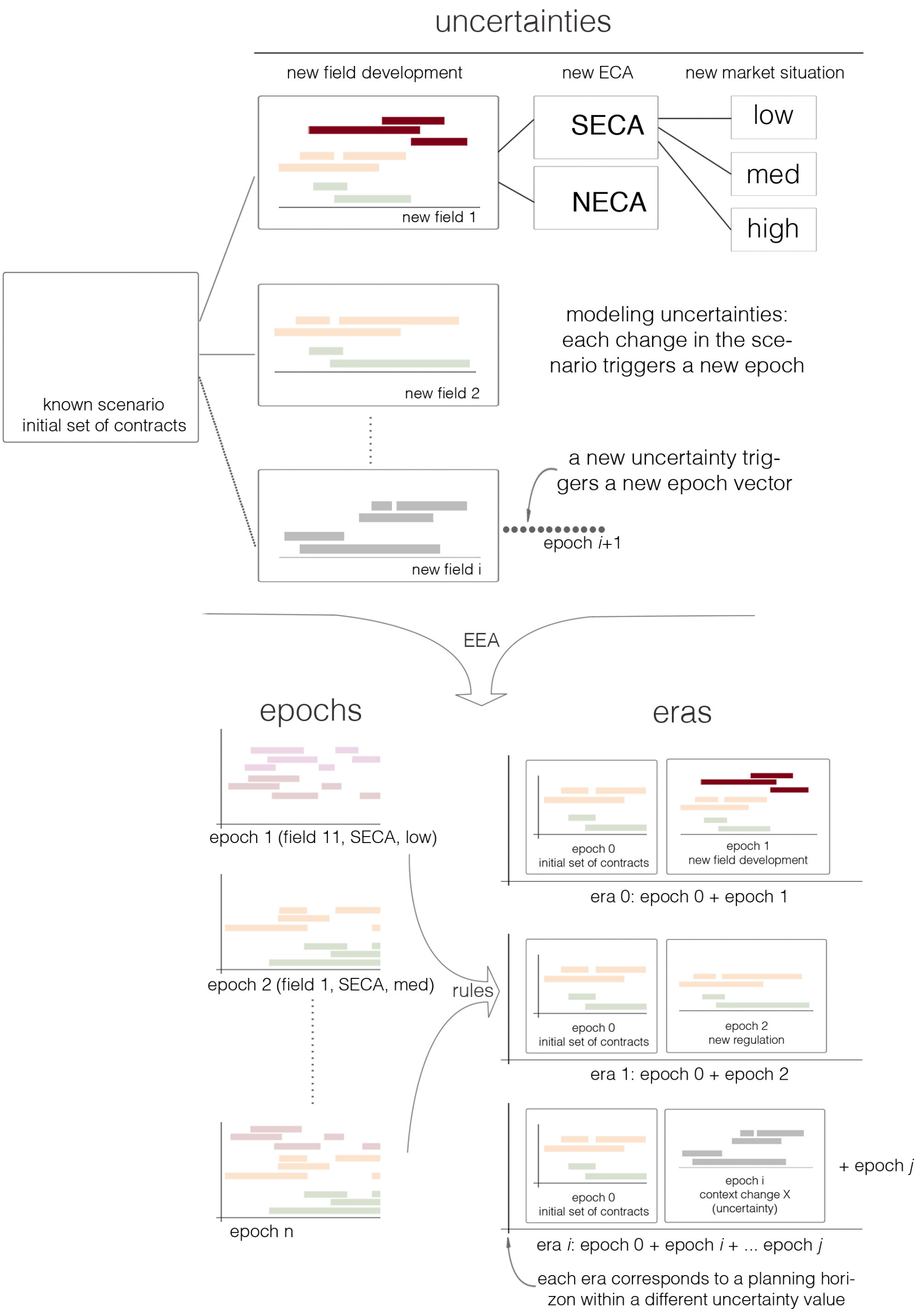

Figure 34: Decomposition of contextual and temporal aspects via epoch-era.

The same principle applies to the temporal aspect. Future scenarios are represented by the discretization of parameters, from a range that considers uncertainties and expectations. The sum of all epochs defines an epoch space. Expectation categories are discretized into a vector of epoch variables, or group of uncertainties. The next step consists of enumerating the variable, which might include selecting a unit for the variable, and its range of minima and maxima, the number of steps, and, optionally, weighting factors related to the impact of a given epoch variable in comparison to others. In the case of AHTS, each epoch variable represents a possible categorical change in a contractual scenario, and is instrument in mapping between context parameters and vessel performance. An era represents the full lifespan of a system, and is constructed by a time-ordered sequence of a given set of epochs. This sequencing must obey consistency rules in the epoch variables such as continuity constraints in the end of epoch e and beginning of epoch f, and consistency in the progression of epoch variables. For example, a new oil and gas field that begins operation in 2015 will likely not disappear in 2020 and reappear in 2025. However, it is possible to have an era during which such a field starts in 2015, another in 2020, and a third in 2025. Stakeholder preferences such as all/no eras that *must contain X* can also be incorporated.

Observed under classic economic concepts of temporal complexity, EEA allows for short- and long-run analyses. The short-run is characterized by a period in which context parameters are fixed and do not change, that is, an epoch. The short-run possibilities, for example, include ranking of the best designs by revenue in each epoch, using the total revenue of the path as utility parameters. A probability weight can be assigned to each epoch, reflecting the likelihood of occurrence. The long-run is characterized by the lifetime period across which parameters may change, that is, an era. The ability to incorporate changes in the lifetime of a system by assembling epochs gives a variable facet to the era. It leads to long-run analysis, incorporating the amount of time necessary to make all production inputs available, which in this case is the entire contract/design deployment. The long-run deals with maximization of profit over an extended period. In addition to the problem of how to ensure correct assembling of an era, with discontinuities and constraints of the given context changes, the primary problem becomes era space. Since the potential era space grows exponentially with the number of epochs, sampling or constraint-based strategies should be used to manage the number of evaluated eras. In the long-run, the epochs are used as modules that can be combined to create the full lifetime of a system, that is, the eras. It is assumed, for example, that the profit for an era can be estimated by summing epoch revenues of that era minus the cost of the ship.

Construction of an era begins with the definition of epoch transition rules, which imposes continuity constraints and variable consistency [96]. The EEA technique offers an explicit benefit to scenario planning problems such as ship design deployment problems (SDDP) [47]. In these cases, selection of a design in the conceptual phase is driven by assessment of the economic return of such a choice in an uncertain future. EEA is a tool malleable enough to deal not only with non-transport ships, but also with the majority of temporal aspects of ship design scenario planning problems.

The EEA approach was developed to demonstrate the context and temporal parameters of encapsulation and decomposition. However, the methodology can be adapted as needed. Another consideration is to realize that the case presented is a theoretical study. Shipping involves a high degree of risk, and probability distributions of profit for a case with real data and assumptions should contain much more information than a single profit plot. For example, they should include how the epochs most likely influence a design's performance, or, similarly, changes in the probability distribution of the contracts should be considered.

In summary, the EEA approach represents a divide-and-conquer method for handling temporal complexity. The shipowner, facing an uncertain future over the 20 to 30 year lifespan of the ship, with possible variations in a number of dimensions, can use the EEA approach to consider manageable chunks in the form of epochs. These epochs provide a foundation for a quantitative performance evaluation of alternative designs, while at the same time offer a means to communicate about future expectations as part of story-telling. Within an epoch, the SDDP is used as a means for translating the context parameter values into a form suitable for performance analysis, the epoch variables, by generating a contract scenario for which a given design optimizes revenue. Combining these epochs into eras, the lifecycle performance of a given design can be found by aggregating performance of the epochs it contains.

My conclusion is that a combination of the SDDP and EEA methods is an efficient approach to handling contextual and temporal complexity problems in early ship design, providing a modular approach to handling uncertainty from a computational perspective and by capturing expectations about the future into manageable chunks.

4.6 The perceptual aspect and the importance of complex value robustness

This last aspect relates to how the system is interpreted from the perspective of system stakeholders. For the sake of example, let us analyze the main stakeholder and needs of an OSV. The direct beneficiary is, naturally, the owner and operator since the vessel must be attractive to get a contract and provide efficiently services demanded in the contract. It is assumed that the concept of safety considers the protection of human life and environment, and efficiency connects primarily to fuel and the cost (or savings) connected to it. The indirect beneficiaries connect to the OSV during its lifetime, including the charterer, who demands efficiency regularity, a green image and safety; the owner's shareholder and the return on investment expected from the ship; suppliers, who see the ship as a potential sale in equipment; regulators and classification societies, who also want to sell services and be assured they are performing their role in protecting the investor, society, and environment; designers, who seek profit, build their brands, and exploit platform opportunities; government, which sees the ship as a source of jobs connected to development of the domestic industry and national content.

The perceptual aspect embraces all others, plus the abstract notion of value exhibited by each decision-maker, that is, their individual preferences (Figure 35). With the addition of multiple viewpoints, sensitivity analysis becomes more extensive and complex (i.e., requiring more information). This aspect answers the question of *how behavior X of system Y in context Z is perceived at time T by stakeholder S?*.

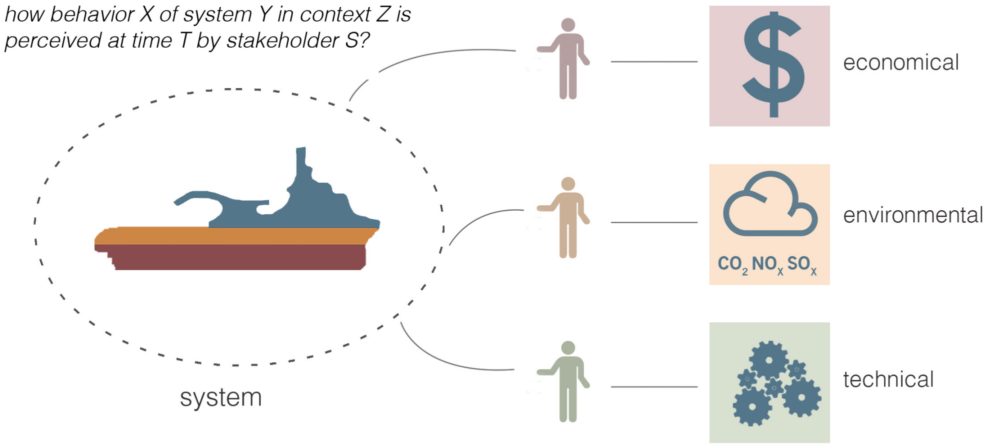

Figure 35: Perceptual Aspect.

