NTNU
Norwegian University of
Science and Technology

Design of Value Robust Container Ship Using the Responsive System Comparison Method

Magnus Dickens

Marine Technology
Submission date: June 2016
Supervisor: Bjørn Egil Asbjørnslett, IMT
Co-supervisor: Espen Gjerde, Ship Finance International

Norwegian University of Science and Technology
Department of Marine Technology

Preface

This thesis is a part of the Master of Science degree in Marine Technology, with specialization in marine systems design at the department of marine technology, Norwegian University of Science and Technology in Trondheim. The workload corresponds to 30 ECTS, one full time semester.

I would like to thank my supervisor, Professor Bjørn Egil Asbjørnslett for providing relevant literature and for valuable comments along the way. I would also like to express my thanks and gratitude to Espen Gjerde, senior vice president at Ship Finance International. This project would never have happened without your initiative and support.

I would finally like to thank PhD candidate Carl Fredrik Rehn and researcher Sigurd Pettersen, both at the Department of Marine Technology at NTNU, for great input and discussions along the way.

Thank you

Magnus Dickens

Magnus Dickens,
Trondheim, June 10., 2016

Abstract

Traditionally the conceptual design phase of ships has focused on the technical analysis - the mapping from the design to the performance space. The performance of the vessel does not fully capture the value of the vessel, and it becomes necessary to perform a mapping from the performance to a value space. Static performance and value models are not sufficient to perform proper evaluation of a design in the early stages. There are likely to be major changes in the operating context of the vessel during its lifecycle, which will greatly influence the performance and value. The quality of a new vessel from the perspective of the ship owner is strongly associated with value robustness of the design. Value robustness is defined as the ability of a system to continue to deliver stakeholder value in the face of shifts in context and needs.

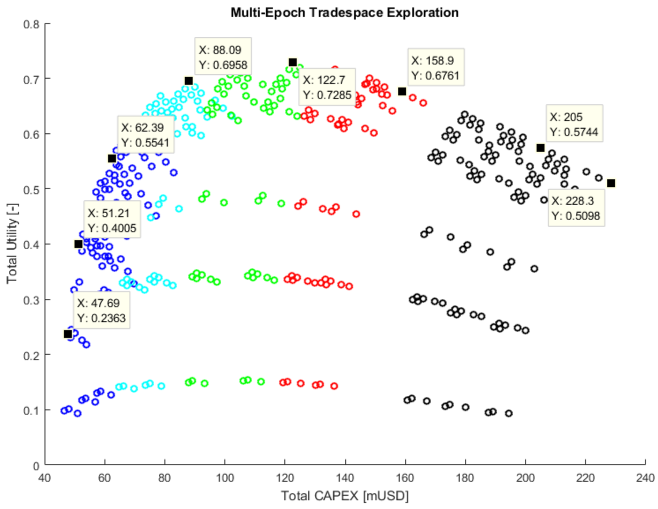
This thesis investigates strategies to expand the boundaries of conceptual ship design. The overall goal has been to examine approaches to handle contextual uncertainties with the goal of achieving value robust designs of transportation vessels.

We present an introduction to conceptual ship design, were the state of the art and motivation for the research questions are presented. We further address the perception of value in ship design, and the influence of uncertainties. This is related to systems engineering approaches to handle complexity in design, and Epoch-Era and the Responsive Systems Comparisons (RSC) method are introduced.

In a case study the RSC method is used as framework for including Epoch-Era Analysis with traditional design methodologies. The basis for the case study is the container market. The case study incorporates some factors specific to the container industry, including the organization of liner services. The general approach demonstrated in the case study are believed to be applicable for most segments of merchant transportation vessels.

We measure the utility as a combination of an objective measure of monetary transportation cost and stakeholder perception of the value of operational flexibility. The number of ports capable of servicing the vessel is used as the basis for assessing the operational flexibility. We develop a cost model to calculate the building cost and capital expenditures, the

operational cost and the fuel based voyage expenditures as a function of the design decisions and market situation. The primary datasource is several databases of ship particulars and historic market development. Regression analysis and other statistical methods are used to construct a model to perform the tradespace exploration and the form-function-value mapping. The model is used to evaluate the designspace across changing context to calculate a robust utility value. The Pareto front of the resulting value space identifies potential value robust design configurations.



Multi-Epoch design space evaluation

The model shows the ability to predict real-life observations and is to a certain degree aligned with findings of other research. The model is strongly influenced by assumptions made based on limited information.

To our knowledge, this is the first attempt to combine the Responsive Systems Comparison method with Epoch-Era analysis to address the value robustness of transportation vessels. We believe the method developed is an interesting take to expand the boundaries of conceptual design of merchant vessels that can be used as a basis for further research and development.

Sammendrag

Tradisjonelt har tekniske analyser stått i fokus ved tidlig-fase skipsdesign. Denne prosessen kan ses på som å utlede sammenhengen mellom design-avgjørelser og tilhørende ytelse og resultater. Dette alene er ikke tilstrekkelig for å verdsette nytten av et design, og det er nødvendig å utlede denne basert preferansene til mulige interessenter. Statiske ytelses- og verdivurderingsmodeller er ikke tilstrekkelig til å utlede verdien av et tidlig-fase design. The er sannsynlig at det vil forekomme store endringer in operasjonsforhold i løpet av livstiden, noe om vil påvirke verdien og nytten. Godheten av et skipsdesign er sterkt knyttet til i hvor stor grad det kan fortsette å utføre sitt oppdrag på en økonomisk konkurransedyktig måte under skiftende omstendigheter. Dette definerer vi som verdi robusthet.

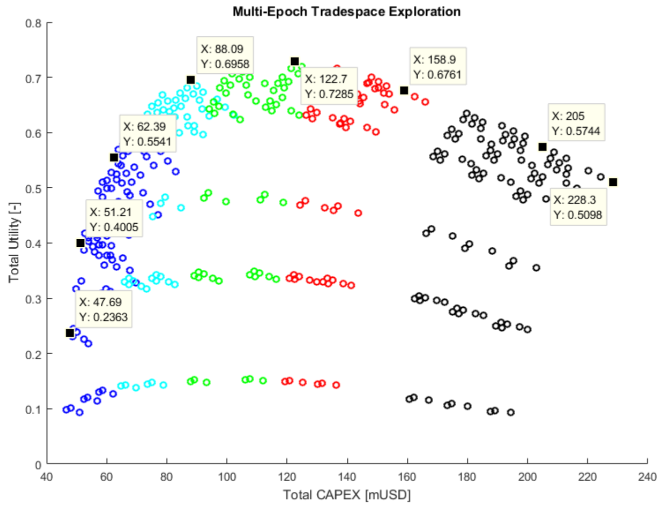
I denne oppgaven vil vi undersøke strategier for å utvide rammene for tidligfase skipsdesign. Målet er undersøke fremgangsmåter for å håndtere usikkerhet for å oppnå et verdi robust design av transportskip.

Vi presenterer en introduksjon til tidligfase skipsdesign, med fokus på state of the art metoder og motivasjon for problemstillingen. Vi vil også introdusere oppfatningen av verdi og innvirkningen av usikkerhet i design.

I en case-studie vil vi bruke *Responsive Systems Comparison*-metoden som et rammeverk for å inkluderer *Epoch-Era* analyse med tradisjonelle design metoder. Utgangspunktet for case-studien er markedet for sjøtransport av konteinere. Vi inkluderer spesifikke forhold relater til markedet, inkludert den unike linje oppbyggingen av transportnettverket. Den generelle fremgangsmåten er anvendelig for de fleste segmenter innen sjøtransport av gods.

Vi måler nytte som en kombinasjon av en objektiv transportkostnad and interessentenes oppfattelse av verdien av operasjonell fleksibilitet. Infrastruktur knyttet til havneanlegg brukes som grunnlag for å vurdere fleksibiliteten. Vi utvikler en kostnadsmodell for beregne bygge, operasjons- og bunkerskostnader basert på design avgjørelser og markedssituasjonen. Datagrunnlaget er hentet fra ledende databaser av skipsopplysninger og historisk markedsutvikling. Statistikkanalyser er brukt for å konstruere en modell for å utforske

design mulighetsrommet og ytelsen. Modellen blir anvendt for å analyserer en rekke designmuligheter under endrede omstendigheter. Ved å kombinere nytten over en rekke scenarioer kan vi identifisere verdirobuste design.



Multi-Epoch verdi robust nytte analyse

Modellen innehar egenskaper som er i samsvar med reelle observasjoner. Resultatene er i stor grad påvirket av antakelse det er nødvendig å gjøre på grunnlag av begrenset informasjon.

Så vidt vi kjenner til, er dette første forsøk på å kombinere *Responsive Systems Comparion*-metoden med Epoch-Era analyse for å undersøke verdirobustheten av tradisjonelle transportskip. Vi tror at denne metoden er et interessant utgangspunkt for videre arbeid.

Contents

1 INTRODUCTION 1

1.1 BACKGROUND 1

1.2 PROBLEM DEFINITION 2

1.3 OBJECTIVES 2

1.4 STRUCTURE OF THE REPORT 3

2 LITERATURE REVIEW 4

3 CONCEPTUAL SHIP DESIGN 7

3.1 MOTIVATION FOR IMPROVED EARLY PHASE DESIGN METHODOLOGY 7

3.2 THE DESIGN PROCESS 8

3.3 UTILITY AS A MEASURE OF VALUE 11

3.4 DESIGN METHODS 12

3.5 DESIGN FOR TRADE SPECIFIC UTILITY 13

3.5.1 The Right Vessel for the Right Trade 13

3.5.2 Design Derived from Operating Profile 19

3.6 UNCERTAINTY 20

3.7 PREDICTING FUTURE DEVELOPMENT 22

3.7.1 Freight Rate Forecasting 22

3.8 DESIGNING FOR FUTURE UNCERTAINTY 26

3.8.1 Flexibility 27

3.9 DESIGN FOR VALUE ROBUSTNESS 28

3.9.1 Stochastic Programming 30

4 COMPLEXITY IN SYSTEMS ENGINEERING 32

4.1 SHIPS AS COMPLEX SYSTEMS 32

4.2 FIVE ASPECTS OF COMPLEXITY 33

4.2.1 Taxonomy of Complexity Applied to Ship Design 33

4.3 HANDLING COMPLEXITY THROUGH DECOMPOSITION AND ENCAPSULATION 35

5 METHODOLOGY: DESIGN FOR VALUE ROBUSTNESS 37

5.1 THE RESPONSIVE SYSTEMS COMPARISON METHOD 37

5.1.1 The Seven Steps of the RSC method 37

6 CONTAINER SHIPPING AND VESSELS 43

6.1 THE VESSEL AND FLEET 43

6.2 CARGO AND MARKET 45

6.3 OPERATION AND TRADE ROUTES 45

6.4 FUNCTIONAL SYSTEM DEFINITION FOR CONTAINER VESSELS 46

6.5 UNCERTAINTIES IN FUTURE OPERATING CONTEXT 47

7 CONTAINER VESSEL: DESIGN FOR VALUE ROBUSTNESS 48

7.1 CASE DESCRIPTION 48

7.2 CHOICE OF METHODOLOGY 49

7.3 RESPONSIVE SYSTEM COMPARISON METHOD APPLIED TO CASE STUDY 51

7.3.1 Value-Driving Context Definition 51

7.3.2 Value-driven design formulation 51

7.3.3 Epoch Characterization 60

7.3.4 Design Tradespace evaluation 65

7.3.5 Multi-Epoch Analysis ... 67

7.3.6 Era Construction ... 68

7.3.7 Life Cycle Path Analysis ... 69

8 RESULTS ... 70

8.1 TRADESPACE EXPLORATION ... 72

8.2 MULTI-EPOCH ANALYSIS ... 76

8.3 ERA ANALYSIS ... 80

9 DISCUSSION ... 83

10 CONCLUDING REMARKS AND FURTHER WORK ... 88

10.1 FURTHER WORK ... 89

BIBLIOGRAPHY ... 91

APPENDIX A: ACRONYMS ... 98

APPENDIX B: ECONOMIC DATA ... 99

B.1 OPERATIONAL EXPENSES ... 99

B.2 BUILDING PRICES ... 100

APPENDIX C: FUEL DATA ... 102

C.1 FUEL CONSUMPTION ... 102

C.2 SPECIFIC FUEL CONSUMPTION ... 103

C.3 ENERGY DENSITY ... 103

C.4 SCRUBBER ... 104

C.5 LNG ... 104

APPENDIX D: SHIP DATA ... 105

D.1 DRAFT VS TEU 105

APPENDIX E: ERA CONSTRUCTION 106

APPENDIX F: MATLAB CODE 107

F.1 PRODTHEORY.M 107

F.2 RSC.M 108

F.3 TRADESPACE.M 110

F.4 ESTIMATEKW.M 110

F.5 CAPEX.M 111

F.6 OPEX.M 112

F.7 EPOCHS.M 112

F.8 FREIGHTRATES.M 113

F.9 LINER.M 114

F.10 FUELCON.M 115

F.11 COST.M 116

F.12 FUELCOST.M 117

F.13 UNITCOST.M 118

F.14 UTILITY.M 119

F.15 MULTIEPOCH.M 120

F.16 ERA.M 120

F.17 MULTIERA.M 122

List of Figures

Figure 3-1: Cumulative expenses: Incurred vs committed cost in product development (adapted from Phillips and Srivastava (1993)). 8