The initial approach to handling the perceptual aspect was based strongly on the proposition discussed previously in this thesis; the traditional challenges during the conceptual ship design phase such as precise estimation of the cost of a ship or its optimum size for a given demand are insufficient to address the needs of efficient solutions for shipping in the future. One reason is that the maritime industry, like other important sectors of society, is adjusting to a bigger "claim" in which the idea of optimum design and cost cannot be considered easily in isolation. Increased attention has been given to other elements such as environmental aspects, risk awareness, and a rapidly changing commercial and regulatory environment. This proposition finds support in a compilation from Michel *et al.* [81], with an online n-gram[5] database of the English corpus containing over five million books. Although not all articles relate to engineering, the authors offer many examples of how this quantitative analysis of culture (*culturomics*) can be used as evidence for scholars in many fields, reflecting the written dynamic of society through the last century quantitatively. Figure 36 presents a plot from this database, supporting this contention, with the frequency of words *cost* and *risk* from the period 1908 through 2008. The corpus demonstrates that the general and traditional idea of cost has been dominant over the past century, to be surpassed by the idea of risk around 2000.

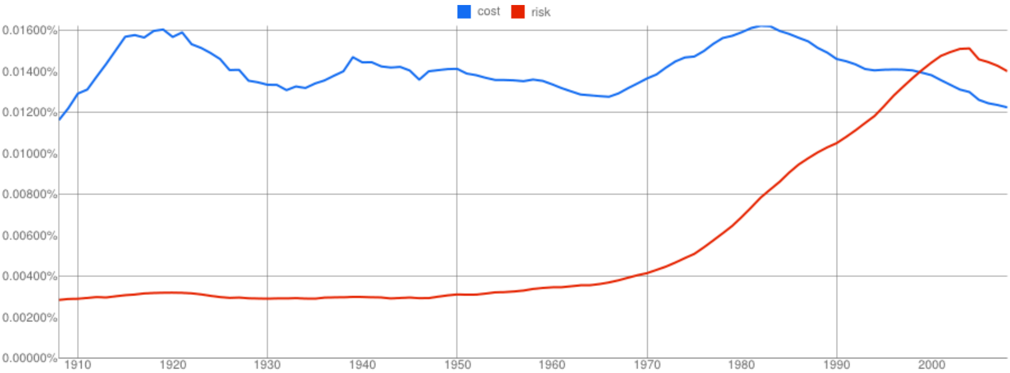

Figure 36: Frequency of words *cost* and *risk* in the English corpus from the period 1908 through 2008.

An educated guess suggests that the value of a system, as a ship, cannot consider cost (or value) purely monetarily, but incorporates the necessity to tolerate risk or, in other terms, designing a system to achieve robust value toward risks faced. This leads the focus of the research to the perception of value robustness in ship design. Value robustness is the ability of a system to continue to deliver stakeholder value in face of shifts in context and needs [95]. During ship design, this means a ship perceived successful by stakeholders. Rather than maximizing value delivered by a ship in one situation, we need to maximize it over a range of expected situations and preferences of the owner (or other constituent). This might reduce the maximum possible reward but also minimize the maximum possible loss, with relevance increasing as uncertainty grows and investors

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[5] A n-gram is a sequence of letters of any length.

become more risk-adverse. As explained by Devanney [36]: *at current and likely bunker prices, a well-designed VLCC will be operating at maximum speed only in a full scale boom, less than 10% of the ship's life. Most of the time, the ship will be operating at a percentage of full power, often much less than full power.* Stakeholders' expectations on this gain or loss, thus, can change or be constant, and those expectations (i.e., certain or uncertain) must be incorporated in design.

The challenge becomes how to incorporate these expectations since future value is uncertain. The research suggests that each previous complexity aspect includes uncertainty, varying from imprecision concerning dimensional measurement of an unforeseen, external event, influencing the entire system's lifecycle. Since complexity increases directly when the amount of information necessary to define a system increases, so do uncertainties increase (Figure 37).

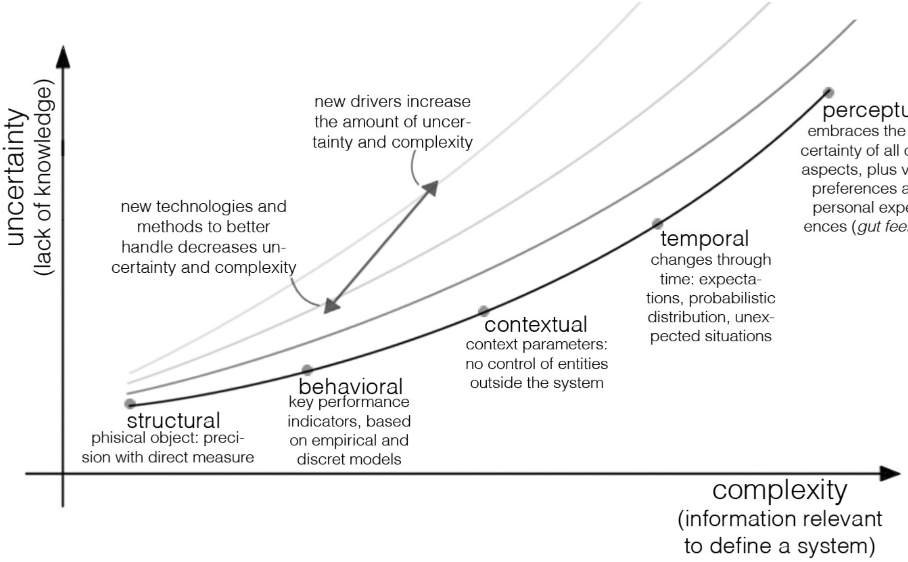


Figure 37: Illustration of the relationship between complexity and the uncertainty connected to each aspect.

Uncertainties regarding the structural aspect relate to imprecision of a system's physical characteristics. It varies from a "trivial" 50 mm difference in the size of sister ships Allures of the Sea and Oasis of the Sea [106] to a serious failure and capsizing as in the classic Liberty ships welding defects during fabrication [111]. The behavioral aspect associates with uncertainty of expected performance after a stimulus. A classic example is the inherent uncertainty in the calculation of hull resistance from Holtrop and Mennen [61] and other empirical methods, and even in new, discrete methods such as CFD and FEM assessment [100].

Entities external to the system have contextual and temporal uncertainties. They consider unexpected stimuli such as a non-planned operation, new regulation, and changes in trade, and environmental control areas (ECAs) are examples of these changes. These types of decisions affect not just the ship, but also fleet aspects. Questions that must appear during early design phases include: *How many ships need to be ECA compliant? Should new builds be made ready for a change in a future scenario, or should all adaptations costs be accepted later?* Even the whole transportation chain may be affected since the number of ships requiring refit may be minimized if the shipowner is able to alter fleet size and mix or the setup of services.

The perceptual aspect must also involve uncertainty about the perception itself (i.e., capturing the value robustness of a system) combined with accumulated uncertainty from structural, behavioral, contextual, and temporal aspects. This occurs nonlinearly since uncertainties "reinforce" each other and the appreciation of utility changes with the situation. For example, we are more inclined to accept more risk when there is little risk to start with than in an already high-risk climate [112]. Another insight (Figure 37) is the idea that new elements and technologies influence the shape of the curve, relating uncertainty and complexity. New drivers increase the complexity of the system since laws, regulations, players, and constraints are added continuously or change. However, research and development is constantly creating new technology and scientific methods to better handle this complexity. One current example is in the case of air emissions, with tighter regulations and criteria, and at the same time, an increasing set of possible solutions and improved optimization methods to select the most cost-effective strategy to comply with those regulations [15]. No matter how good the methods and technologies are, we are always left with significant residual information.

The assumption then is that the degree of robustness a system must have connects strongly to the amount of uncertainty the system will face during its lifetime. For the sake of argument, let us say that one is certain about a fact, for example, the nature of the buoyancy force. No one really believes that in a future scenario we should construct ships considering a change in this basic principle, or that we should prepare the hull for a gravitational constant two or three times bigger than the one currently in use. However, natural phenomena with significant variations such as freak waves and hurricanes are more uncertain. Thus, one needs to decide, for example, whether an offshore platform must withstand waves as large as the North Sea Draupner wave or the Gulf of Mexico's Katrina hurricane winds ([59], [70]). The same type of reasoning applies to uncertainties such as prediction of market situations, future demand, freight rates, and stakeholder preferences. When discussing complex artificial systems (i.e., artificial science), there may not necessarily be an explicit relationship between cause and effect as one observes in natural sciences, but a field of factors that, combined, leads to a probable outcome ([103], [78]). By residual we mean information that cannot be quantified, even though it is necessary to evaluate a complex system fully, inserting it in the scope of a residual category [102]. It means the information that due to reasons of ability or capacity or time constraint, must remain unknown, creating inherent uncertainty, and therefore requiring robustness.

It is possible to analyze future scenarios for the OSV case using three archetypes: positive, neutral, and negative expectations. A *positive* future connects to continued economic growth, coupled with ordering discipline from players. Emergent countries, for example, will continue to drive toward growth and creating new opportunities, and are also likely to cause continued high contract prices and strong demand. The expectation converges on higher contract prices, more customized ships, and greater supply capacities. *Neutral* expectations connect to moderate economic growth, with fluctuation in the supply/demand balance caused by over/under ordering and other offshore market occurrences. Moderate growth still means continuation of current oil and gas fields, with slow opening of new opportunities in emergent countries and stability in current European and American fields, with moderate demand. A slowdown in economic growth connects to a *negative* scenario, with emergent countries canceling current plans to expand offshore such as cessation of the opening of new, deepwater fields in Brazil. In this case, oversupply of vessels will get worse, and fuel and crew cost will be at a medium level. Weaker demand, however, will lead to low contract prices and low sailing speed.