Figure 3-2: Evans' design spiral. Illustrating the iterative design process and exemplifies main technical analysis (Evans, 1959) 9

Figure 3-3: Representation of the design process. Based on Schaffner (2014) and Erikstad (1996). 10

Figure 3-4: Mapping from performance attributes to utility 12

Figure 3-5: The right vessel for the right mission (Gaspar et al., 2016) 13

Figure 3-6: Input and outputs in container liner production model 14

Figure 3-7: Left: Lines of constant annual transportation (isoquants), right: 3D surface plot. Both plot show the same range of values. 16

Figure 3-8: Left: Isoprofit lines showing the annual revenue as function of capacity and speed. Right: 3D surface plot of the same range and values 18

Figure 3-9: Example of operating profile and design point of large container vessel (Svensen & DNV-GL, 2012) 19

Figure 3-10: Specific fuel consumption (based on data from MAN Diesel (2016) 20

Figure 3-11: Macroeconomic shipping model (based on Stopford (2009)). 23

Figure 3-12: Typical cargo forecast and optimal ship size (Benford, 1967). 26

Figure 3-13: Two stage stochastic decision process (adapted from Popela, Novotný, Roupec, Hrabec, and Olstad (2014)) 31

Figure 4-1. Hierarchy of complexity in marine systems (adapted from Gaspar (2013)). 33

Figure 4-2: Five aspects of complexity applied to conceptual ship design (Gaspar, 2013). 35

Figure 4-3: Decomposition and encapsulation to handle complexity in systems (Gaspar, 2013). 36

Figure 5-1: Tradespace with Pareto front highlighted 40

Figure 5-2: The seven steps of the responsive system comparison method (Gaspar, Balland, Aspen, Ross, & Erikstad, 2015). 42

Figure 6-1: Functional system breakdown of container vessel (based on Levander (2012)) 46

Figure 6-2: design problem under uncertainty 47

Figure 7-1: Principal actors in the container shipping market 49

Figure 7-2: Principal methodology used in the case study 50

Figure 7-3: TEU vs length and breadth (based on *IHS Fairplay* 2016)) 53

Figure 7-4: Discrete design space. Capacity as function of length and breadth Bergman (2014) 54

Figure 7-5: Principal cost model used in case study 56

Figure 7-6: Principal components of the operating expenditures, based on Drewry Shipping Consultant (2015) 58

Figure 7-7: Operating costs for container vessels. Adapted from Drewry Shipping Consultant (2015). 58

Figure 7-8: Fuel consumption as function of cargo capacity 60

Figure 7-9: Container demand model 62

Figure 7-10: Principal procedure for tradespace evaluation (Adapted from Gaspar et al. (2015) and Ross et al. (2009)) 66

Figure 7-11: Example of tradespace evaluation for one epoch 67

Figure 8-1: Single epoch tradespace exploration for high demand epoch, grouped after capacity. 73

Figure 8-2: Single tradespace exploration for low demand epoch, grouped after capacity. 73

Figure 8-3: Single epoch tradespace exploration, grouped after machinery configuration. 74

Figure 8-4: Single epoch tradespace exploration, grouped after machinery configuration 75

Figure 8-5: Single epoch tradespace exploration grouped after design speed. 76

Figure 8-6: Multi-Epoch tradespace exploration 77

Figure 8-7: Multi-Epoch tradespace exploration grouped after machinery configuration. 79

Figure 8-8: Multi-Epoch tradespace exploration grouped after design speed 79

Figure 8-9: Context- and trade parameters 80

Figure 8-10: The construction of eras and the relationship between trades and epochs 81

Figure 9-1: High level illustration of the analysis process 83

List of Tables

Table 3-1: The effect of changing parameter values on the annual transportation capacity elasticity with respect to vessel capacity and speed. The table indicates the effect of an increase in any of the parameters will have on the elasticities. 17

Table 3-2: Framework for handling uncertainties and their effects (Gaspar et al., 2016; McManus & Hastings, 2005) 21

Table 3-3: Variables in the shipping market model. (Based on Stopford (2009)). 22

Table 3-4: Design strategy related uncertainty in context and objective (Based on Saleh (2001)) 29

Table 6-1: External dimensions of the standard shipping containers................................ 43

Table 6-2: Classification of container vessels. Based on (Clarkson Research, 2015). 44

Table 6-3: Examples of uncertainties in marine systems design, based on Erikstad and Rehn (2015) 47

Table 7-1: Performance attributes selected for the container vessel 51

Table 7-2: Design variables for the container vessel... 52

Table 7-3: Length, breadth and capacity defining the design space 54

Table 7-4: Investment costs of the engine configurations (Based on Rehn et al. (2016)) . 57

Table 7-5: Epoch characterization... 61

Table 7-6: Trade-specific factors (Clarkson Research, 2015; *IHS Fairplay*, 2016) 62

Table 7-7: Qualitatively relationship between epoch variables and change in liner network configuration 64

Table 7-8: Qualitatively relationship between epoch-variables and freight rates 64

Table 8-1: Summary of the framework used in the case study. 71

Table 8-2: Colour legend for tradespace representation grouped after cargo capacity...... 72

Table 8-3: Colour legend for tradespace value plot grouped after design speed. 75

Table 8-4: Design variables for key designs identified in the multi-epoch analysis.......... 78

Table 8-5. Result of multi era analysis 82

1 Introduction

1.1 Background

Traditional ship design focuses on the technical analysis of the structure and performance. The attention have been to improve the various aspects of technical analysis – the mapping from the design to performance space (see e.g. Eyres, 2007a). The performance of the vessel does not fully capture the value, and it becomes necessary to perform a mapping from a performance to the value space. Ross (2006) makes a distinction between real and perceived spaces. Performance attributes are to a large degree believed to be objective and not influenced by individual opinions. The performance space is therefore in the realm of real spaces. On the other hand, the stakeholders' perception of a system and the functions greatly influences the value, making the value space a perceived space.

Design under uncertainty have been a constant topic of research without any universally established methods emerging as acknowledged best practise approaches. Static performance models are not sufficient to perform proper evaluation of a design in the early stages. There are likely to be major changes in the operating context of the vessel during the lifecycle, which can greatly influence the value. The quality of new vessel from the perspective of the ship owner is strongly connected to the robustness of the design. Value robustness is defined as the ability of a system to continue to deliver stakeholder value in the face of shifts in context and needs (Adam M. Ross & Donna H. Rhodes, 2008).

The value of merchant vessels will depend on the specific trade the vessel is engaged in. New builds are often designed based on a mission profile, which describes the trade specific considerations (Cuesta, Grimstad, & Hagen, 2009). This will often be the first trade the vessel is planned for, and will often be based on observations of current similar vessels in the market.

1.2 Problem Definition

The basis for the problem is the complex nature of conceptual ship design. The early trade space exploration deals with complex evaluation from the performance- to the perceived value space. The quality of a vessel seen from the perspective of a ship owner will depend on the trade-specific utility, and the value robustness over the entire life span.

The goal of this thesis is to investigate strategies to include uncertainty in the conceptual design of merchant transportation vessels. We will focus on the container segment and incorporate industry specific considerations

The problem definition leads to the first of two main research questions:

1. *How do we include uncertainty to identify value robust container vessel designs?*

In this thesis we will work within the boundaries of established design solutions, and do *not* seek to expand the designspace with innovative features. Our aim is to investigate strategies to expand the boundaries of the design process by combing traditionally techniques with emerging methodologies. This leads us to the second research question:

2. *Which methodologies exist that can be combined with state of the art marine design practises to provide decision support for conceptual design of transportation vessels under uncertainty?*

1.3 Objectives

To address the research questions we will cover the following objectives:

1. Present an introduction, addressing the state of the art, covering the following topics:
    a. Conceptual ship design, focusing on the uncertainty and complexity inherent in initial design of complex systems.
    b. Modelling approaches applicable for trade space exploration, dealing with both the performance and value space representation.
    c. Methods for predicting and modelling the future.

    d. Approaches to include future uncertainty in the design of marine logistics systems.
2. Present and discuss a framework to address trade specific utility and value robustness for use as decision support during the design phase of container vessels.
3. Present an illustrative case study where the framework is demonstrated.
4. Discuss and conclude on the methods for early design decision support in marine systems design

1.4 Structure of the Report

The thesis consists of five main parts: introduction, methodology case study, results and discussions, presented in that order.

Introduction

Chapter 2 is a literature study to present main pieces of relevant literature that are used later in the thesis.

In chapter 3 and 4 we extend the literature review to address research question 1

Methodology

Chapter 5 presents the main methodologies used in the case study: The responsive system comparison method, including multi-attribute tradespace exploration and epoch-era analysis.

Case Study

The methodology is demonstrated in a case study. In chapter 6 We give an introduction to the container market, with focus on the market context and design features. In chapter 7 the responsive system comparison method is used to model and analyse the case.

Results and Discussions

In chapter 8 we present the results from the case study. The evaluation, discussion and conclusion, including recommendation for further work, are presented in chapter 9 and 10.

2 Literature Review

The address the topics presented under objective one, the literature presented in this chapter have been valuable. The topics introduced here will be addressed more in detail in the next two chapters, 3 and 4, were we will introduced additional supporting literature.

The conceptual phase of ship design appears in the literature under many names: Initial-, preliminary and contact design are some common used terms (Eyres, 2007a). Various literature operates with different definitions of what the early stages of ship design includes. Typically the output are the principal particulars and main design values (Eyres, 2007b). Arguably the most well-known and influential ship design methodology is the classical spiral introduced by Evans (1959). The spiral is used to visualize the sequential and iterative nature of the design process. Andrews (1981) expanded on the work done by Evans (1959) and added time as a dimension, transforming the two dimensional spiral into a three dimensional cone, including constraints imposed by the design- process and environment.

The design spiral is often regarded more valuable as an abstract representation than a process description (Collette et al., 2015). The spiral approach is also criticized for iterating on a decreasing range of design options dictated by the initial assumption. The System Based approach (Levander, 2012) emphasizes on not specifying the form until a well-balanced solution can be proposed by developing a functional description based on high-level requirements.

Design-for-x (dfx) is a term used for the design for a specific performance aspect. Papanikolaou et al. (2009) presents the state of the art on design for several performance goals, including design for safety, risk-based design, and design for production. In this thesis we emphasis on design for value robustness (Gaspar, Hagen, & Erikstad, 2016). Benford (1967) approaches the design of robust cargo ship as matching the right design, with focus on size, to the typical mission forecast.

Erikstad and Rehn (2015) presents a state of the art on uncertainty in marine system design. Increased uncertainty is strongly connected to complexity. McManus and Hastings (2005) provides a framework for understanding uncertainty, where uncertainties are related to risk, and techniques to handle the risk to achieve robustness is presented. Rhodes and Ross (2010) presents a five aspect taxonomy for uncertainties in systems design. Complexity is decomposed into the structural, behavioural, contextual, temporal and perceptual aspects. Gaspar (2013) applies the five aspect taxonomy to ship design, focusing on specialized offshore vessels. The structural and behavioural aspects have been given most attention, and is handled by traditional ship design approaches, focusing on technical analysis to derive the form-function mapping (Gaspar, Rhodes, Ross, & Erikstad, 2012). Some recent work have been done to expand the domain of systems. Hagen and Grimstad (2010) calls for a broader scope on conceptual ship design by including the transportation system as an integral part. Brett and Ulstein (2012) emphasises on including the operational and commercial context when evaluating ship design options.

Gaspar (2013) approach to marine design was based on mostly non-marine application in Systems Engineering. Recent advances in systems engineering and the understanding of complex systems are attributed to the community at Massachusetts Institute of Technology (MIT), and the Systems Engineering Research Initiative (SEARI). Adam M. Ross and Donne H. Rhodes (2008) introduces epoch-era analysis (EEA) to handle the contextual and temporal aspects of complex systems engineering by parametrizing future uncertainty in static epochs and dynamic eras. Ross, McManus, Rhodes, Hastings, and Long (2009) introduces the Responsive systems comparison (RSC) method as a framework to combine traditional and emerging techniques such as EEA in the design on value robust systems. The method has shown its adaptability for a wide range of complex system design problems. Ross et al. (2009) demonstrated its use in the space industry. In the marine industry it has been applied in the conceptual design of naval vessels (Schaffner, 2014), and Gaspar et al. (2012) uses an anchor handling vessel as example to illustrate the use of RSC to achieve value robustness in marine design.