To investigate the relationship between robustness and uncertainty, the research proposes a graph such as the one shown in Figure 38. This relationship complements Figure 4 since more uncertain scenarios require more robust systems. By diminishing residual information, one may select a less robust, more optimized system. Additional technology or research may improve the correlation between both concepts, or extend practical limits within time/cost constraints.

In theory, residual information concerning system performance can be minimized when we encapsulate, freeze, and consider all possible factors. This theoretical option of analyzing tradeoffs among many possible solutions in even more possible scenarios is, however, limited by physical memory and computational power, such as Bremmerman's limit [108]. In practice, another type of constraint influences much more: time and cost. In the real world, there is neither time nor resources sufficient to produce and analyze all imagined scenarios, even if the technology to do so is available. Decisions need to be made increasingly faster, increasing residual information and therefore risk. March ([77], [78]) calls these deadlines and commitments part of an infinite game with ourselves since we treat preferences strategically rather than absolutely. Understanding how much value robustness is required relies on understanding how much residual information associates with each complexity aspect. Traditionally, the focus of a design project is, as previously noted, on structural and behavioral aspects since they are understood well in engineering practice. Although the other three aspects are not new to engineering, we corroborate the opinions of Rhodes and Ross [92] that they have not received adequate focus given their importance to engineering value systems. It may not be wrong to state that this lack of focus relates to lack of established techniques to handle and control these other aspects, due to their high uncertainty and residual information. Not being able fully to control these elements, however, does not mean that one is unable to obtain some understand-

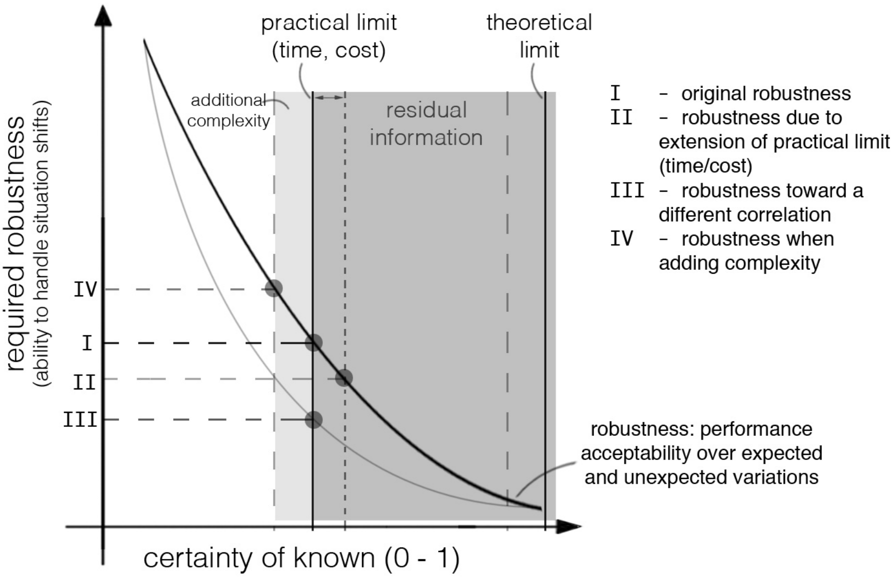


Figure 38: Illustration of the relationship between required robustness and certainty of known.

ing and cause-consequence relationship. The ambiguity of accepting residual information, hence, is not a fault but a form of intelligence ([77], [78]) that requires refinement through science and technology.

To obtain practical outcomes from this complex viewpoint, the presented ideas on value robustness and rational decision-making required translation to complex systems model methods. This is clearly a challenge, due primarily to the difficulty of decomposing and quantifying its factors. The methodology presented in the next subsection works as a proposal, intended to place handling of the five aspects under a common framework.

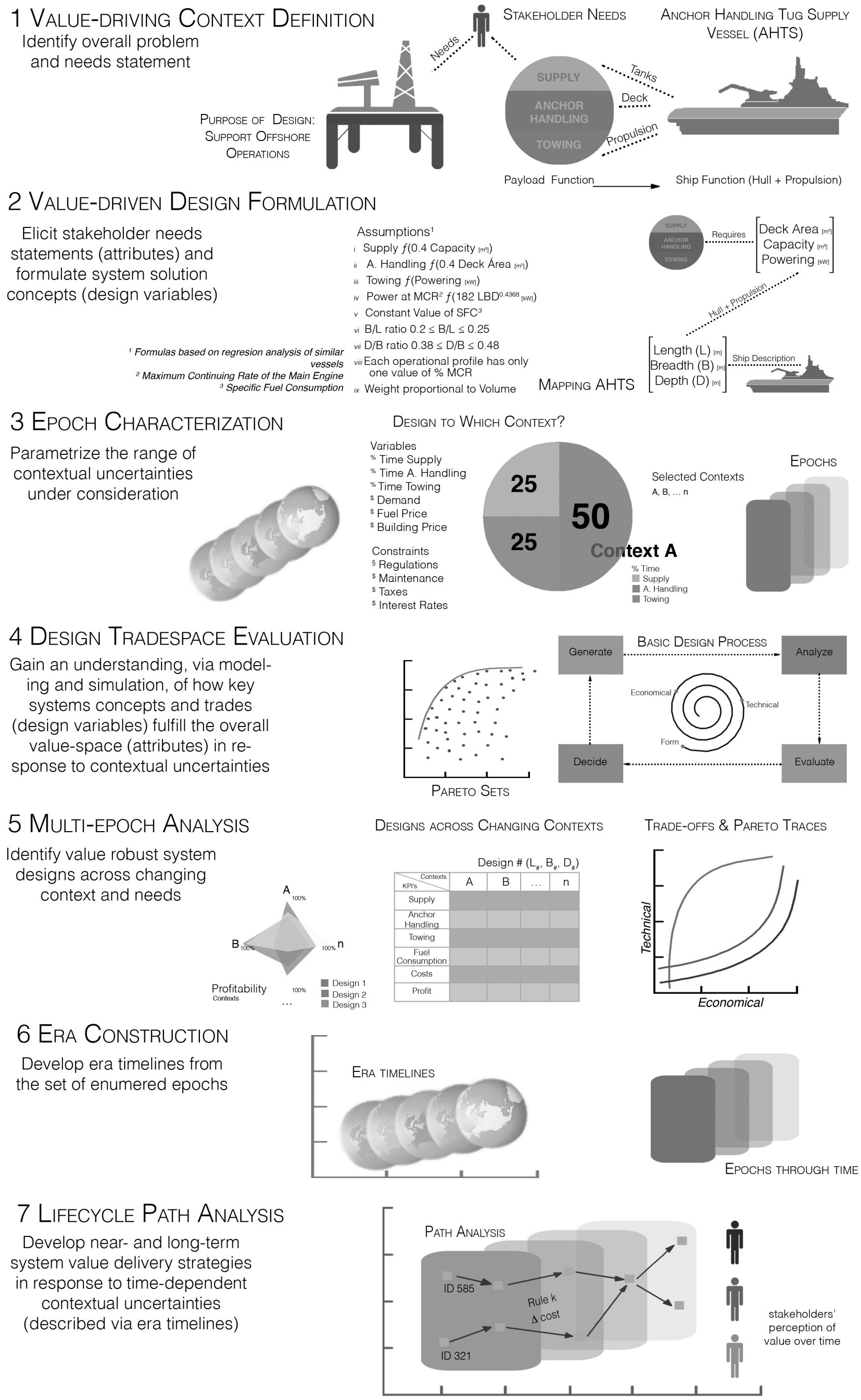
4.7 Responsive systems comparison as a method able to incorporate the five aspects

A natural step was to investigate a method that incorporates the five aspects concurrently. The responsive systems comparison method (RSC) [94] was selected among many other SE methods to address complexity aspects since the method offers a suite of techniques adaptable to a broad range of complex systems, not just a type of ship or scenario. It is not a stand-alone technique; it has the advantage merging with many traditional and novel design methods. It also accords with the SE definition of complexity, handling it by decomposing and encapsulating the information necessary to define the system.

The RSC method represents an efficient approach to the five aspects. Structural handling is conducted through decomposition of the structural aspects via discretization of design variables with a given max-min range, creating a design space. Evaluation and refinement of the design space though the processes leads to a flexible group of choices, not based on a single design point like the traditional spiral method. Performance attributes guide the design set choice, which is evaluated through a series of possible contexts, tackling the behavioral aspect. The design space evaluation process is less iterative than the traditional spiral, related more to the concurrent engineering process since all design space is evaluated for all epochs in the same phase. This allows parallel evaluation of performance attribute evaluations, making design comparisons faster. Context factors decompose during epoch characterization. Therefore, a large number of scenarios are evaluated in the following process, capturing expectations and uncertainties. A discrete context allows for manipulation of future scenario constructions through era construction, therefore dealing with the temporal aspect. Lifecycle analysis is a powerful way to evaluate the behavior of a given design set under many alternative future scenarios. The method also has the advantage of considering multiple stakeholder perceptions. It begins with defining what is valuable and proposing a utility range in the attributes able to grade designs according to a performance attribute value. The attributes are also normalized under a common utility metric, facilitating solution comparisons and tradeoffs. It allows a customized selection of the design set toward specific decision-maker preferences.

Part of the current research focuses on understanding, implementing, and developing the RSC method toward conceptual ship design scenarios. This led to adaptation of Ross and Rhodes' flowchart for the process shown in Figure 39.

The value-drive context is the first step, capturing the overall problem statement. It consists of selecting the value proposition for a design, key constraints, and context and stakeholders to be considered. This process filters information, establishing expected results for a design to be value robust under stakeholder perceptions. This information links to the perceptual aspect, and must be gathered into an efficient statement of the problem to define and evaluate the designed system. Summarily for the AHTS case, it means a ship performing its mission efficiently, comprised of supply, anchor handling, and towing tasks. This process influences strongly the definition of what is a value robust



1 VALUE-DRIVING CONTEXT DEFINITION
Identify overall problem and needs statement

2 VALUE-DRIVEN DESIGN FORMULATION
Elicit stakeholder needs statements (attributes) and formulate system solution concepts (design variables)

Assumptions[1]
i Supply ƒ(0.4 Capacity $_{[m^3]}$)
ii A. Handling ƒ(0.4 Deck Área $_{[m^2]}$)
iii Towing ƒ(Powering $_{[kW]}$)
iv Power at MCR[2] ƒ(182 $LBD^{0.4368}$ $_{[kW]}$)
v Constant Value of SFC[3]
vi B/L ratio $0.2 \leq B/L \leq 0.25$
vii D/B ratio $0.38 \leq D/B \leq 0.48$
viii Each operational profile has only one value of % MCR
ix Weight proportional to Volume

[1] Formulas based on regresion analysis of similar vessels
[2] Maximum Continuing Rate of the Main Engine
[3] Specific Fuel Consumption

3 EPOCH CHARACTERIZATION
Parametrize the range of contextual uncertainties under consideration

4 DESIGN TRADESPACE EVALUATION
Gain an understanding, via modeling and simulation, of how key systems concepts and trades (design variables) fulfill the overall value-space (attributes) in response to contextual uncertainties

5 MULTI-EPOCH ANALYSIS
Identify value robust system designs across changing context and needs

6 ERA CONSTRUCTION
Develop era timelines from the set of enumered epochs

7 LIFECYCLE PATH ANALYSIS
Develop near- and long-term system value delivery strategies in response to time-dependent contextual uncertainties (described via era timelines)

Figure 39: Responsive systems comparison method applied to the design of offshore support vessels.

design, that is, *what* is the problem, *why* it is important, *who* cares about it, and *which* types of value are required for a solution to be satisfactory over its lifespan.

The second step consists of the value-driving design formulation in which needs and requirements are expressed as objectives. It includes decomposition of the mission of the ship, design assumptions, and the primary performance attributes to achieve these goals. The process contains two parts: first, the quantification of performance attributes, with a range of minimum/maximum values based on stakeholder preferences. The attribute performance reflects the behavioral aspect, and the definition of acceptability, that is, acceptance ranges of the attributes along with utility function, as perceptual. The second part is generation and proposition of the concepts and associated design variables. Those variables are the decomposition of the structural aspect, which will drive stakeholder-expressed attributes.

Epoch characterization follows, dealing with potential contexts in which a ship will be inserted. It includes operational variables such as percentage in time supplying, anchor handling, and towing, and external constraints such as regulations and market fluctuations. Discussed in Section 4.4, it considers contextual information and transforms these into parameters to describe not only a fixed context (e.g., a snapshot of the present situation) but also alternative, potential contexts resulting from shifts and uncertainties. The interval of time within a fixed set of contextual factors, that is, a vector of epoch variables, is encapsulated in an *epoch.* A potential *epoch space* is defined at the end of this process, with enumeration of many possible epochs to create a set of contexts. Each epoch encapsulates a fixed context, that is, a *snapshot* of a certain period in which the epoch variables will not shift.

The fourth step, design tradespace evaluation, is a process in which many design alternatives in each selected epoch are evaluated in terms of (performance) attributes, utilities, and costs of each design. It means applying the basic design process to a ship, evaluating its behavior for each scenario. Many computer tools are available on the market to calculate primary attributes given a range of design variables, based on regression analysis, analytical and discrete models, etc. Optimization methods can also be applied. The main function of this process is decomposition of the behavioral aspect, offering understanding of the design space. Evaluation of the design space converges (i.e., encapsulate/filter) into a set of selected designs (e.g., via Pareto set). After evaluation, the product is a large amount of data, the analysis of which is conducted in the following processes.

Multi-epoch analysis begins the process of organizing data obtained from process (4). This produces a large number of ship design descriptions, organized by common metrics, the utilities and costs defined in process (2). Selection of designs that will be part of the next process can be done in many ways. The temporal aspect is decomposed into epochs, and it is possible to evaluate the design space behavior in each of these epochs, for example, comparing how ships *A, B,* and *C* will behave in scenarios *X, Y,* and *Z*, ranking and quantifying the result. Evaluation of the design across these epochs contributes to filtering or classification of the most robust designs, considering probabilistic distribution, stakeholder preferences, and extensive epoch space searches.

Era construction, the sixth step, is the phase in which to develop timelines based on the epochs. They connect to the expectation discussed in Section 4.6, with general archetypes positive, neutral, and negative. Various potential eras will be generated during era construction, which results in a group of eras arranged in a way that represents potential lifetimes (eras) the AHTS may face. This process promotes understanding of the impact of time-dependency within selected lifespan scenarios for potential designs, including time sequences of such point scenarios as high expected demand, followed by a crisis, followed by changes in regulations or emergence of new technologies.

The last process, lifecycle path analysis deals with strategies to sustain the value of designs across potential eras. Lifecycle path analysis allows for an understanding of the cost of modifications that designs possess to perform better when a shift in one of the epochs in an era occurs, such as CAPEX/OPEX analysis of installing a new capability [15]. This process answers two questions: *Which modifications do the designs need to perform better within a given era? and What are the costs and benefits of these changes?*

The conclusion is that the RSC method accords with the current aim of this research for a new method to handle complexity in the early stages of design. For example, the tradespace evaluation process shares some characteristics from the set-based design [105] to deal with structural and behavioral aspects such as establishment of feasibility before commitment, keeping *good solutions* to evolve in parallel instead of remaining with a single point. Fuller appreciation of the RSC method is possible through handling of the contextual, temporal, and perceptual aspects. The multi-epoch and era analysis allows for the modeling of uncertainties, handling the contextual aspect and evaluating many contexts at the same phase of design. The temporal aspect appears in these processes, including changes to the context over time, and creating tradeoffs among designs under varying scenarios. Lifecycle path analysis proposes strategies to adapt designs to perform better across unfolding era uncertainties. The perceptual aspect is exploited by use of *What-If* situations, through era construction and lifecycle analysis. It means not just one design is evaluated, but a design set, comparing each solution for each of the envisioned scenarios.

5 Discussion of Contributions

5.1 Main research contributions

This section compiles the contributions of the research to the state of the art, presented in two parts. First is an overview of the research contributions, connected to research questions and results. Second is an analysis of the contributions from each paper, more connected to the gaps regarding the state of the art.

The four primary contributions of the thesis to extant conceptual ship design engineering literature are summarized as a cascade of factors: characterization of conceptual ship design as a complex systems engineering task; decomposition and encapsulation as a general principle to handle complexity during the conceptual phase of ship design; categorization of the conceptual ship design task through a five-aspect taxonomy; and development and improvement of methods to handle the five aspects. Regarding handling of each aspect, a subset of four contributions includes: investigation of structural and behavioral aspects, merging traditional and novel techniques; using epoch-era analysis and a ship design deployment problem to handle contextual and temporal aspects; using complex value robustness to handle the perceptual aspect; and integrating and assessing concurrently all five aspects in a theoretical framework through a responsive systems comparison method (Figure 40).

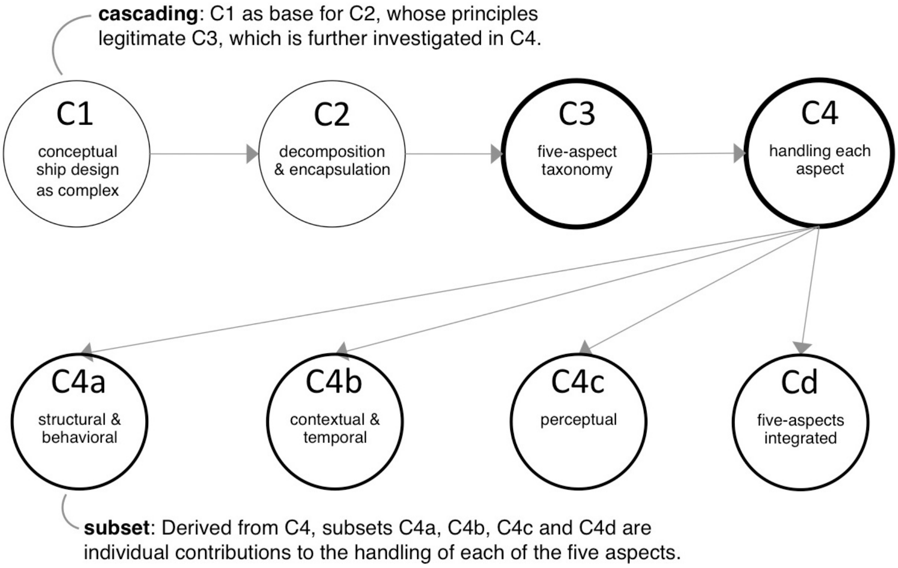


Figure 40: Thesis' contributions.

The ship design as systems engineering is a well-accepted concept, but incorporation of complex systems engineering methods (C1) lays the foundation for dealing with the type of not well-understood information discussed in the background. The first contribution is necessary as a reinforcement of the statement that conceptual ship design is a complex systems engineering problem. Although not the strongest contribution of the research, this statement is necessary to avoid an oversimplified notion of a ship, neglecting important information that should be considered. This thesis exemplified this oversimplification by the traditional assumption of designing a ship for a small set of operational profiles, without considering the contextual, temporal, and perceptual aspects. The danger is simplifying a design procedure in a way that the final option appears optimal or efficient enough when it is not.

The following contribution (C2) filters many design approaches into two fundamental patterns to handle complexity. Characterizing ship design as a complex system problem led to recognition of many facets the meaning of complexity may have, and selection of a definition based on the amount of relevant information naturally conducted the research toward a search for a general approach to handle complexity in the conceptual phase of ship design. This work presented a search for a high-level pattern found in many of the scientific techniques that deal with complex systems. Herbert Simon [101], Eisner [39], Gamma *et al.* [50], Suh [109] and Kolmogorov's definition of complexity [71] influenced this approach strongly. It may not be considered a strong contribution for the same reason that much work in the field of systems engineering has been done. However, it is necessary because it lays the foundation for the next contributions, stating that a simple but strong couple of concepts can be powerful when handling complexity. As argued by Simon and others, the architecture of complex systems relies on its hierarchization, and therefore proper decomposition of factors. However, the obvious approach to handle complexity is to simplify, requiring good encapsulation of what kind of information is received as input and delivered as output. This general process is common in most design procedures for complex systems, and it is not wrong to affirm that hierarchization is an accepted approach. This contribution leads to the definition of efficient hierarchization, decomposing all relevant information and encapsulating it into relevant aspects.