The motivation for designing for value robustness seems clear also in the design of transport ship, there exist a gap in the research. While the have been applied in the design of novel, specialized systems, there seem to lack any research combining systems engineering techniques with traditional methods for the design of marine transportation vessels.

3 Conceptual Ship Design

Inspiration to modern approaches to early phase marine design is found in literature spanning more than half a century. In this chapter we will attempt to create an understanding of the design process and introduce some specific methods to design for certain objectives and features

3.1 Motivation for Improved Early Phase Design Methodology

An inherent dilemma of the design process arises from the fact that the knowledge of the design is least early in process, when the freedom to influence and change the design is the greatest (Erikstad, 1996). All later design decisions are constrained by the initial choices. As a result, the committed costs are much higher than the actual occurred. Phillips and Srivastava (1993) proposes a general relationship between the committed and incurred costs throughout the lifecycle seen in figure 3-1. It is likely that a similar relationship holds true for ship design.

The cost to extract defects increases throughout the stages of design and development. The cost of extract errors can be up to 1000 times greater in the operation phase compared to the early design stages (Gaspar, 2013). The trade-off between depth and breadth, or exploration and exploitation is central for understanding the design process (Erikstad, 2014b). The general approach is to start broad, and then migrate towards higher fidelity models in the detailed design stages (Collette et al., 2015).

The limited knowledge and high consequence of error in the early design phase results in a motivation for improved methodologies for conceptual ship design.

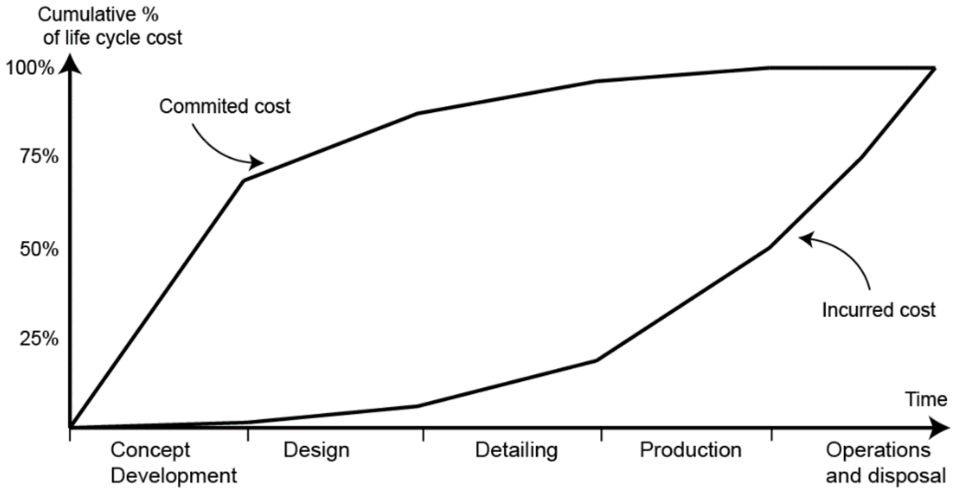


Figure 3-1: Cumulative expenses: Incurred vs committed cost in product development (adapted from Phillips and Srivastava (1993)).

3.2 The Design Process

Fundamental aspect of modern ship design was described by Evans (1959) in *Basic Design Concepts*. Evans is accredited with introducing the design spiral to model and visualize the iterative nature of ship design (see Figure 3-2). Andrews (1981) included time as an extra dimension to the spiral, transforming the spiral to a 3-dimensional cone, capturing constraints on the design process. The spokes of the spiral represent technical analysis performed as part of the form to function mapping. There exist several computing strategies to support the form-function mapping. Some the most dominant are optimization, simulation and statistical analysis.

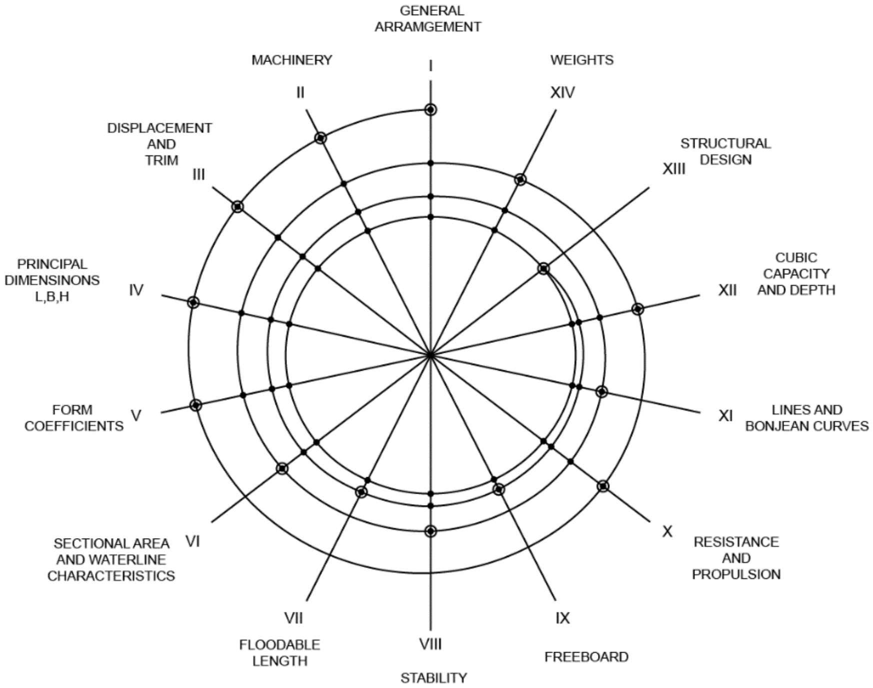


Figure 3-2: Evans' design spiral. Illustrating the iterative design process and exemplifies main technical analysis (Evans, 1959)

Most attempts to describe the design process put emphasis on the iterative nature. It is common to illustrate the design process as an loop (see e.g. Erikstad, 1996; Levander, 2012). Erikstad (1996) describes the process as an iterative sequence consisting of four main steps: Generate, analyse, evaluate and decide. Andrews (1985) emphasises the importance of performing needs analysis as a prerequisite for the generation and further evaluation.

The design process is often understood as a mapping between various representations of the design object. Fundamentally the design process can be defined as the mapping from the function space describing the needs and requirements to the form space containing the description of the final design (Rosenman, Radford, & Gero, 1990). The spaces are two different representations of the object. The form representation is spanned by a numerical description of the ship. The performance space describes the design in terms of the functions delivered. Engineering analysis is fundamentally to derive the function from the form, while the design process aims to do the opposite, by deducing the form resulting in the desired functions.

A three space representation of the design space is common in several publication dealing with the design of complex systems (see e.g Ross, 2006; Schaffner, 2014) The three main representational space are the design space, performance space and value space. The mapping from the design to the performance space is analogous with the form-function mapping. The value space is introduced to take into account that the goodness of a design cannot be described purely by the set of capabilities (Ross, 2006).

The space representation of the design process can be related to the four steps described by Erikstad (1996). The analyse step can be seen as the mapping from design- to performance space, and the evaluation as the mapping from performance to the value space. The first step, generation, would be a prerequisite for defining the design space. An understanding of the design processes based on a combination of the four step (generate, analyse, evaluate, decide) and a mapping between the three representational spaces is illustrated in figure 3-3.

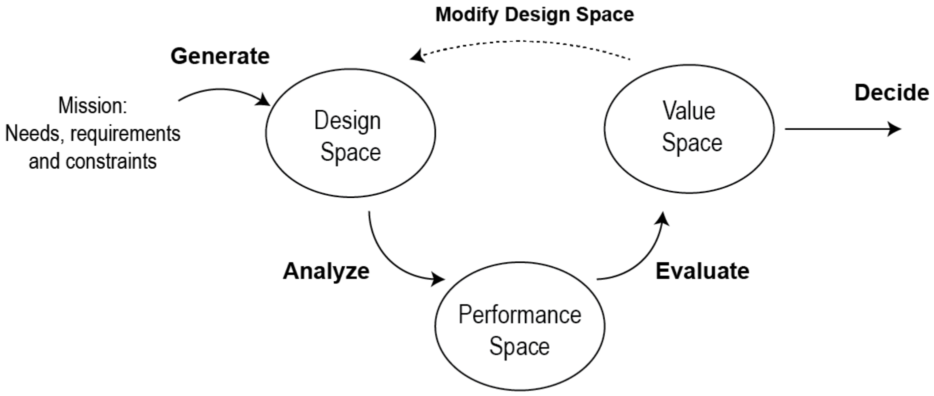


Figure 3-3: Representation of the design process. Based on Schaffner (2014) and Erikstad (1996).

3.3 Utility as a Measure of Value

Value is tied to the trade-off between various aspects of performances and the associated cost. Different stakeholders will have varying motives and perceive the value of identical systems differently.

The number of trade-offs quickly becomes too large for humans to handle by intuition alone. In economic theory, the concept of utility is used as a metric to explain the preferences of consumers (Begg, Vernasca, Fischer, & Dornbusch, 2014). Ross (2003) used utility theory in the design of complex systems. In figure 3-4 we illustrate how the mapping from performance to utility can be done. In the example the design speed is a performance attribute for a stakeholder when ordering a new vessel. The ideal vessel will have a design speed of 23 knots and the minimum acceptable is 17. The utility for these extremes are defined as 1 and 0. The intermediate values are assigned a utility based on a mapping function determined by the preference of the stakeholder. Based on the mapping function the utility score for the same attribute value can vary greatly, from U_1 to U_3. A similar process can be done for a range of attributes. The individual utilities can be combined to a multi attribute utility (MAU) score. By assuming preferential and utility independence between attributes the MAU can be calculated by equation 1 (Schaffner, 2014).

$$MAU = \sum_{i}^{N} k_i U_i(X_i) \tag{1}$$

Where U_i is the utility value derived from attribute X_i, and k_i is the weighting factor, constrained by equation 2.

$$\sum_{i}^{N} k_i = 1 \tag{2}$$

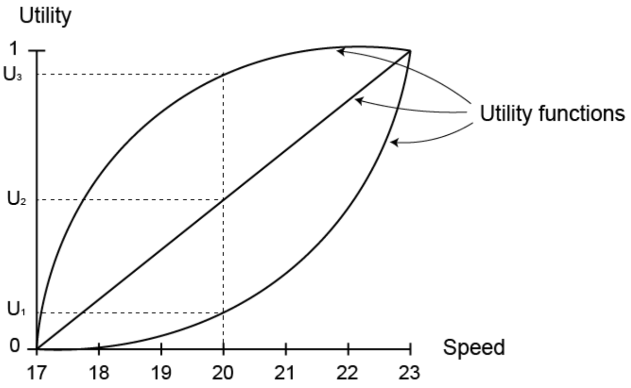


Figure 3-4: Mapping from performance attributes to utility

3.4 Design Methods

Evans (1959) approach is an example of point-based design. All later choices are based on the initial assumption, iterating over a decreasing range of options. The method is well suited for finding a feasible design while optimality is not in focus (Collette et al., 2015).

Set based design increases the scope by developing a number of designs spanning the design space. The designs are analysed in parallel and evaluated against a set of requirements. Those who meet the requirements and are Pareto optimal are kept, and those who do not meet the requirements or are Pareto Dominated are either discarded or modified (Singer, Doerry, & Buckley, 2009). SBD facilitates a greater knowledge of the design problem by delaying critical decision. By delaying the cost commitment we increase the time in which stakeholders can influence the design without causing significant increases in cost (Singer et al., 2009). Similarly, System Based design (Levander, 2012) emphasizes not specifying the form until a well-balanced solution can be proposed by developing a functional description based on high-level requirements.

Computer aided ship design started in the 1960s when mainframe machines were used for computationally intensive stability, hydrodynamics and structural calculations (Nowacki, 2010). With the increase in computational power, advanced techniques such a computational fluid dynamics and finite element analysis have become widespread. There are significant advantages with the possibilities that come with high power computing methods, but at the same the development have increased the tendency of using high fidelity models in the early stages. This might come with the potential drawbacks of not exploring other preferred solutions (Collette et al., 2015).

There exist several design methods not addressed here. The choice of methodology will be influenced by the design context and goals. In the following sections we will discuss a few specific scenarios relevant for the proposed research questions and objectives.

3.5 Design for Trade Specific Utility

Several of the design methods addresses the importance of specifying the needs and develop goals to perform the evaluation of the design and define the utility- attributes and functions. One approach is to base the mission on the specific trade or operation the vessel is expected to be used for.