Use of a five-aspect taxonomy to address the problem of incorporating other kinds of information during the conceptual phase of design is one of the principal contributions of the research (C3). It demonstrates that the five-aspect taxonomy is an intelligent encapsulation of the relevant factors that should be incorporated during ship design, useful, for example, when applied to the original problem of a ship facing multiple operational profiles in its lifetime. This categorization required the original work of organizing the current literature into the five aspects and decomposing information gathered from the literature, classifying it into each aspect. It provided an overview of the literature under the five-aspect taxonomy to understand what can be adapted and what needs to be developed to make proper use of the taxonomy. Given the taxonomy's novelty, application of this framework into a complex system is a contribution per se since no previous examples have been made in such detail. Application of methods such as EEA and RSC find examples in aerospace research, but no explicit merging of the five-aspect framework and methods were published prior to the date of the articles in this thesis. It works toward consensus-building of proposing an *intelligent* way to classify the type of information that is not always included in the traditional *tender specification*, or *shipowner requirement*, incorporating, for example, new regulatory constraints into contextual aspect or the broad range of possible future operational profiles into the temporal aspect.

Use of the taxonomy is a foundation for handling complexity aspects (C4), the central contribution of this thesis. Based on the taxonomy, this research examined how each of the aspects could be handled. It led to development and implementation of design support tools able to analyze a large amount of information, extracting knowledge from each aspect, such as EEA, SDDP, and RSC.

Structural and behavioral aspects are covered broadly in extant literature, having a higher level of management and understanding when compared to the other three aspects. Therefore, this contribution is divided in four sub-contributions, demonstrating that the method is valid and useful to handle not only tradition structural and behavioral (C4a) aspects, but especially the definition of what is defined as contextual, temporal (C4b), and perceptual (C4c) in maritime design, and how the five aspects can be integrated into a single framework (C4d). The primary contribution is not the final word on one method or another, but more fundamentally, offers first a set of tools that are efficient when combined and are able to handle these aspects in a single framework. Use of RSC or EEA does not lead to a definitive or closed methodology, and the ideas behind this thesis can be extended to handle even more complicated situations. The objective was to present a design procedure able to handle the five aspects, gaining understanding of the complexity inherent to the system and producing better designs.

5.2 Contributions of the Papers to the State of the Art

The first paper, *Handling Temporal Aspects of Complexity in the Design of Non-Transport Ships*, presents an introduction to the five-aspect taxonomy, focusing on temporal changes over contextual factors. Contextual and temporal aspects are considered new or extended aspects of analysis, that is, they are present in the traditional techniques but usually given insufficient attention to address the importance of their characteristics. The methodology to handle it is based on the original combination of EEA and SDDP. This was the first application of EEA in the maritime field, requiring development of *epoch variables* for the ship case, how to define an epoch properly, and what aspects of the lifecycle of a ship should be considered when creating an era. The work clarifies early assessment of profitability by evaluating performance of design under seasonal contract variation, based on probabilistic distribution for future contracts.

Addressing Complexity Aspects in Conceptual Ship Design, the second paper, presents conceptual ship design as a complex systems engineering problem, describing in detail what each aspect mean, and how they are decomposed and evaluated for the ship case. Accepting complex systems engineering thinking means to incorporate features external to the traditional design process in the design environment, setting a design space, and consequently a model able to produce a final set of possible solutions that can be evaluated under the variations of these external factors such as multiple operational profiles and changes in the current market structure. This work was the first of its kind to apply the five-aspect taxonomy in a practical engineering domain, with the nominal enumeration of information connected to each aspect. It also contributes in a structured way to incorporate more relevant information in conceptual design since decomposition and encapsulation of factors led to simpler understanding of what is relevant. The work proposes a general approach to handling the complexity aspects of maritime design, merging innovative and traditional techniques. The technological advancements contained in such research take two paths. The first advancement is extension of the ship design scope. This work calls for an understanding of the importance of the extended aspects of conceptual ship design (i.e., contextual, temporal, and perceptual). The other advancement is in the form of a collection of techniques and methodologies that handle these five complexity aspects as a whole, integrating analyses in the conceptual design stage, which can then be readily used in the marine industry. This permits efficient assessment of the evaluation criteria of ship design during the conceptual phase.

The third study, *Assessing Air Emissions for Uncertain Lifecycle Scenarios via Responsive Systems Comparison Method*, applies the methodology developed in the previous two papers toward problems tackled in the initial part of the research. The paper extends the proposed methodology to another level of the system since the structure now is the subsystem of a ship (machinery), and behavior focuses on environmental performance. The paper presents the ship lifecycle air emission assessment for uncertain operational scenarios, using the RSC method. To my knowledge, this is the first work to assess lifecycle air emission from the machinery configuration viewpoint, using ship operational profile as the primary input to create future scenarios. This study should be of interest to broad readership, including those interested in the air emission lifecycle, complex systems engineering methods, efficient machinery design during early stages, and air emission controls.

The perceptual aspect and the multi-dimensional notion of value are studied in *On Perception of a Ship: Designing for Complex Value Robustness*, the fourth paper. Although value is a necessary topic to be included in any type of conceptual ship design assessment, this paper introduces the notion of *value robustness* to the maritime field from the complex systems engineering view. It proposes that value is obtained when we understand which elements are important when perceiving the *goodness* of a ship. Traditional driving factors such as cost and value for money are augmented by additional ones such as environmental issues and increasing risks associated with a rapidly changing commercial and regulatory environment. This paper proposes how these new elements should be incorporated in the perception of a *value robust ship*. The paper proposes mitigation of uncertainties for each aspect as a critical factor to obtain good perception and therefore value over the lifecycle of the ship. The study also contributes to the idea of the meaning of a simple perception. If we handle complexity through simplicity, it is important to understand that simplicity relates normally to encapsulation of the system rather than simplification of it. A simple way to perceive the good solution connects rarely to a simple approach to the solution. One might wish the real world were simple, but since it is not, it is a mistake to neglect complexity during decision-making.

The last paper, *Handling Complexity Aspects in Conceptual Ship Design*, was planned as an application of the literature review. Much of its results are incorporated in this thesis, and its contribution relies on the realization that using the five-aspect taxonomy allows one to incorporate method and thinking currently in use by the literature. This work's contribution to the literature also reinforces the idea of ship design as a complex systems engineering task, adapting complex systems engineering thinking to the conceptual ship design problem. It includes placement of the ship as a complex system, and presents similarities between traditional ship design and systems engineering methods.

Maritime is a mature field and so requires the consensus we find in other fields such as hydrodynamic [8]. This chapter demonstrates that the five-aspect taxonomy is a valid option for handling complexity in conceptual ship design. Although absolute consensus is far from reality regarding *how to best design a ship*, an important result of the research is the level of debate and attention that it received, exemplified by a discussion published in RINA and SNAME Transactions (Paper 1 and Paper 2). Based on that review, the research found consensus in presenting itself as a valid option when dealing with these recent trends and needs from the market such as multiple operational profiles and multi-stakeholder perceptions of value. A valid criticism is found in the unclear distinction between product (ship) and process (design), given the blurred distinction between each aspect that should focus on the structure of the ship, and therefore the product, and on the mapping between context parameters and ship performance, related to process.

A legitimate taxonomy, however, does not mean that the five-aspects and the methods connected to them are the best way to decompose and encapsulate relevant information on ship design, and I conclude that more research is required, especially concerning the most abstract and therefore neglected aspect: the perception of good design. The fourth paper presents some glimpses of what should be considered when discussing value-robust design, but much work is required to define and evaluate it.

5.3 Research Questions, Papers, and Contributions

Three research questions drove this thesis (Figure 5):

RQ1: Which general complex systems theory premises can be used to define complexity in conceptual ship design?

RQ2: What general principles for organizing and simplifying complexity fit the conceptual ship design task?

RQ3: what methods efficiently handle primary complexity aspects during conceptual ship design?

Table 6 presents the connection between the papers with the research questions and contributions (Figure 40) discussed previously.

Table 6: Relations between research question and papers

Research Question	**Contribution**	**Papers**
RQ1	C1	P2, P5, Thesis
RQ2	C2	P5, Thesis
RQ3	C3, C4	All Papers and Thesis
	C4a	P2, P5, Thesis
	C4b	P1
	C4c	P4
	C4d	P2, P3

6 Concluding Remarks and Future Work

This thesis presents an assessment of conceptual ship design as a complex systems problem, focusing on its primary aspects. An important part of quality assurance for this research was based on peer review through publication in international journals and conference proceedings. A portion of the research was conducted internationally in collaboration with MIT. The core contributions of this thesis do not rely on linear problem solving, neither can it be called a problem-driven thesis. It was knowledge-driven, with the intention of leveraging extant knowledge required to design a ship conceptually since current literature is unclear or contains conflicting opinions on how to deal with factors I classify in this thesis as contextual, temporal, and perceptual. The path may not have been perfect, but it presents a direction in which more studies should be conducted. I believe the five-aspect taxonomy is a useful way to classify complex systems, and the techniques presented provide an efficient way to handle complexity aspects for the ship design case. I defend a *divide-and-conquer* approach to handling the five aspects, based on decomposition and encapsulation of information.

Traditional ship design approaches link form/function to the basic design process and therefore thoroughly address the structural and behavioral aspects of conceptual ship design. The five-aspect taxonomy, encompassing the three extended aspects sometimes neglected during the conceptual phase, presents a significant modification to traditional ship design approaches. Externalities that affect a ship are considered in the contextual aspect. Uncertainties toward context parameters and future scenarios associated with the temporal complexity, which a society with rapidly shifting markets and uncertainty about the health of major economies and forthcoming regulations generally requires. The perceptual aspect relates to the perspective from which system stakeholders interpret and understand how the ship is interpreted, embracing not only perception regarding factual information from all other aspects, but also an abstract notion of value exhibited by individual decision-maker.