3.5.1 The Right Vessel for the Right Trade

When discussing value, Gaspar et al. (2016) starts by assuming *"that the most valuable vessel is the one that perfectly matches the mission requirements with its capabilities."* This concept is illustrated in figure 3-5. If the vessel is over specified it will be able to fully serve the market, but do so at a higher cost than necessary. If the vessel is underspecified, it will not be able to fully serve the market.

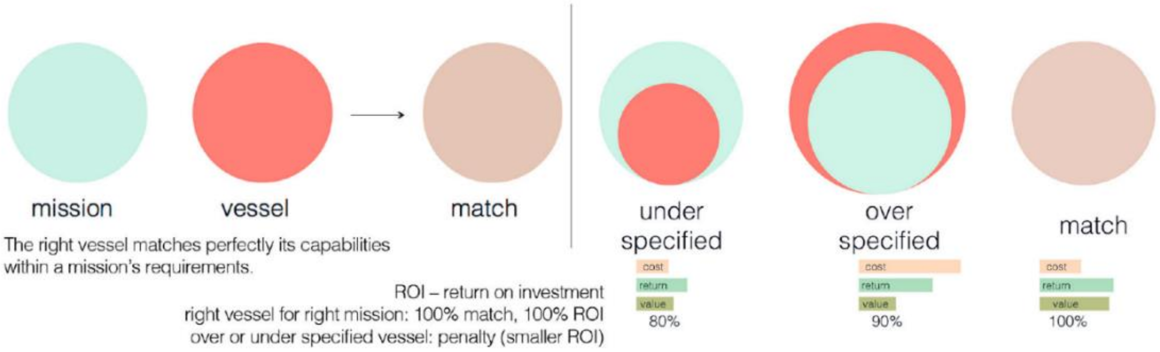


Figure 3-5: The right vessel for the right mission (Gaspar et al., 2016)

For transportation vessels, the mission is to transport goods. In a simple model the vessel can be described by the yearly transportation capacity. By using economic production theory, it is possible to analyse part of the *right vessel for the right mission* problem. In economic production theory the relationship between input and outputs are modelled, and the objective is to minimize cost associated with a set of inputs for a given output (Begg et al., 2014).

In the following paragraph we will outline the foundation for using production theory to assess the optimal size and speed of a vessel for a given transportation capacity. The case is based on a typical trans-Atlantic container trade. The actual data used is presented in appendix F.1. The results provide insight into how key parameters effect the design decisions which will be used in the case study. The general approach is inspired by Caracostas (1979) and Erikstad (2014a).

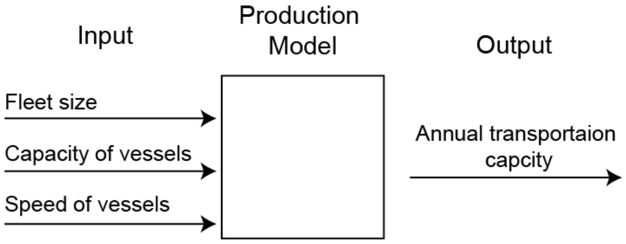


Figure 3-6: Input and outputs in container liner production model

The annual transportation capacity (Q) for a vessel with a cargo capacity N is expressed by equation 3.

$$Q = 2 \cdot N \cdot L \cdot RT \tag{3}$$

Where L is the average loading utilization factor and RT are the number of roundtrips per year. The number of roundtrips depend of the number of days of operation, D, and the roundtrip time, T_R. Days of operation is 365 minus the days off-hire for maintenance, classification etc. The roundtrip time is the sum of the sailing time (T_s), time in port (T_p) and waiting time (T_w), expressed by equation 4

$$T_R = T_s + T_p + T_w \tag{4}$$

Where,

$$T_s = \frac{DIST}{V \cdot 24} \tag{5}$$

The time in port is given by the effective cargo capacity and the unloading rate

$$T_p = \frac{N \cdot L}{12 \cdot R_h(N)} \tag{6}$$

Where R_h(N) is the unloading rate per hour at port. The unloading rate can be constant for a given port or it can be a function of the capacity of the vessel. A larger vessel can in some cases be served by more cranes at the same time or other cargo handling equipment, and have a higher unloading rate. For the rest of this section we will assume that the unloading rate to be independent of the vessel capacity. The remaining time spent manoeuvring and waiting in port is included in T_w. By including these relationships the annual cargo capacity can be expressed by equation 7.

$$Q = \frac{2 \cdot N \cdot L \cdot (365 - OH)}{\frac{N \cdot L}{12 \cdot R_h} + \frac{DIST}{V \cdot 24} + T_w} \tag{7}$$

Where OH is the number of days off-hire during one year.

There is an infinite number of N, capacity, and V, speed, corresponding to a given Q, annual cargo capacity. All combination of N and V can be graphed as isoquant lines. An isoquant is the line containing the set of N and V that generates a constant output, i.e. lines of constant annual capacity. figure 3-7 shows an example of isoquants line together with the corresponding 3D surface plot.

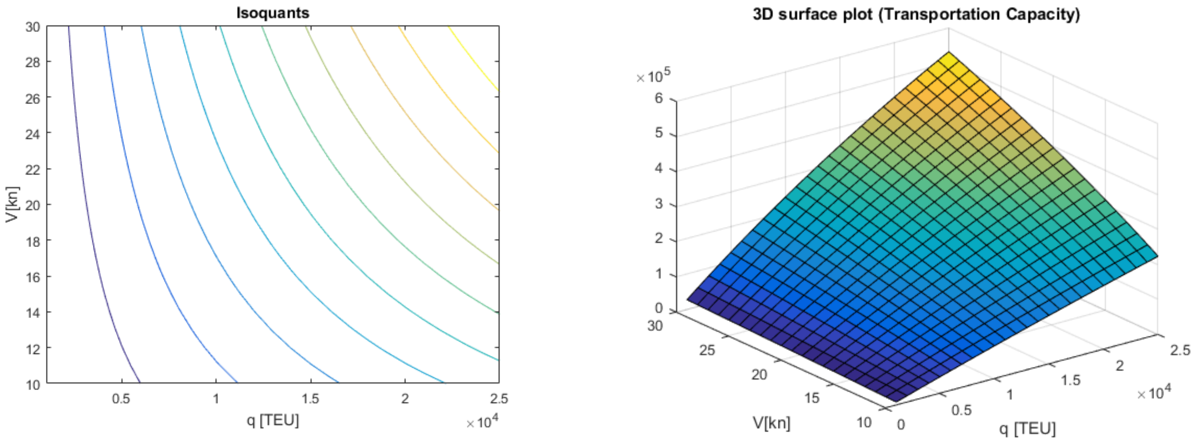


Figure 3-7: Left: Lines of constant annual transportation (isoquants), right: 3D surface plot. Both plot show the same range of values.

The returns of scale can be measured by the transport elasticity with respect to N and V. The elasticity is a measure of the relative change in transportation capacity with respect to change in the vessel capacity or speed. The transport elasticity with respect to capacity and speed is given by equation 8 and 9 respectively.

$$\varepsilon_N = \frac{N}{Q} \cdot \frac{\delta Q}{\delta N} = \frac{T_s + T_w}{T_R} = 1 - \frac{T_p}{T_R} \tag{8}$$

$$\varepsilon_V = \frac{V}{Q} \cdot \frac{\delta Q}{\delta V} = \frac{T_s}{T_R} \tag{9}$$

The elasticities can be used to evaluate the influence changes in the parameters have on the overall output. Table 3-1 indicates if an increase in one of the parameters, all else equal, leads to an increase (+) or decrease (-) on the elasticities.

Table 3-1: The effect of changing parameter values on the annual transportation capacity elasticity with respect to vessel capacity and speed. The table indicates the effect of an increase in any of the parameters will have on the elasticities.

	Speed V	Capacity, N	Loading factor, L	Unloading rate	Waiting time	Distance
ε_N	-	-	-	+	+	+
ε_V	-	-	-	+	-	+

The cost can also be seen as an output, where a combination of input values (speed and capacity) results in a given cost. The three main cost components associated with a transportation vessel is the capital expenditures (CAPEX), operational expenditures (OPEX) and voyage expenditures (VOYEX).

The main cost driver of the voyage expenditures is the fuel cost. The fuel consumption is dependent on the power (P) required to maintain a certain speed for a given vessel size given expressed by equation 10.

$$P(N,V) = k \cdot N^{\alpha} \cdot V^{\beta} \tag{10}$$

Where k is a scaling factor, and α and β are model parameters, decided by either analytical, statistical or other methods.

The fuel cost (C^F) is dependent on the power required, the fuel price and sailing time.

$$C^F = p_f \cdot f \cdot P \cdot \frac{T_s}{T_R} \cdot (365 - OH) \cdot 24 \tag{11}$$

Where p_f is the fuel price and f is the specific fuel consumption (SFOC).

The fuel consumption while loading and waiting at port is additional expenses not included in 11.

The capital cost is dependent on the newbuilding price of the vessel. It is reasonable to assume that the size (capacity) and installed power (speed) is two major cost drives of the building cost. A linear relationship between the cost and capacity and speed is given in equation 12.

$$C^{I} = N \cdot k_1 + V \cdot k_2 + a \tag{12}$$

Where k_1 is the marginal cost of capacity, and k_2 is the marginal cost of installed power to maintain a given speed. A is a constant.

The building cost can be converted to an annual cost using the formula 13 (Titman & Martin, 2010).

$$P = \frac{r(PV)}{1-(1+r)^{-n}} \tag{13}$$

Where PV is the present value, r the discount (interest) rate, and n the payback time in years.

Based on the relationships above the total annual cost can be calculated for the combinations of N and V. This is seen in figure 3-8.

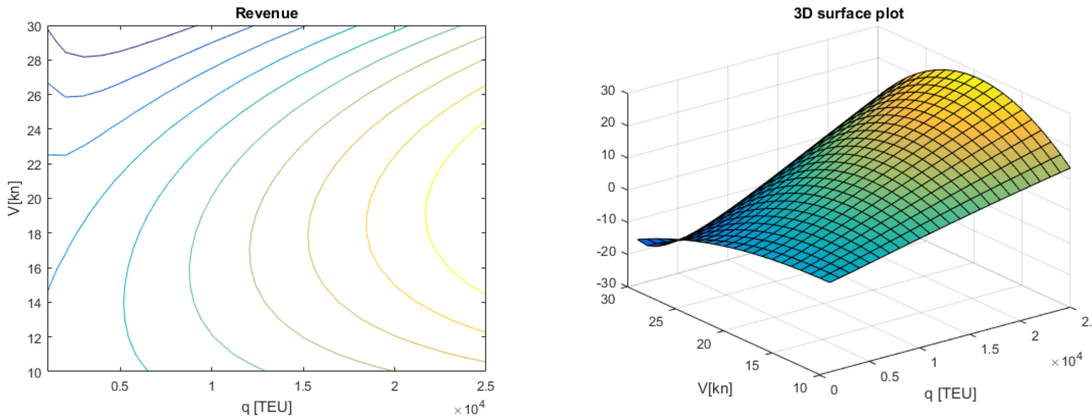


Figure 3-8: Left: Isoprofit lines showing the annual revenue as function of capacity and speed. Right: 3D surface plot of the same range and values

We can observe how the revenue is maximised when the capacity is at the upper limit, while the speed has a defined maximum on the interior. This is due to the cost of building a larger vessels in generally low compared to the revenue and the cost of increasing the speed to achieve the same capacity increase. This is an important driving force behind the upscaling of vessel size and the adaption of slow steaming in the container market.

3.5.2 Design Derived from Operating Profile

Vessels are often designed for peak operating condition, with full load and speed. In most cases it will operate in this condition only a small fraction of the time. A well designed tanker is likely to operate at maximum design speed less than 10 % of the time (Devanney, 2011). Svensen and DNV-GL (2012) presents and analysis of the operating profile of large container vessels. They found that the actual design condition made up a very small part of the operating profile.

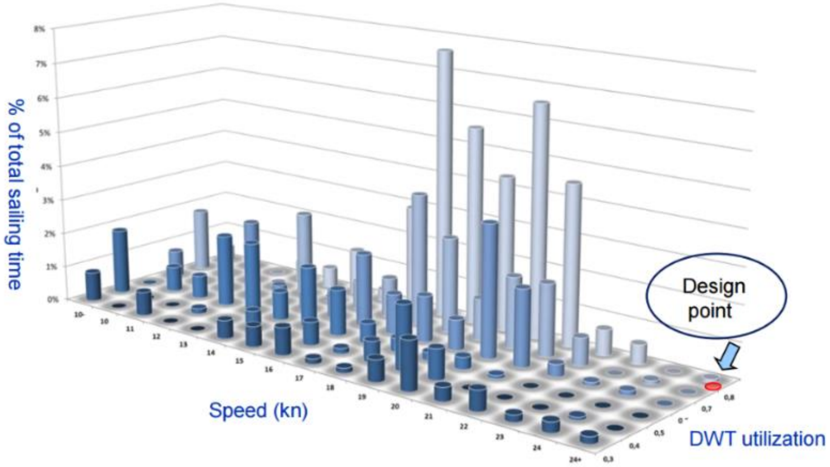


Figure 3-9: Example of operating profile and design point of large container vessel (Svensen & DNV-GL, 2012).

The extra investment cost for designing a vessel for the extreme end of the operating spectrum is significant. Major support systems, such as fuel tanks and pumps, bunkers treatment and lube oil systems are designed based on the installed power, and will have to be scaled accordingly.

Marine engines are designed to operate at a given load, usually corresponding to the expected load at the deign point. At higher or lower loads, the machinery is less efficient with a higher specific fuel consumption. A machinery system designed to operate at 85%

load at a design speed of 25 knots will only operate at about 40% load if the speed is reduced to 19 knots. In addition, other systems such as waste heat recovery is not functioning optimally at off load conditions. Figure 3-10 illustrates a typical specific fuel consumption curve for a low speed two stroke marine diesel engine. The penalty of operating at off-design conditions are significant.

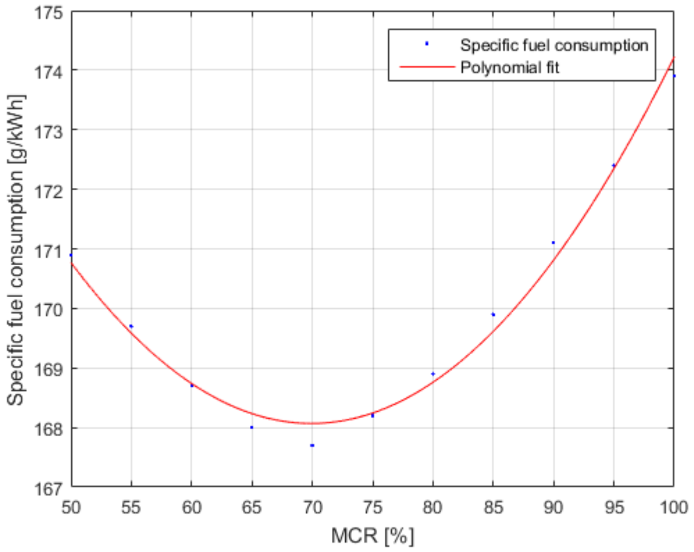


Figure 3-10: Specific fuel consumption (based on data from MAN Diesel (2016)

The operating condition is often uncertain at the time of investment, making it difficult to effectively design the machinery system.

3.6 Uncertainty

McManus and Hastings (2005) define uncertainty as “things that are not known, or known only imprecisely”. Powell and Topaloglu (2003) lists three scenarios under which uncertainties are present:

1. *“The information is not yet known, but will become known at some point in the future.*
2. *Information is known to someone, but not to the decision makers.*
3. *The information will never be known for any of a variety of economic or technical reasons.”*

The first scenario represents the standard model of uncertainty. The annoying uncertainty associated with this week's lotto numbers fall into this category. The same does a wide range of contextual factors such as the oil price one year from now or the demand for transportation of fridges from China to Europe. In the second scenario the information is known to someone, but not the decision maker. This opens for the possibility of acquiring this information, and calls for methods to assess the value of information.

The third scenario is related to the inherent residual information. Gaspar (2016) defines residual information as *"information which must remain unknown, either for reason of capability or capacity".* In real world situations the time and cost constraint is often the most prevailing when it comes to limiting the residual information. The effort to reduce residual information is related to the inherent dilemma of the design process: How much resources should be spent on exploring and on attempts to reduce the uncertainties, and how much should be spent on exploiting the existing knowledge to achieve better solutions.

McManus and Hastings (2005) develop a framework to handle uncertainties in complex systems (Table 3-2). The traditional approach has been on risk analysis and risk mitigating measures through introducing barriers and margins in the design process. In their framework McManus and Hastings (2005) relate the various aspects of uncertainties to risk, which can be mitigated or exploited by various techniques to achieve robustness.

Table 3-2: Framework for handling uncertainties and their effects (Gaspar et al., 2016; McManus & Hastings, 2005)

Uncertainties	Causes: Risk	Handled by: Mitigations/exploitations	Resulting in: Outcomes
Lack of knowledge, lack of definitions, unknown unknowns, known unknowns, statistically characterised variables	Disaster/Failure, cost schedule (+/-), need shifts (+/-), degradation, extra capacity. Emergent capabilities, market shift (+/-)	Margins, upgradeability, redundancy, modularity, design choices, tradespace exploration, verification and test, generality, portfolios and real options	Robustness, reliability, versatility, flexibility, evolvability, interoperability

3.7 Predicting future development

Historical records are often used as input in models to predict future development. The strong assumption that the past can describe the future must hold true for this approach to be used (Erikstad and Rehn, 2015).

3.7.1 Freight Rate Forecasting

The perhaps most common requirement in maritime transportation forecasting is to predict the freight rates. The classical approach is to develop a model based on the supply-demand balance. Stopford (2009) identifies ten variables effecting the supply-demand balance in the shipping market model (table 3-3).

Table 3-3: Variables in the shipping market model. (Based on Stopford (2009)).

Demand	Supply
The World Economy	World Fleet
Seaborne commodity trade	Fleet productivity
Average haul	Ship building production
Random Shocks	Scrapping and losing
Transport Costs	Freight Revenue

The macroeconomic shipping model is illustrated in figure 3-11. The fundamental inputs to determine the supply-demand balance is the demand of sea based transportation of goods and commodities and the available fleet.

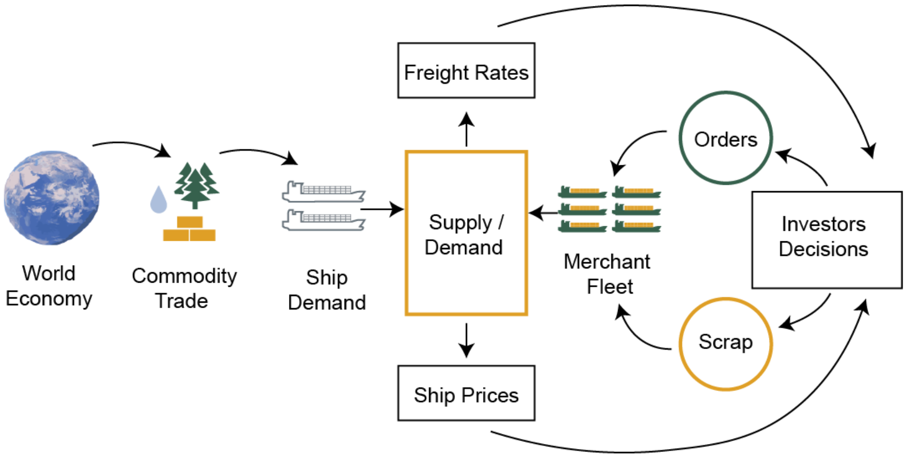


Figure 3-11: Macroeconomic shipping model (based on Stopford (2009)).

Ezekiel (1939) book “*Tanker Freight Rates and Tankship Building: An Analysis of cyclical Fluctuations*” represents one of the earliest analysis of the maritime transportation market. The title reveals that the cyclical characteristic of the shipping market have been known and addressed for a long time. Stopford (2009) describes four phases of a typical shipping cycle:

1. Trough: The market is characterized by surplus capacity with freight rates falling to the operating costs of the least efficient vessels. The second hand and scrapping market is active. Combined with limited new building this leads to the beginning of recovery.
2. Recovery: Supply and demand moves towards balance and the market is characterized by signs of optimism as laid up tonnage is put back into use. The freight rates and newbuilding activity increases.
3. Peak/Plateau: During the peak all available capacity operates at full speed, and the freight rates can be several times greater than the operating costs. High level of new building and trading.
4. Collapse: As the supplied capacity passes the transportation demand the rates collapses. The long lead time on new capacity, typically around 18 months, results in new tonnage being delivered in this period, resulting in additional downward pressure on the rates.

Models based on asset pricing have gained traction the last couple of decades in maritime forecasting. The framework is based on financial valuation were stochastic processes are often used for modelling fluctuation in assets over time. Two types stochastic processes are often associated with maritime freight rate forecasting: The Geometric Brownian Motion (GBM) and a mean-reverting process (MRP) (Manzanero & Krupp, 2009). Equation 14 gives the stochastic differential equation for the GBM.

$$dY_t = \mu Y_t dt + \sigma Y_t dZ_t \tag{14}$$

Where μ expected growth rate, σ is the standard deviation of the incremental relative change in Y_t and dZ_t is the increment of a standard Brownian motion, that is often implemented as normally distributed random number, $dZ_t \sim N[0, dt]$. As the expected value are not dependent on past movement the GBM is path independent. The famous Black-Scholes formula used to value financial options uses the GBM process (Black & Scholes, 1973). Tvedt (2003) uses the GBM to model the dynamic in the demand for shipping services.

Mean reversion refers the tendency of a time series to centre around a long term average value. The Ornstein-Uhlenbeck process is mean reverting process given by equation 15.

$$dY_t = \kappa(\bar{Y} - Y_t)dt + \sigma dZ_t \tag{15}$$

Where κ is the drift, or mean reverting rate, and $\bar{Y}$ is the long-term mean. The notation is otherwise the same as for the GBM.

Bjerksund and Ekern (1992) uses the Ornstein-Uhlenbeck to model the spot freight rates. The theoretical foundation for the cyclical nature of the shipping market is often used as a basis for modelling the freight rates as a mean reverting stochastic process (Tvedt, 2003). Manzanero and Krupp (2009) presents a literature review showing mixed results when comparing the results of empirical research to assess the suitability of MRP to model freight rates in shipping.

The dynamic interaction between the supply and demand balance and the freight rates in maritime transportation have been studied extensively. Beenstock and Vergottis (1993) developed a market equilibrium model for the tanker and dry bulk market (see also Beenstock & Vergottis, 1989a, 1989b). Beenstock and Vergottis developed their model based on the assumption of explicit profit optimization on the supply side and perfect competition on the demand side. Manzanero and Krupp (2009) argues that the demand and supply in the container liner industry are both flexible enough that the assumption made by Beenstock and Vergottis is applicable. Based on this they develop a dynamic model for the liner industry. They start by assuming that the number of new orders placed in year t are proportional to the industry profit:

$$N_t = \eta * Profit_t \tag{16}$$

Where the profit is a function of the freight rates, fixed cost and the fuel price. Stopford (2009) emphasizes that the relatively long lead time in investment in new tonnage makes the new capacity entering the market dependent on new building decisions made 18 months earlier. Equation 17 express the change in capacity in year t.

$$\Delta X_t = N_{t-\theta} - S_t \tag{17}$$

Where θ is the average lag, the time from placing and order until the vessel is available in the market. S_t is the scrapped capacity.

The change in freight rates, P, is given by:

$$\Delta P_t = \delta(\Delta Y_t - \varphi \Delta X_t) \tag{18}$$

Where δ is the adjustment factor due to the demand and supply shifts, and φ is the TEU slot productivity (annual reuse rate). To model the change in freight rates the properties of the demand and supply curve most be known. Some factors such as marginal cost pricing and the ability to influence the capacity by operational measures on the supply side and the cost of alternatives on the demand side can be used. However, to develop an analytical demand and supply description that have good predictive capabilities have proven difficult (Manzanero & Krupp, 2009). The coefficients in demand-supply dynamic model can alternatively be estimated by statistical analysis of observed changes in the freight rate in response to shifts in the past (Luo, Fan, & Liu, 2009).

3.8 Designing for Future Uncertainty

Benford (1967) approaches the design problem of cargo ship as matching the right design, with focus on size, to the typical mission cargo forecast. The demand for transportation is here modelled for the lifespan of the vessel with seasonal fluctuations on the inbound and outbound leg. As illustrated in Figure 3-12 the optimal size is found in a range between the minimum and maximum of the expected available cargo.

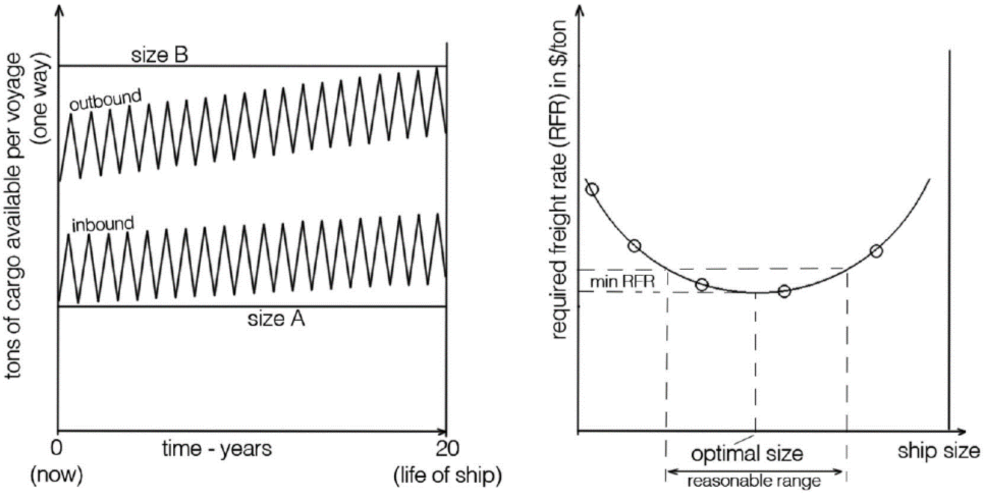


Figure 3-12: Typical cargo forecast and optimal ship size (Benford, 1967).