The complex systems approach requires decomposition and encapsulation of the design problem to manage and handle complexities. Since it is not always possible to reduce complexity, that is, to reduce required information to define a good system, the objective of the design process becomes controlling current information and reducing a portion of the information that cannot be handled easily. This residual part, the *gut feeling*, may never be controlled completely, but extension of the aspects at least offers more understanding of uncertainties.

Contributions of this thesis also respond to current calls for new methods to handle complexity in the early stages of design, for example, the RSC method. In it, the tradespace evaluation process shares some characteristics with set-based design [105] to deal with structural and behavioral aspects such as establishment of feasibility before commitment, keeping good solutions to evolve in parallel instead of holding on to a single point. Both methods use low computational cost tests to prove infeasibility or identify Pareto dominance. The examples in the papers, using OSVs, are simple implementations of the method since the structural/behavioral aspects are handled primarily with regression analysis. An extension of the method would be use of simulation, for example, computational fluid dynamics (CFD), to improve energy efficiency evaluation [60], or use of modularization as building elements ([6], [45]), with a design space constructed from possible interactions of the modules.

This thesis main contributions is through its handling of contextual, temporal, and perceptual aspects. The multi-epoch and era analysis, for example, models uncertainties, handling the contextual aspect and evaluating many contexts at the same phase of the design process. The temporal aspect is also handled, including changes in context over time, and creating tradeoffs among designs under various scenarios. The lifecycle path analysis also proposes strategies to adapt designs to perform better across unfolding era uncertainties. The perceptual aspect is exploited by use of *What-If* situations through era construction and lifecycle analysis. Not just one design is evaluated, but a design set, comparing each solution with each envisioned scenario.

This work concludes that complex systems theory provides an efficient way to handle complexity aspects in the conceptual phase of ship design. The discretization of the system into five aspects and use of an overall method to address all aspects such as RSC advances the current ship design task, allowing use and integration of novel and well-established techniques. Use of an overall method to address all aspects is a benefit for current ship design, allowing merging of novel and traditional techniques.

Since this work classifies ship design from a complexity viewpoint, there is much more potential work to be developed. Measuring complexity will continue to grow as ship design becomes increasingly complex. Many of the proposals observed in the literature measure the amount of complexity during early stages of design, considering only the structural part, usually measuring a ship by its number of components and connections. Although this analysis offers interesting insights, it does not consider other important aspects when discussing complexity, and measurement of all perspectives of a concept as abstract as complexity is a respectable challenge. Future research should explore use of information theory, breaking information into bits to measure it. It is clear that this approach works better in digital form than in large physical systems such as ships, but the fact that most of the conceptual ship design information nowadays is found in digital form, via computational modules/components libraries and performance analysis, it opens space for this kind of investigation.

Merging techniques offers an additional avenue for future research. Much of this thesis was based on combining novel techniques such as EEA, SDDP, and RSC with traditional approaches such as system-based ship design. More can be developed for analysis of conceptual ship design, for example, use of optimization tools, stochastic analysis, and other design methodologies.

Adaptation of the methodology might allow future researchers to use this work's methodology during the entire ship design value chain, especially in relation to modularity. Combining the building block approach during the general arrangement phase [6], or choice of machinery configuration, might respond well to this methodology. The methods discussed here might apply to the operational phase to estimate behavior of a system given unpredicted changes in the context. Future researchers should also study how the complex systems engineering approach considers several system quality attributes, called *ilities*, during conceptual ship design. Each accords with the complex systems approach and applies to the ship design case, such as adaptability, reliability, survivability, and modularity. Future research should explore discrete analysis in the conceptual phase. This work presents only a beginning. For example, it would be interesting to merge a technique such as RSC with a CFD or finite element method. Data analysis presents another area for future research. A complex design process naturally generates a large amount of data. Proper handling of this data is a beneficial extension of this work. Response surface methodology, for example, appears to be an efficient way to handle the large amount of data obtained during epoch-era analysis. More research is also needed to understand the relationship between the five aspects and the human factor as an aspect of complexity. Although the human as a system interacting with the ship fits the structural aspect well, for example, the operator as part of the structural system, it also plays an important role in the perceptual aspect since the user is also an important stakeholder. Similarly, incorporation of the perceptual aspect into early stages opens space for deeper study of the intricate and subjective process of decision-making, for example, behavioral science, used strongly in economic decision-making as a model to estimate decisions from various stakeholders' profiles under uncertainty.

Finally, future researchers should apply development of engineering methodologies provided in this paper to industry. Stakeholders agree there exists a gap between this type of research and usefulness in industry, even more so in the case of industries with strong domain traditions such as maritime. The five-aspect taxonomy can be incorporated into other activities from the ship design value-chain, beyond the conceptual phase. For instance, the consideration of the emergent factors (Figure 2) and stakeholders' expectations (Figure 35) during design of modules and subsystems, detailed engineering, construction and operation.

References

[1] Alexiou, K., Johnson, J., and Zamenopoulos, T. Embracing complexity in design. *Routledge - New York* (2010).

[2] Andrews, D. An integrated approach to ship synthesis. *Transactions of RINA 128* (1986), 73–102.

[3] Andrews, D. Preliminary warship design. *Transactions of RINA 136* (1994), 37–55.

[4] Andrews, D. Design methodology. *in State of Art Reports, 6th International Maritime Design Conference - IMDC* (1997).

[5] Andrews, D. A comprehensive methodology for the design of ships (and other complex systems). *Proc. R. Soc. Lond. A 454* (1998), 187–211.

[6] Andrews, D. A creative approach to ship architecture. *International Journal of Maritime Engineering* (2003).

[7] Andrews, D. Design methodology. *in State of Art Reports, 10th International Maritime Design Conference - IMDC, Trondheim* (2009).

[8] Andrews, D. Is marine design now a mature discipline? *International Maritime Design Conference - Glasgow* (2012).

[9] Andrews, D., and et al. Design methodology. *in State of Art Reports, 9th International Maritime Design Conference - IMDC* (2006).

[10] Andrews, D., and Pawling, R. The impact of simulation on preliminary ship design. *IMDC Trondheim* (2009).

[11] Andrews, D. J. Marine design: requirement elucidation rather tahn requirement engineering. *IMDC Athens* (2003).

[12] Andrews, D. J. Simulation and the design building block approach in the design of ships and other complex systems. *Proc. R. Soc. Lond. A 462* (2006).

[13] Andrews, D. J. Art and science in the design of physically large and complex systems. *Proc. R. Soc. A published ahead of print December 7, 2011, doi:10.1098/rspa.2011.0590* (2011).

[14] Andrews, D. J. Marine requirements elucidation and the nature of preliminary ship design. *Transactions of RINA 153* (2011), 23–39.

[15] Balland, O., Erikstad, S. O., and Fagerholt, K. Optimized selection of air emission controls for vessels. *Maritime Policy and Management 39*, 4 (2012).

[16] Balland, O., Solem, S., Hagen, A., and Erikstad, S. O. A decision support framework for the concurrent selection of multiple air emission controls. *9th Inter-*

national Conference on Computer and IT Applications in the Maritime Industries - COMPIT (2010).

[17] Balland, O., Ste, Kj, and Wallace, S. W. Planning vessel air emission regulations compliance under uncertainty. *Journal of Marine Science and Technology Feb.* (2013), 1–9.

[18] Ben-Ari, G., and Chao, P. A. Organizing for a complex world: Developing tomorrow's defense and net-centric systems. *Center for Strategic and International Studies - CSIS* (2009).

[19] Benford, H. On the rational selection of ship size. *Society of Naval Architects and Marine Engineers* (1967).

[20] Bertram, V., Fach, K., Sames, P., and Hoppne, V. Engineering options to reduce emissions. *10th International Maritime Design Conference - IMDC, Trondheim* (2009).

[21] Bertram, V., and Thiart, G. D. Simulation-based ship design. *Oceans - Europe* (2005).

[22] Bodénes, G. Bourbon into the future. *Norwegian Maritime Centre of Expertise NCE Annual Conference, Ålesund,* (2013).

[23] Braha, D., Minai, A. A., and Bar-Yam, Y. Complex engineered systems. *Springer - NECSI, Cambridge* (2006).

[24] Brown, A., Brown, B. H. A., Brown, B. H. A., Brown, B. H. A., and Haugene, B. Assessing the impact of management and organizational factors on the risk of tanker grounding. *8th International Offshore and Polar Engineering Conference - ISOPE* (1998).

[25] Buxton, I. L. Engineering economics and ship design. *British Ship Research Association* (1976).

[26] Buxton, I. L. Engineering economics and ship design. *British Maritime Technology* (1987).

[27] Buxton, I. L. Design for operation. *in State of Art Reports, 6th International Maritime Design Conference - IMDC* (1997).

[28] Cabezas-Basurkoa, O., Mesbahia, E., and Moloneya, S. R. Methodology for sustainability analysis of ships. *Ships and Offshore Structures 3*, 1 (2008).

[29] Caprace, J.-D. Cost effectiveness and complexity assessment in ship design within a concurrent engineering and "design for x" framework. *Universite de Liege* (2010).

[30] Caprace, J.-D., and Rigo, P. Ship complexity assessment at the concept design stage. *Journal of Marine Science and Technology 16* (2011).

[31] CCM. Overview of the offshore supply vessel industry. *Marine Money International Clarkson Capital Market - May 2012, http://www.marinemoney.com/* (2012).

[32] Corbett, and Chapman. An environmental decision framework applied to engine control technologies. *Journal of the Air and Waste Management Association* (2006).

[33] Coyne, R. D., Rosenman, M. A., Radford, A. D., Balachandran, M., and Gero, J. S. Knowledge-based design systems. *University of Sydney* (1990).

[34] Cuesta, E. F., Grimstad, A., and Hagen, A. Integrating a maritime transport chain perspective into ship design. *8th International Conference on Computer and IT Applications in the Maritime Industries* (2009).

[35] Dahl, H. J. Systems engineering course - lecture notes. *NTNU* (2009).

[36] Devanney, J. Detailed studies of the impact of eedi on vlcc design and co2 emissions. *Center for Tankship Excellence, Tvaernier, Florida.* (2010).

[37] DNV. Environmental performance... an urgent challenge. *Det Norsk Veritas - DNV* (2010).