Benford (1967) used the required freight rate as an utility function to represent the value of the vessel. The notion of an optimal ship size defined by a convex utility function is widely used (see e.g. Jansson & Shneerson, 1982). The convexity of the unit transportation function has its basis in the operation of a vessel, and the economies and diseconomies of scale present at the various stages. According to Britannica Academic (2015) economies of scale is defined as "*the relationship between the size of a plant or industry and the lowest possible cost of a product*". This definition can be adapted to the world of maritime transportation by regarding the vessel as the plant and the transportation of goods as the product. The cost of transportation increases less than the increased capacity as the size increase, and there is a general consensus that it exists economies of scale when considering the sea transportation leg. When considering the handling of the cargo, that is the port operation, storing and intermodal transportation beyond the sea leg, there is reason to believe that after a certain point we see diseconomies of scale (Tran & Haasis, 2015). Jansson and Shneerson (1982) argued that as the unit transportation cost as a function of capacity decreased for cargo transportation and increased for the cargo handling. The total unit cost is thus a convex function, and the optimal size is found when the marginal change of these contributions are equal, i.e. when the decrease in transportation cost is counterbalanced by the increase of the handling cost.

Extension of the ship size problem is represented in a range of literature. Notable extension includes modelling the effective vessel capacity as a function of the size and speed, allowing the two design variables to be defined independent of each other, and considering the entire fleet, determining the optimal mix of vessels with different characteristics (see e.g. Christiansen, Fagerholt, Nygreen, & Ronen, 2007).

Shipping markets are known to be extremely volatile. The traditional approach in marine design have been to assume a fixed set of requirement. Scenario analysis are then performed based on the most likely outcome, and uncertainties are handled by sensitivity analysis of the final design (Collette et al., 2015). Gaspar (2013) argues that this approach will not be sufficient in the future: *"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"*.

3.8.1 Flexibility

There are examples of flexibility being used as a strategy to handle uncertainty in marine design. Flexibility is one of the most mentioned *ility,* both in scientific publications and in the general media (De Weck, Roos, & Magee, 2011). Ilities are a common term for the desired properties of a system. They often, but not always, end with -ility (reliability, flexibility, quality, robustness). These properties are not the primary functional requirements, but typically concern the wider impact with respect to time and stakeholders (De Weck et al., 2011).

De Weck et al. (2011) shows how flexibility has two main manifestations: operational flexibility and flexibility related to redesign. A vessel with a large fuel capacity is flexible in terms of range and the ability to change between short and longer routes. This is flexibility in the regime of operation. How easy a system can be adapted or modified to accommodate a new function is flexibility in the regime of redesign. Converting an oil tanker into a floating storage and offloading vessel is an example of flexibility related to redesign.

Operational flexibility can be achieved by multifunctionality. By installing additional equipment and specialized arrangements, a vessel can serve different segments within a market or various markets. This is most common in the specialized offshore segment. Ulstein and Brett (2015) points out the importance of avoiding *"design for multi uselessness"* when facilitating for multifunctionality. The now obsolete combined wet and dry bulk carriers are an example of multifunctionality applied to the design of merchant transport vessels. They proved commercially tricky to operate, and are no longer popular (Gaspar et al., 2016). Tankers able to transport a range of petroleum products and car-carriers with hostable decks are examples of more successful strategies involving flexibility.

Flexibility are closely related to several other *ilities.* De Weck et al. (2011) found that ilities such as robustness, modularity, extensibility, scalability, modularity and adaptability are often mentioned in the same context as flexibility.

3.9 Design for Value Robustness

It is useful to introduce this section with specify what we mean with value robustness. In this work we have focused on one general definition applicable to all systems, and one interpretation found useful in ship design.

First, the general definition:

- Adam M. Ross and Donne H. Rhodes (2008)
  "The ability of a system to continue to deliver stakeholder value in face of changing context and needs."

And the interpretation for marine design:

- Gaspar et al. (2016)
  "Rather than maximising the value delivered by the ship in one situation, we need to maximise it over a range of expected situations and the preferences of the owner."

The degree of robustness required by a system is related to the degree of uncertainty. Saleh (2001) relates the choice of design strategy to the change and uncertainty in the environment and objectives during the lifecycle (Table 3-4).

Table 3-4: Design strategy related uncertainty in context and objective (Based on Saleh (2001))

Environment Objective	Fixed	Changing / Unknown
Fixed	Optimized Design	Robust Design
Changing	Poor Design	Flexible Design

It is common to distinguish between active and passive value robustness. Passive value robustness is achieved by maintaining value through changes during the complete life cycle, while active value robustness is achieved by strategies for changing and adaption of a system to meet changes (Ross & Hastings, 2008). In this thesis we will primarily focus on passive value robustness. Active value robustness is to large extent overlapping with flexibility.

3.9.1 Stochastic Programming

In operation research, traditionally contextual aspects are handled by post processing to assess the sensitivity of the solution to changes in the parameters (Lundgren, Ronnqvist, & Varbrand, 2010). Stochastic programming extends the scope of traditional operation research to handle future uncertainty by portioning the decisions into two sets (Diez & Peri, 2010). The first set contains variables that have to be decided before the uncertainty is resolved, while the second set of variables is decided at stage two, after the stochastic parameters are known. The problem is solved as nested loop, combining the robustness of the first stage and the flexibility of the second stage decision (Diez & Peri, 2010).

A two-stage stochastic problem can be written on the general form (Birge & Louveaux, 2011):

First Stage:

$$\min\ C^T \mathrm{x} + E_w Q(x, w) \tag{19}$$

$$\mathrm{Ax} = \mathrm{b} \tag{20}$$

$$x \geq 0 \tag{21}$$

Here $E_w Q(x, w)$ is the expectation of the second stage problem, given by:

$$Q(x, w) = \min\ d_w^T\, y \tag{22}$$

$$T_w x + W_w y = h_w \tag{23}$$

$$y\ \geq 0 \tag{24}$$

Here w represent a scenario given as a realization of the uncertain contextual and operational conditions. x denotes the first-stage variables and y the second stage variables. The parameters (any or all of) d, h, W and T are realization of the stochastic process. 5 describes the relationship and between the stages restricting the opportunity space in the second step.

In the first stage we minimize the cost of the first stage decision and the cost of the expected second stage decision.

Figure 3-13: Two stage stochastic decision process (adapted from Popela, Novotný, Roupec, Hrabec, and Olstad (2014))

The two nested loop structure of the two stage problem increases the complexity and the computational burden significantly. It is also possible with more than two stages, which increases the complexity significantly (Dyer & Stougie, 2006).

4 Complexity in Systems Engineering

De Weck et al. (2011) discusses how engineering have evolved since the industrial revolution, from focusing on relatively narrow technical problems to addressing complex sociotechnical engineering systems. The increasing complexity can be seen as a result of increasing interactions and dependencies between systems. De Weck et al. (2011) introduce the following definition of engineering systems:

> *"A class of systems, characterized by a high degree of technical complexity, social intricacy, and elaborate processes, aimed at fulfilling important functions in society"*

4.1 Ships as Complex Systems

The notion of a ship as a complex system can be found in several publications. Evans (1959) described ship design as "extremely complex problems", emphasising that they are complex structures with a transportation function. Hagen and Grimstad (2010) argues that the transportation need should be the starting point for the design process. Figure 4-1 illustrates the hierarchic system that a ship is part of. The main postulate made by Hagen and Grimstad (2010) is that we need to extend the boundaries of ship design to include the entire logistic chain, i.e. start from the right in figure 4-1 and work our way down the hierarchy. By incorporating this extended view, the ship as part of a transportation network meets the definition of a highly complex engineering system by De Weck et al. (2011).

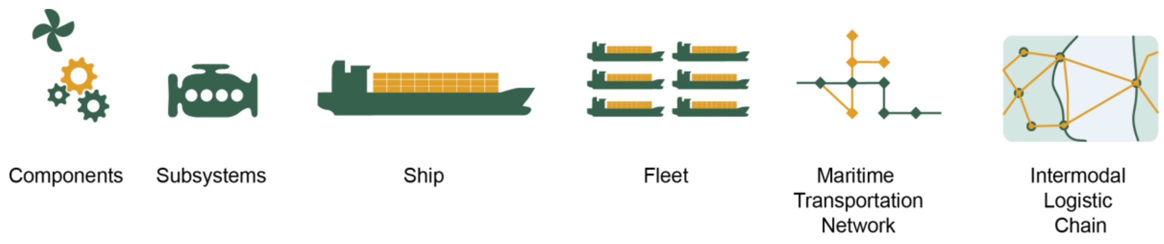


Figure 4-1. Hierarchy of complexity in marine systems (adapted from Gaspar (2013)).

4.2 Five Aspects of Complexity

Rhodes and Ross (2010) introduce five aspects of complexity to be considered in the engineering of complex systems. Systems engineering is a field of engineering that focuses on the design and management of complex systems. The traditional systems engineering methods addresses the structural and behavioural aspects of complexity, while the contextual, perceptual and temporal aspects extend the boundary of the design problem.

4.2.1 Taxonomy of Complexity Applied to Ship Design

Gaspar (2013) applies the five-aspect taxonomy to conceptual ship design:

Structural. The structural aspect is related to the form of the system and components. The ship can be considered as a large, self-contained, system, with several integrated and interconnected subsystems. The propulsion system is one such subsystem, which again consist of several components and other subsystems. All components are subject to weight and volume constraints, and the high degree of interactions and interdependencies constitutes a significant aspect of complexity.

Behavioural. Related to the performance of the vessel, and the response to external stimuli (e.g. waves) or internal stimuli from a subsystem (e.g. the propeller). In conceptual ship design this complexity is addressed by technical analysis to derive the performance measured by key performance indicators (KPIs), such as air emissions and the seakeeping performance.

Contextual. Contextual aspects addresses factors outside the control of the ship designer, that may affect the behaviour and performance of the system. External influence can be divided in three categories: market (transportation demand, fuel prices), technological (new hull form or fuel) and political (taxes, emission regulations).

Temporal. The temporal aspect is related to the uncertainty in the external context. The lifecycle of most vessels are at least 20 years, and there are likely to be many shifts in context during that period. The temporal aspect to be quantified by relating the contextual parameters to an operational profile. If a set of parameters describing context A, the operational profile will be given as B, and then design X will deliver the best value. A change in the parameters can result in a different context and operation, and design Y might perform better. For instance, stricter emission regulations can lead to a change in the type of fuel used, and a different machinery arrangement will be necessary.

Perceptual. Several stakeholders will perceive the value of design decisions differently based on their preferences, perceptions and biases. A ship owner who buys a ship for the chartering market might value a flexible ship that is attractive to a range of customers, while the charterer will put greater emphasis on how well the design matches their specific use. A broader set of stakeholders include the shipyard, which might value standardized design and large series of ships, while comfort and safety is more important to the crew and the labour organizations. Perception of value can shift as the context change, thus including the temporal aspect.

The three extended aspects have generally not received as much attention in the design of engineering systems. Rhodes and Ross (2010) argues that they in fact have not "received adequate attention given their importance to engineering value systems." The reasons why the three emerging aspects have not received as much focus is likely to be due to lack of well-established techniques to handle and control the uncertainties they represent (Adam M. Ross & Donna H. Rhodes, 2008). However, as Gaspar et al. (2016) notes: "*not being able to fully control these elements, does not mean that one is unable to obtain some understanding and some level of cause-consequence relationship*".

From Evans (1959) single point design approach focusing on technical feasibility, to the inclusion of market forecast to support a rationale selection of principal dimensions based market forecasts (Benford, 1967) representes a significant increase in information to consider during conceptual design. By expanding the designspace and evaluate a range of designs in parallel in set-based design increases the available data further. The systems engineering approach, and inclusion of the emerging aspects of complexity signifies another level of information. The same does Hagen and Grimstad (2010) call to extend the boundaries of ship design. One measure of complexity is related to the number of components or amount of information needed to describe the system. By this definition the significant information growth in ship design translates to increased complexity, and the requisite for methods to incorporate this.