[38] Eide, M. S., Endresen, O., Skjong, R., Longva, T., and Alvik, S. Cost-effectiveness assessment of co2 reducing measures in shipping. *Journal of Maritime Policy and Management* (2009).

[39] Eisner, H. Managing complex systems: Thinking outside the box. *Wiley Interscience* (2005).

[40] ENTEC. Service contract on ship emissions: Assignment, abatement and market-based instruments. *European Commission Directorate General Environment* (2005).

[41] Erichsen, S. Management of marine design. *Butterwords* (1989).

[42] Erikstad, S. O. A decision support model for preliminary ship design. *PhD thesis, NTNU* (1996).

[43] Erikstad, S. O. Efficient exploitation of existing corporate knowledge in conceptual ship design. *Ship Technology Research, vol. 54* (2007).

[44] Erikstad, S. O. Ship-4c - competence project for conceptual design methods for complex, customized ship. *NTNU - Project Description* (2007).

[45] Erikstad, S. O. Modularisation in shipbuilding and modular production. *Innovation in Global Maritime Production* (2009).

[46] Erikstad, S. O., and Levander, K. System based design of offshore support vessels. *International Maritime Design Conference - Glasgow* (2012).

[47] Erikstad, S. O., Solem, S., and Fagerholt, K. A ship design and deployment model for non-transport vessels. *Ship Technology Research 58*, 3 (2011).

[48] Evans, J. H. Basic design concepts. *A. S. N. E. Journal* (1959).

[49] Fet, A. M. Sustainability reporting in shipping. *Journal of Marine Design and Operations* (2003).

[50] Gamma, E., Helm, R., Johnson, R., and Vlissides, J. Design patters: Elements of reusable object-oriented software. *Addison-Wesley Publishing Company* (1994).

[51] Gaspar, H. M., and Balland, O. Approaching environmental performance in conceptual ship design. *PRADS - Rio de Janeiro* (2010).

[52] Gaspar, H. M., and Erikstad, S. O. Extending the energy efficiency design index to handle non-transport vessels. *8th International Conference on Computer and IT Applications in the Maritime Industries, COMPIT - Budapest* (2009).

[53] Gaspar, H. M., Neumann-Larsen, E., Grimstad, A., and Erikstad, S. O. Efficient design of advanced machinery systems for complex operational profiles. *9th International Conference on Computer and IT Applications in the Maritime Industries - COMPIT* (2010).

[54] Gray, A. W., Daniels, A. S., and Singer, D. J. Impacts of fuzzy logic modeling for constraints optimization. *Naval Engineers Journal 122* (2010).

[55] Gualeni, P., and Dazzy, N. Naval architecture and systems engineering: a deal for naval ship design evolution. *IJME Rina A 151* (2009).

[56] Hagen, A. The framework of a design process language. *PhD thesis, NTH (NTNU)* (1993).

[57] Hagen, A., and Grimstad, A. The extension of system boundaries in ship design. *Transactions of RINA, vol. 152* (2010).

[58] Hastings, D., and McManus, H. A framework for understanding uncertainty and its mitigation and explotation in complex systems. *Engineering Management Review, IEEE 34*, 3 (2006).

[59] Haver, S. Freak wave evenet at draupner jacket januar. *Statoil, PTT-KU-MA* (2004).

[60] Hochkirch, K., and Bertram, V. Slow steaming bulbous bow optimization for a large containership. *8th International Conference on Computer and IT Applications in the Maritime Industries* (2008).

[61] Holtrop, J., and Mennen, G. G. An approximate power prediction method. *Int. Shipbuild. Progress 29* (1982).

[62] Hubka, V., and Eder, W. E. Theory of technical systems: A total concept theory for engineering design. *Springer-Verlag* (1988).

[63] IMO, M. Imo's work on the reduction of greenhouse gas emission from ships. *Pre Oslo Summary - 58th Session of the Marine Environment Protection Committee - IMO* (2008).

[64] IMO, M. Prevention of air pollution from ships - new ship design co2, submitted by finland and sweden. *58th Session of the Marine Environment Protection Committee - IMO* (2008).

[65] IMO, M. Prevention of air pollution from ships. *59th Session of the Marine Environment Protection Committee - IMO* (2009).

[66] INCOSE. Systems engineering handbook v3.1. *INCOSE* (2007).

[67] Insensee, J., and Bertram, V. Quantifying external costs of emissions due to ship operation. *Journal of Engineering for the Maritime Environment* (2004).

[68] Johnsen, T. A. V., Holte, E., and Aastad, P. Maritime fleet planning - a domain model. *Ship4C Report* (2009).

[69] Journal, M. Far samson' breaks bollard pull records. *Maritime Journal http://www.maritimejournal.com/* (2009).

[70] Kliewer, G. Hurricane lessons bring new rules, floating system designs. *Offshore Magazine 69*, 6 (2007).

[71] Kolmogorov, A. N. Combinatorial foundations of information theory and the calculus of probabilities. *Russian Math. Surveys, 38:4* (1983).

[72] Konovessis, D., and Vassalos, D. Risk evaluation for ropax vessels. *Journal of Engineering for the Maritime Environment* (2008).

[73] Lamb, T. A ship design procedure. *Marine Technology*, 362-405 (1969).

[74] Lamb, T., and et al. Ship design and construction vol. 1. *SNAME* (2004).

[75] Levander, K. System based ship design. *NTNU* (2006).

[76] Magee, C. L., and de Weck, O. L. Complex system classification. *14th INCOSE* (2004).

[77] March, J. G. Bounded rationality, ambiguity, and the engineering of choice. *The Bell Journal of Economics 9*, 2 (1978), 587–608.

[78] March, J. G. A primer on decision making: How decisions happen. *The Free Press, New York* (1994).

[79] McClamrock, R. Existential cognition: Computational minds in the world. *Univ. of Chicago Press* (1995).

[80] McDonald, T. P. A library based approach for exploring style in preliminary ship design. *PhD thesis, UCL* (2010).

[81] Michel, J., Shen, Y. K., Aiden, A. P., and et al. Quantitative analysis of culture using millions of digitized books. *Science 331*, 6014 (2012), 176–182.

[82] Mistree, F., Smith, W. F., Bras, B. A., Allen, J. K., and Muster, D. Decision-based design: A contemporary paradigm for ship design. *SNAME Annual Meeting, San Francisco CA, November 3* (1990).

[83] Mitchell, M. Complexity: A guided tour. *Oxford University Press* (2009).

[84] Moghadam, M. K., Bonsall, S., Wang, J., and Wall, A. Application of multiple attribute decision-making (madm) and analytical hierarchy process (ahp) methods in the selection decisions for a container yard operating system. *Marine Technology Society Journal 43*, 3 (2009), 34–50(17).

[85] NASA. Systems engineering handbook. *National Aeronautical and Space Administration* (2007).

[86] Oliver, D. W., Kelliher, T. P., and Keegan, J. G. Engineering complex systems with models and objects. *McGraw-Hill* (1997).

[87] Pahl, G., and Beitz, W. Engineering design. *Springer-Verlag* (1998).

[88] Papanikolau, A. Risk-based ship design: Methods, tools and applications. *Springer* (2009).

[89] Papanikolau, A., and Andrews, D. Design for x. *in State of Art Reports, 11th International Maritime Design Conference - Glasgow* (2012).

[90] Parsons, M. G. Parametric design, chapter 11 in ship design and construction vol. 1. *SNAME* (2004).

[91] Parsons, M. G. Imdc proceedings. *9th International Maritime Design Conference - IMDC* (2006).

[92] Rhodes, D. H., and Ross, A. M. Five aspects of engineering complex systems. *SysCon - IEEE International Systems Conference* (2010).

[93] Rhodes, D. H., and Ross, A. M. Shaping socio-technical system innovation strategies using a five aspects taxonomy. *EuSEC 2010, Stockholm* (2010).

[94] Ross, A. M., McManus, H., Rhodes, D. H., Hastings, D., and Long, A. Responsive systems comparison method: Dynamic insights into designing a satellite radar system. *AIAA Space - Pasadena, CA* (2009).

[95] Ross, A. M., and Rhodes, D. H. Architecting systems for value robustness: Research motivations and progress. *SysCon 2008 – IEEE International Systems Conference* (2008).

[96] Ross, A. M., and Rhodes, D. H. Using natural value-centric time scales for conceptualizing system timelines through epoch-era analysis. *INCOSE International Symposium 2008, Utrecht, the Netherlands* (2008).

[97] Schneekluth, H., and Bertram, V. Ship design for efficiency and economy. *Butterworth-Heinemann, 1998* (1998).

[98] Sen, P., and Birmingham, R. Imdc proceedings. *6th International Maritime Design Conference - IMDC* (1997).

[99] Sha, L. Using simplicity to control complexity. *IEEE Software July/August* (2001).

[100] Sharma, R., wan Kim, T., Storch, R. L., Hopman, H. J., and Erikstad, S. O. Challenges in computer applications for ship and floating structure design and analysis. *Computer-Aided Design 44* (2012).

[101] Simon, H. The architecture of complexity. *Proceedings of the American Philosophical Society 106*, 6 (1962), 467–482.

[102] Simon, H. The structure of ill structured problems. *Artificial Inteligence 4* (1973), 181–200.

[103] Simon, H. The sciences of the articial. *MIT Press* (1996).

[104] Singer, D. J. Design for production. *in State of Art Reports, 11th International Maritime Design Conference - Glasgow* (2012).

[105] Singer, D. J., Doerry, N., and Buckley, M. E. What is set-based design? *Naval Engineers Journal 121*, 4 (2009).

[106] Sjostrom, P.-H. Larger than her sister. *Shipgaz 6* (2010).

[107] Smith, W. F. The modeling and exploration of ship systems in the early stages of decision-based design. *PhD Thesis, University of Houston* (1992).

[108] Suh, N. P. The principles of design. *MIT Press* (1990).

[109] Suh, N. P. Complexity - theory and applications. *Oxford University Press* (2005).

[110] Tasaka, H. Twenty-first-century management and the complexity paradigm. *Emergence 1*, 4 (1999), 115–123.

[111] Thompson, P. How much did the liberty shipbuilders learn? new evidence for an old case study. *Journal of Political Economy 109*, 1 (2001), 103–137.

[112] Tversky, A., and Kahneman, D. Advances in prospect theory: Cumulative representation of uncertainty. *Journal of Risk and Uncertainty 5*, 4 (1992), 297 – 323.

[113] Ulstein, T., and Brett, P. O. Seeing whats' next in design solutions: Developing the capability to build a disruptive commercial growth engine in marine design. *International Maritime Design Conference - Trondheim* (2009).

[114] Ulstein, T., and Brett, P. O. Critical systems thinking in ship design approaches. *International Maritime Design Conference - Glasgow* (2012).

[115] Watson, D. G. Practical ship design vol 1. *Ocean Engineering Series Editor - Elsevier* (1998).

[116] Whitfield, R. I., Hills, B., and Coates, G. The application of multiobjective robust design methods in ship design. *University of Newcastle* (1999).

[117] Winnes, H., and Ulfvarson, A. Environmental improvements in ship design bu the use of scoring functions. *Journal of Engineering for the Maritime Environment* (2006).

[118] Yang, Y.-S. Marine design application of design theory and methodology. *International Conference on Axiomatic Design (ICAD) - Seoul, Korea* (2004).

[119] Yeo, A., and y, M. M. O. Introduction to offshore support vessels. *Marine Money Offshore* (2011).

Part II

Main Papers

Paper 1 (Journal)

Henrique M. Gaspar, Adam M. Ross and Stein Ove Erikstad: *Handling Temporal Complexity in the Design of Non-Transport Ships Using Epoch-Era Analysis.* Transactions RINA, Vol 154, Part A3, International Journal Maritime Engineering, Jul-Sep 2012
Discussion published on Transactions RINA, Vol 155, Part A3, Jul-Sep 2013
DOI No: 10.3940/rina.ijme.2012.a3.230

Paper 2 (Journal):

Henrique M. Gaspar, Adam Ross, Donna M. Rhodes and Steiv Ove Erikstad: *Addressing Complexity Aspects in Conceptual Ship Design - A Systems Engineering Approach.* Journal of Ship Production and Design, Vol. 28, No. 4, November 2012, pp. 1-15
DOI: http://dx.doi.org/10.5957/JSPD.28.4.120015
Selected to be part of the *Transactions of SNAME*, Vol. 120, 2013 - with added discussions

Paper 3 (Journal)

Henrique M. Gaspar, Océane Balland, Dina M. Aspen, Adam M. Ross and Stein Ove Erikstad: *Assessing air emissions for uncertain lifecycle scenarios via responsive systems comparison method.* Submitted to an international peer-reviewed journal (June 2013)

Paper 4 (Journal)

Henrique M. Gaspar, Arnulf Hagen and Stein Ove Erikstad: *Designing a Ship for Complex Value Robustness.* Submitted to an international peer-reviewed journal (June 2013)

Paper 5 (Peer Review Conference):

Henrique M. Gaspar, Donna H. Rhodes, Adam M. Ross and Stein Ove Erikstad: *Handling Complexity Aspects in Conceptual Ship Design*, Proc. 11th International Maritime Design Conference, Glasgow-UK, June 2012

Papers 1-5

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A Secondary Papers - Abstracts

Abstract of other papers developed during the PhD, briefly commented in Section 3.

Paper 6 (Peer Review Conference):

Gaspar, H. M., Balland, O., Erikstad, S.O., *Approaching Environmental Performance in Conceptual Ship Design* - 11th International Symposium on Practical Design of Ships an Other Floating Structures, Rio de Janeiro, 2010.

Abstract: Environmental issues have gained importance during the last decades. The traditional ship design procedure already includes a well established tradeoff between economical and technical performance. However, the integration of environmental analysis is relatively new, and there are many research questions to be answered.

In this context we wish to suggest some relevant tasks to address environmental issues in the preliminary stage, primarily focusing on air emissions and energy efficiency topics.

The present work discusses thus these tasks inside the procedure of a generic conceptual design methodology. It also briefly mentions two important subjects in the field. First, defining a common understanding on the environmental impact of a ship and an overview on the recent studies. And second, presenting the characteristics of the conceptual ship design domain, enhancing the importance of the inclusion of environmental issues in the stage where changes have a bigger impact. Two use cases are presented as example, an AHTS vessel and the role of the operational profile, and a RoRo ship and the impact of air emission control.

We also introduce at the end of the work ten research topics, with the intention of instigate bright minds ex- ploit the field in the future.

Paper 7 (Conference):

Gaspar, H. M., Larsen, E., Grimstad, A., Erikstad, S.O, *Efficient Design of Advanced Machinery Systems for Complex Operational Profiles*, 9th International Conference on Computer Applications and Information Technology in the Maritime Industries, Italy, 2010.

Abstract: During the last decade offshore support vessels have faced a market with requirements for increasingly demanding operations, especially deep water and High North activities, an increased focus on environmental performance, as well as a higher degree of uncertainty in terms of contract horizon and predictability of future operations.

As a result, we have seen a development towards more advanced and complex machinery systems, typically containing diesel-electric or diesel-hybrid engine con-

figurations combined with azimuth and podded propulsion. While representing a significantly higher investment cost, these machinery solutions have increased their market share based on improved energy efficiency and higher degree of flexibility towards the complex, demanding and multi-faceted operational profiles that these vessels actually meet.

Related to this development, there are two main issues that are addressed in this paper: First, how can we efficiently design these complex systems in the tendering phase of project development, based on the actual expected operating profile of the vessel? And second, how can the system performance, in terms of cost, energy efficiency, emissions, flexibility and availability, be documented towards the customer so as to increase the likelihood of winning the contract.

Thus, the overall objective of the paper is to define a methodology and specify the structure of a tool that can fully or partially answer these questions. The paper will be based on an ongoing project within NTNU, with DNV and STX Europe as partners.

Paper 8 (Technical Report):

Larsen, E., Sole, S., Gaspar, H. M., *Ship Machinery Configuration Comparison*, Report IMT/S4C/2-2009, NTNU, July 2009.

Summary: This report presents the results from the project Ship Machinery Configuration Comparison, developed in June/09. The project was carried out as a sub-project under the Ship 4C KMB by Norges TekniskNaturvitenskaplige Universitet (NTNU) and Det Norske Veritas (DNV), where focus of interest was ship machinery configuration performance.

The overall objective of the project was to investigate the possibilities of developing a decision support tool to enhance the machinery configuration process in the early vessel design phase. The objective of the work was to define a methodology for evaluating ship machinery configuration performance based on a given vessel operation. The scope also included the development of a simplified tool for comparing ship machinery configurations based on the defined methodology.

The main tasks were defined as; acquire knowledge on basic processes of machinery configuration and operation, and define a performance evaluation methodology; develop a simplified comparison tool in excel for comparing machinery configurations and validate the defined methodology and tool by conducting a case study of comparing two distinct configurations; develop database schemes and a mock-up for later prototyping of the comparison tool.

Paper 9 (Conference):

Balland, O., Gaspar, H. M., Erikstad, S.O., *A Decision Model Comparing the*

Cost Efficiency of Air Emissions Abatement Methods of a Fleet for IMO Compliance, International Symposium on Ship Design & Construction - The Environmental Friendly Ship, Tokio, 2009.

Abstract: This paper presents a decision model able to compare the cost of different technologies and strategies that reduce the emissions to air of a fleet.

The model calculates the emissions of CO2, SOX and NOX of a fleet and takes into consideration the main technologies to reduce SOX and NOX and the already existing or planned IMO air emissions regulations. The model narrows down the variables that affect the emissions of a fleet to the main ones, such as speed and fleet size. A cost analysis acts as a decision basis to select the technologies that will make the fleet comply with the regulations, for the lowest fleet lifecycle cost. If the installation of technologies is not sufficient to comply with the regulations, a speed reduction is used to reduce the emissions to a level corresponding to the IMO regulations. A sensitivity analysis of the main variables is performed, including fuel price and demand. The model can handle most types of transport vessels, as well as the study of customized routes.

Two study cases are presented to exemplify the methodology: A Ro/Ro fleet that sails from Europe to the US, in the SECA area; and an LNG route, also from Europe to the US, but not entering any existing control area. The cases illustrate how the model can be used to select a cost efficient abatement method in order to comply with the regulations.

Paper 10 (Conference):

Gaspar, H. M., Erikstad, S.O., *Extending the Energy Efficiency Design Index to Handle Non-Transport Vessels*, 8th International Conference on Computer Applications and Information Technology in the Maritime Industries, Budapest, 2009.

Abstract: The current environmental concerns demand efforts to improve the energy efficiency in the maritime sector, requiring design improvements of new ships. At the moment of the writing, the focus is on transportation vessels, and IMO intends to implement a mandatory energy efficiency design index by the end of 2009. In the longer term, it is likely that also non-transport vessels, such as offshore support vessels, will be included. The nature of both the design and the operation of these vessels will require a different index calculation model from the one actually proposed by IMO. In this paper, we discuss some of the key deficiencies of the current approach, and propose as alternative an extended model, that takes the inherent characteristics of these vessels into account.

The proposed model defines a set of functions related to the main missions undertaken by the vessel. These functions are then mapped to a corresponding measurement of the work, or utility, exhibited by the function on the one hand, and to the direct and indirect powering requirements, and corresponding CO2 emissions, on

the other hand. A case study of an AHTS is presented at the end, with its main operational profiles and an index linked to it.

B Previous PhD theses published at the Dept. 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)
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61		Circular Cylinders in Wave Zones. (Dr.Ing. Thesis)
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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)
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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)
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MTA-97-116	Moksnes, Paul O., MM	Modelling Two-Phase Thermo-Fluid Systems Using Bond Graphs. (Dr.Ing. Thesis)
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MTA-97-118	Igland, Ragnar T., MK	Reliability Analysis of Pipelines during Laying, considering Ultimate Strength under Combined Loads. (Dr.Ing. Thesis)
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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)
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MTA-2001-143	Baarholm, Rolf Jarle, MH	Theoretical and experimental studies of wave impact underneath decks of offshore platforms. (Dr.Ing. Thesis)
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