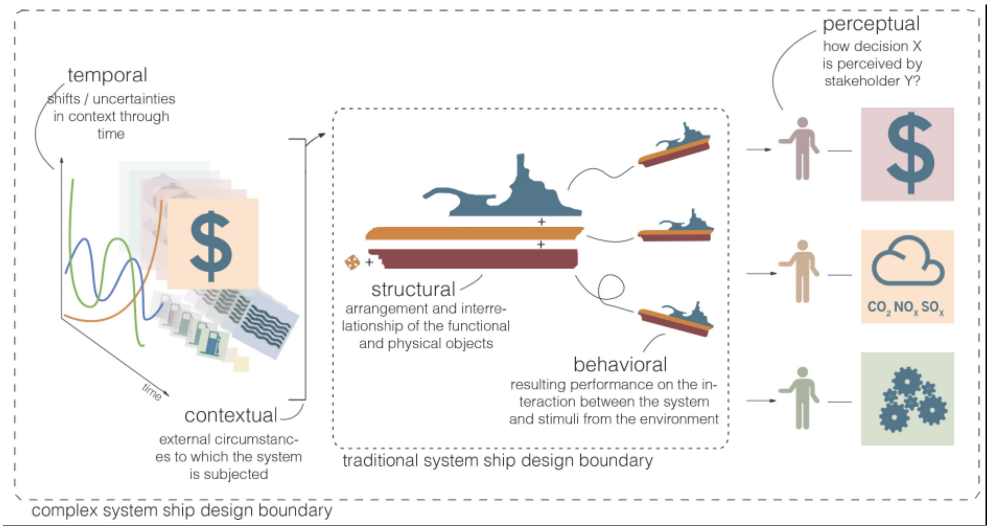


Figure 4-2: Five aspects of complexity applied to conceptual ship design (Gaspar, 2013).

4.3 Handling Complexity through Decomposition and Encapsulation

As mentioned, the idea of complexity is related to the amount of information. In *Architecture of complexity*, Simon (1962) proposes an understanding of complex systems a hierarchy of simpler subsystems, or said with the authors own eloquent words: "*on theoretical grounds we could expect complex systems to be hierarchies in a world in which complexity had to evolve from simplicity.*" Just as in nature, decomposition in systems engineering describes the process of breaking down a system into more comprehensible subsystems.

Simon (1962) related the decomposition to the formation of hierarchies, making the hierarchy illustrated in figure 4-1 a visualisation of the decomposition of a marine transportation systems.

Decomposition leads to the concept of encapsulation of the parts. Encapsulation aims to simplify the interconnections between parts and subsystems (Gaspar, 2013). By regarding a system as a “black box function”, only defined by a set of inputs (variables) and outputs (performance) (Gaspar, Ross, Rhodes, & Erikstad, 2012). Figure 4-3 illustrates the principal of the decomposition/encapsulation strategy from a systems engineering point of view.

The concepts of decomposition and encapsulation as a general strategy is central in most approaches to conceptual ship design. Evans (1959) design spiral and System based ship design (Levander, 2012) are both examples of design methodologies that utilizes the principle of dividing the overall problem into manageable chunks of information, or subsystems, (decomposition) with clearly defined functional interactions (encapsulation).

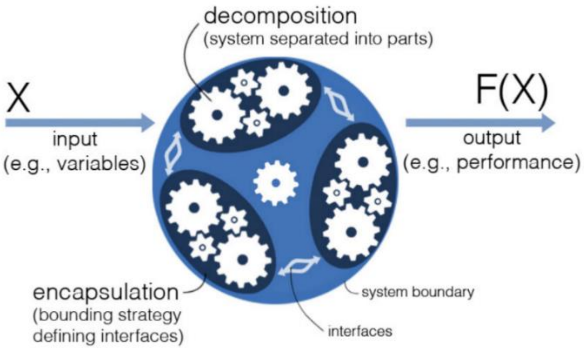


Figure 4-3: Decomposition and encapsulation to handle complexity in systems (Gaspar, 2013).

The traditional aspects of complexity, structural and behavioural, are in general handled well by state of the art design approaches and models to perform the form-function mapping. In this reports the contextual aspect will be handled by decomposing market development to reflect changes in trades, and encapsulate the changes to determine trade specific utility of transportation vessels. The temporal aspect will be handled by epoch-era analysis. The life span of the vessel is decomposed to static epochs, and eras are constructed from epochs to encapsulate changes and uncertainties.

5 Methodology: Design for Value Robustness

5.1 The Responsive Systems Comparison Method

The framework and illustrative case presented in this paper is based on the Responsive Systems Comparison (RSC) method. Rhodes and Ross (2010) states the following objective for using the RSC method:

> "*The goal of the method is to generate knowledge about trade-offs, compromises, and risks to a system development project, and identify system concepts that are actively and/or passively value robust.*"

The RSC method is a recent methodology developed as part of the systems engineering advancement research initiative (SEARI) at the Massachusetts Institute of Technology (MIT) (Ross et al., 2009; Adam M. Ross & Donne H. Rhodes, 2008). The RSC methodology is not a stand-alone technique, and it can be combined with traditional and emerging design methods (Gaspar, 2013). In the case study the RSC method is combined with classical engineering techniques and marine design principals in order to merge the system engineering approach with marine design principals.

The method has shown its adaptability for a wide range of complex system design problems. Ross et al. (2009) demonstrated its use in the space industry for the design of a satellite radar system. In the marine industry it has been applied in the conceptual design of naval vessels (Schaffner, 2014), and H. M. Gaspar, Dh Rhodes, et al. (2012) uses an anchor handling vessel as example to illustrate the use of RSC to achieve value robustness.

5.1.1 The Seven Steps of the RSC method

Here we will present the outline of the RSC method, and describe the individual parts. The method is described through a seven process framework (Ross et al., 2009), describing the design process from problem definition, to concept generation, evaluation and selection.

Step 1: Value-driving Context Definition

The goal of the first step is to identify the overall problem, and capture the problem statement: What is the problem, why is it important, and who care about the solution (Ross et al., 2009). At this stage it is important to filter the information and establish the overall criteria for a value robust design. The outcome from this stage should include an value proposition, key constraints, and the stakeholders and contexts to consider (H. M. Gaspar, Dh Rhodes, et al., 2012).

Step 2: Value-driven design formulation

The second process consists of identifying a range of important performance attributes based on the value proposition from step 1. These attributes are the criteria used to measure the “goodness” of the design alternatives (Ross et al., 2009). Based on the attributes the designer develops one or several main concepts, each with a set of associated design variables. The design variables are represented as discrete variables, making it possible to enumerate the design space (Pettersen, 2015). The discretization of design variables captures and handles the structural aspect of the five aspect taxonomy through decomposition (Gaspar, 2013).

Step 3: Epoch characterization

In the third step we seek to characterize uncertainties related to the contextual aspect (Ross et al., 2009). This is done by deriving a set of parameters, decomposing the complexity related to future uncertainties (H. M. Gaspar, Dh Rhodes, et al., 2012). In the same way as the design variables defines the design space, the epoch-parameters define the complete set of considered future scenarios, the epoch-space. Each of the epoch-variables has a defined range. A vector of epoch variables describes an interval of time with fixed set of contextual factors. This snapshot of the operating context is a single epoch (Adam M. Ross & Donna H. Rhodes, 2008). The change of one or several of the parameters results in a change to a new epoch, describing an alternative potential context. The third step is completed by formulating the relationship between the design and epoch variables and the performance attributes. This can be related to the design process as the analysis step, or the mapping from the design- to performance space. The set of epochs allows for evaluation of the performance across a range of different manifestations of future situations. (Ross et al., 2009).

Step 4: Design Tradespace Evaluation

In the fourth step the design space, the span of enumerated design variables are evaluated for each epoch (Ross et al., 2009). The RSC framework offers great flexibility when it comes to choosing the model(s) and method(s) to use for the evaluation. Several traditional design methods exist for calculating attributes from a set of design variables, such as analytical and discrete models, regression analysis and simulation-based approaches (H. M. Gaspar, Dh Rhodes, et al., 2012). The choice of methods will often be similar as the once used during the mapping from performance to value space, the evaluation phase in the design loop.

Based on the criteria determined in step 2, the attributes attained through the evaluation can be aggregated to a single measure of goodness for each design represented by a utility value (Ross, Rhodes, & Fitzgerald, 2015). The main goal of the stage is to decompose the behavioural aspect of complexity, and gain understanding of the trade space and how key system concepts and trades (design variables) fulfil the overall value-space (attributes) in response to contextual uncertainties (epochs) (Ross et al., 2009). After this stage the design space is typically presented as a scatter plot, where the utility vs cost (both investment- and lifecycle cost are used) is plotted. Each point represents a feasible design for the given epoch.

Step 5: Multi-epoch analysis

As a result of step 4 we have a large amount of data. In step 5 the objective is to apply techniques to analyse the performance of the designs across the epochs (H. M. Gaspar, Dh Rhodes, et al., 2012). The goal is to identify design that are passively value robust and perform well across a range of expected contextual situations. Designs with the highest utility for a given cost is referred to as non-dominated. Non-dominated designs are so called Pareto-optimal, and make up the Pareto front (Ross et al., 2009). For any given epoch the design that maximises the utility for any given budget constraint is found among the set of Pareto optimal designs. The performance and utility of a design is context dependent, and the Pareto optimal design will vary across epochs. The Pareto trace is a number indicating the frequency of which a design is non-dominated when considering a range of epochs (Ross et al., 2009). A high Pareto trace indicates that a design delivers value in the face of changing context and is therefore value robust.

A complete multi epoch analysis can become computational expensive and potentially obscure the evaluation. Depending on epoch characterization defined in step 3 some combination of epoch parameters might be infeasible or very unlikely to occur. Ross et al. (2009) discusses how tradespace yield, the percentage of designs found feasible in a given epoch, can be used as a criterion for epoch selection. It is also possible to backtrack from step 6, and limit the analysis to the epochs that are included in an era (Pettersen, 2015).

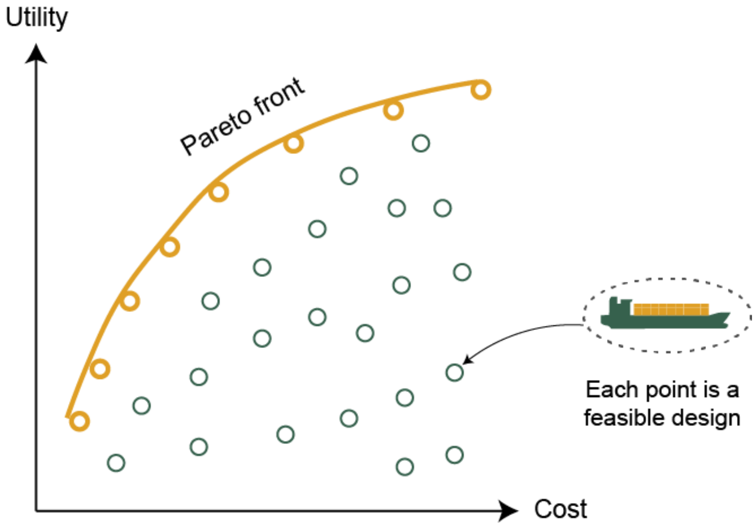


Figure 5-1: Tradespace with Pareto front highlighted

Step 6: Era construction

An era is a set of epochs organized as a timeline. An era represents an entire possible lifecycle of the system (Adam M. Ross & Donna H. Rhodes, 2008). An epoch can be visualized as a single frame of a film reel, representing a static snapshot. Several single frames placed on a timeline can result in movement, and represent change in context.

In the sixth step various potential eras is generated. Eras can be constructed manually to reflect and capture the expectation of stakeholders or expert opinions (H. M. Gaspar, Dh Rhodes, et al., 2012), or based on computational methods based and a set of epoch transition logic rules (Roberts, Richards, Ross, Rhodes, & Hastings, 2009). It is important to adhere to some consistency rules and continuity constraints when constructing eras in order to not break chronology (Gaspar, Erikstad, & Ross, 2012). A new technology development are not likely to disappear from one epoch to the next as we progress, and the probability of a new regulation being reversed should be carefully considered.

Step 7: Lifecycle Path Analysis

In the final process we seek to answer two main questions: “Which modification do the design need to perform better within a given era? And what are the costs and benefits of these changes?” (Gaspar, 2013). It is possible to use statistical methods to assess the relative importance of the design variables on the utility, and identify design, operation and management strategies to achieve value robustness. Various methods can be used at this stage. H. M. Gaspar, Dh Rhodes, et al. (2012) discusses how to include calculations of return on investment (ROI) for various periods, and (Pettersen, 2015) uses real option analysis to value flexibility at this stage.

The RSC framework was built around already existing systems engineering methods to create a combined application to complex system design (Schaffner, 2014). The two most important methods are methods Multi-attribute tradespace exploration (MATE) and epoch-era analysis (EEA). The two methods can be applied independently of each other, or in combination with other methods and approaches.

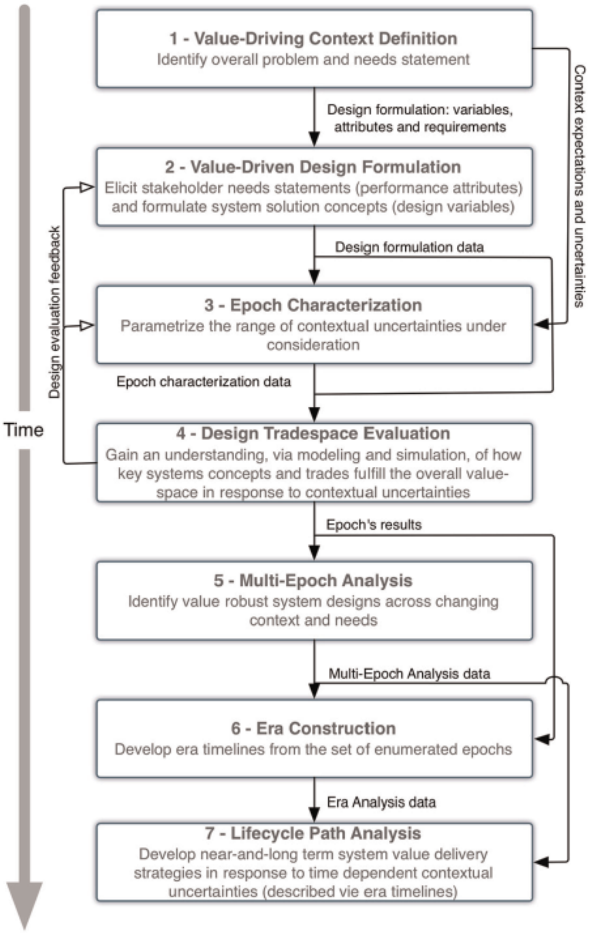


Figure 5-2: The seven steps of the responsive system comparison method (Gaspar, Balland, Aspen, Ross, & Erikstad, 2015).

6 Container Shipping and Vessels

Container shipping is one of the main segments in merchant shipping. In this chapter we will describe the market as a basis for the case study presented in chapter 7. Parts of this and the next chapter are based on the project thesis written last semester (Dickens, 2015).

6.1 The Vessel and Fleet

Containers are transported by purpose-built container vessels, fitted with cell grids to accommodate stacking of containers. Container ships are categorized based on their cargo capacity, measured in terms of the number of twenty foot equivalent units (TEU) they can carry. One TEU is one standard sized 20-foot-long container – making one 40-foot standard container (FEU) equal to two TEUs.

Table 6-1: External dimensions of the standard shipping containers

	Length		Width		Height			
					Standard		High Cube	
	feet	meters	feet	meters	feet	meters	feet	meters
20 foot	20'	6.06	8'	2.44	8' 6"	2.59	-	-
40 foot	40'	13.72	8'	2.44	8' 6"	2.59	9' 6"	2.90

Container vessels are categorized based on their principal dimensions and cargo capacity. The most common categories, along with the current fleet and typical usage are presented in table 6-2.

Table 6-2: Classification of container vessels. Based on (Clarkson Research, 2015).

Cargo Capacity	Type	Current fleet	Comment
100-1,000	Feeder	1069	Used on short distance, intra-regional trades and niche operations. Used as feeders to connect smaller ports to larger hubs on the major trade lines.
1,000-2,999	Handy / Sub Panamax	1885	Used as feeder vessels on larger intra-regional trade routes. Also used on some North-South trades.
3,000-5,000	Panamax	844	Main dimensions small enough to pass through the Panama Canal locks. They are unhindered in terms of operating, and have been seen as a "work horse" of the sea. Used on a wide range of trades. With the expansion of the Panama Canal they are losing their importance.
3,500-8,000	Post Panamax / Large container-ships (LCS).	680	Overlap the Panamax segment in terms of capacity, while the principal dimensions are too large for the current Panama Canal. Deployed on a variety of routes such as large volume intra-regional, North-South routes and trans-Atlantic and transpacific.
8,000-12,000	Post Panamax / Very Large container-ships (VLCS)	531	Mainly been used on the main East-West routes. Affected by the cascading, and we are starting to see these vessels on main north-south routes (currently 13% now operating on North-South trade lanes).
12,000+	Ultra large containerships (ULCS)	237	The first 12,000+ TEU vessel where built 10 years ago, and the fleet have been rapidly growing since. Principally used on the Far East-Europe routes, where this segment makes up 70% of the capacity.

6.2 Cargo and Market

The container market is close to the costumer, and the demand for cargo have followed the economic development, while historically at a higher pace. Between 1983 and 2005 the world GDP grew by 4.8 per year, in the same time the volume of containerized cargo grew by 10 % (Stopford, 2009), indicating that container growth followed the world economic growth with a factor of 2.1 in this period. This number is known as the GDP-multiplier, and is an important tool in analytical forecasting. At the same time the export value of manufactures grew by 6.8 %. The fact that container growth was substantially higher than the general growth is due to the increasing containerization. Continuously new products were being transported by containers in this period taking market shares from other segments. .

Some research indicate that the level of containerization has plateaued, and that the offshoring of production is approaching its limit. This would indicate a lowering of the GDP multiplier, and in an analysis by BCG (2015) the forecasted GDP multiplier would be 1.3 over the next four years.

6.3 Operation and Trade Routes

The container fleet operates as liner services. These type of operations are relatively new in the history of shipping, dating back to when the steam ship technology of the late 1800s allowed for reliable voyage times, not dependent on the wind and currents (Stopford, 2009). Container liner services are by some referred to as the busses of the ocean, as they operate much the same way as bus or airline services, with a regular schedule with predetermined port calls at defined times. One route can contain two or more port calls and be organized with the same port calls both ways or as a roundtrip. The routes are referred to as liner services, loops or trades.

The main trades are located along an east-west line. From the Far East you have one important service network going west to Europe, and another going east to Canada and the U.S. The east-west network is completed with a major trade route across the Atlantic, from Europe to North America (Rodrigue & Slack, 2013). In addition to the main-lane routes, there are several trades going North-South, with South America and Oceania as two important sectors.

6.4 Functional System Definition for Container Vessels

A functional breakdown for container vessels is done to address the structural and behavioural aspects of complexity through decomposition and encapsulation (Gaspar, 2013). The functional breakdown is based on the system based design methodology (Levander, 2012). This is used as a basis for the second step of the RSC method: the identification and discretization of design variables, and for modelling the relationship between design variables and attributes.

A part of the system based ship design methodology a high level hierarchy is based separating the payload- and ship systems.

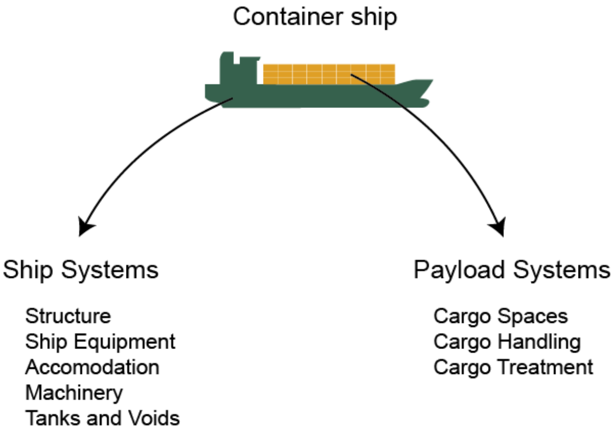


Figure 6-1: Functional system breakdown of container vessel (based on Levander (2012))

In the case we focus on the cargo space, defined as the capacity in number of TEUs. The hull provides the buoyancy and structural integrity necessary to support the cargo. The machinery system is the second main focus of interest in the case study. The main machinery need to be sufficient to maintain the desired design speed in the given operating conditions.

6.5 Uncertainties in Future Operating Context

Several factors influence the operating context of merchant vessels, and sources of uncertainties are present in various dimensions. Erikstad and Rehn (2015) provide an overview of uncertainties present in marine system design (table 6-3)

Table 6-3: Examples of uncertainties in marine systems design, based on Erikstad and Rehn (2015)

Field	**Examples**
Economic	Oil prices, freight rates, interest rates, supply/demand, gross domestic product, geographical production distribution
Technology	Energy efficiency improvements, lifetime enhancements
Regulatory	Emission control areas, ballast water treatment
Physical	Infrastructure restrictions (ports, canals, bridges etc.), sea states, sea ice, extreme weather

The economic factors are directly related to the macroeconomic supply and demand model discussed in section 0. Technological developments can be separated in two categories: (1) gradual and expected efficiency improvements, and (2) disruptive developments shifting the entire market balance. The latter is notoriously difficult to predict when it comes to timing and influence. The adaption of mission control areas (ECA) are a regulatory development that have had, and continues to have, great influence on the market. Vessels operating within defined control zones must comply with limitations dictating the maximum allowed emissions of sulphur and/or nitrogen oxides.

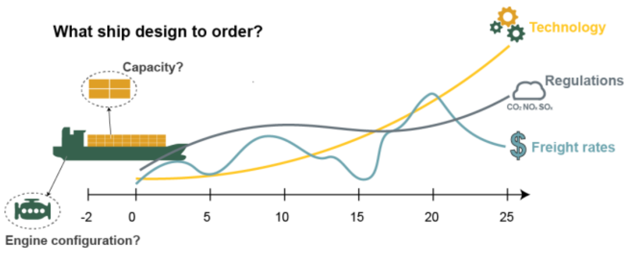


Figure 6-2: design problem under uncertainty

7 Container Vessel: Design for Value Robustness

In this chapter we will demonstrate some of the principals and methods discussed. The goal is to illustrate a possible strategiy for designing a value robust container vessel given uncertainties in the operating context.

7.1 Case Description

About 50 % of the container fleet is owned by independent ship owners that charters vessel to the liner companies. Figure 7-1 illustrates the market mechanisms. This case study is developed based on the viewpoint of an independent ship-owner.

The independent ship owner faces two principal sources of uncertainties. The first is the classical sources shown in table 6-2. These are the uncertainties related to be contextual aspect. The second aspect of uncertainty is how the liner companies adapt their operation to the contextual changes. A change in external parameters will influence the liner companies network decisions, which will influence the characteristics of the vessel they will demand. The recent adoption of slow steaming is an example that illustrate this. Since the 2007 financial crisis supply grew faster than demand. This caused a collapse of the freight rates. To save cost and effectively reduce the excess capacity the liner companies reduced the average speed, adding extra vessels to maintain service frequency. Ship owners that had attractive vessels for this change had a better position.

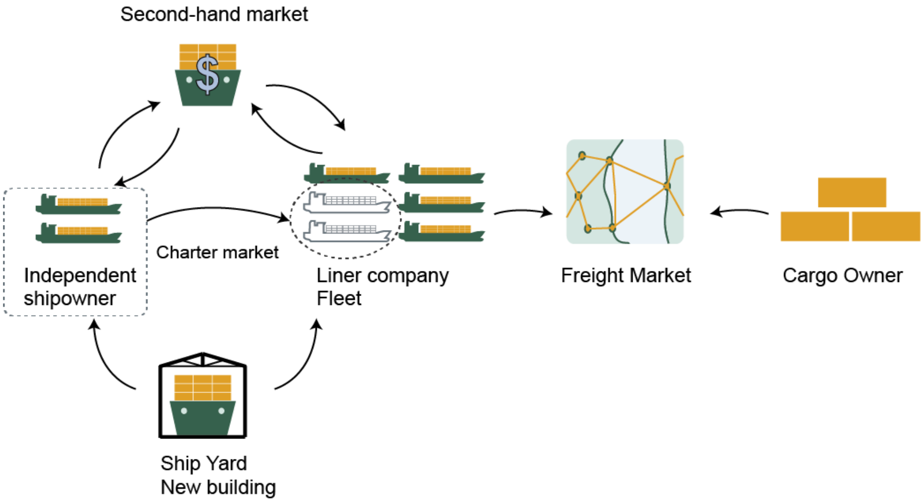


Figure 7-1: Principal actors in the container shipping market

7.2 Choice of Methodology

The responsive system comparison method are used as on principal framework in the case study. The RSC provides a structured approach to including several of the desing approaches discussed previously. The parametrization of the design space are similar to the set-based design approach as several solutions are generated at the same stage. The inclusion of epoch-era analysis (EEA) provides the basis for incorporating the contextual and temporal aspects. Scenario analysis have been applied to handle uncertainty in marine design. EEA extends the scenarios analysis by enumerating the epoch space and includes the stakeholders’ expectations through the construction of eras.

The RSC method offers great flexibility when it comes to the selection of methods to perform the mapping. Figure 7-2 illustrates the main approach used to incorporate marine design principles with the RSC methodology. The individual steps and models will be further explained in the following sections.

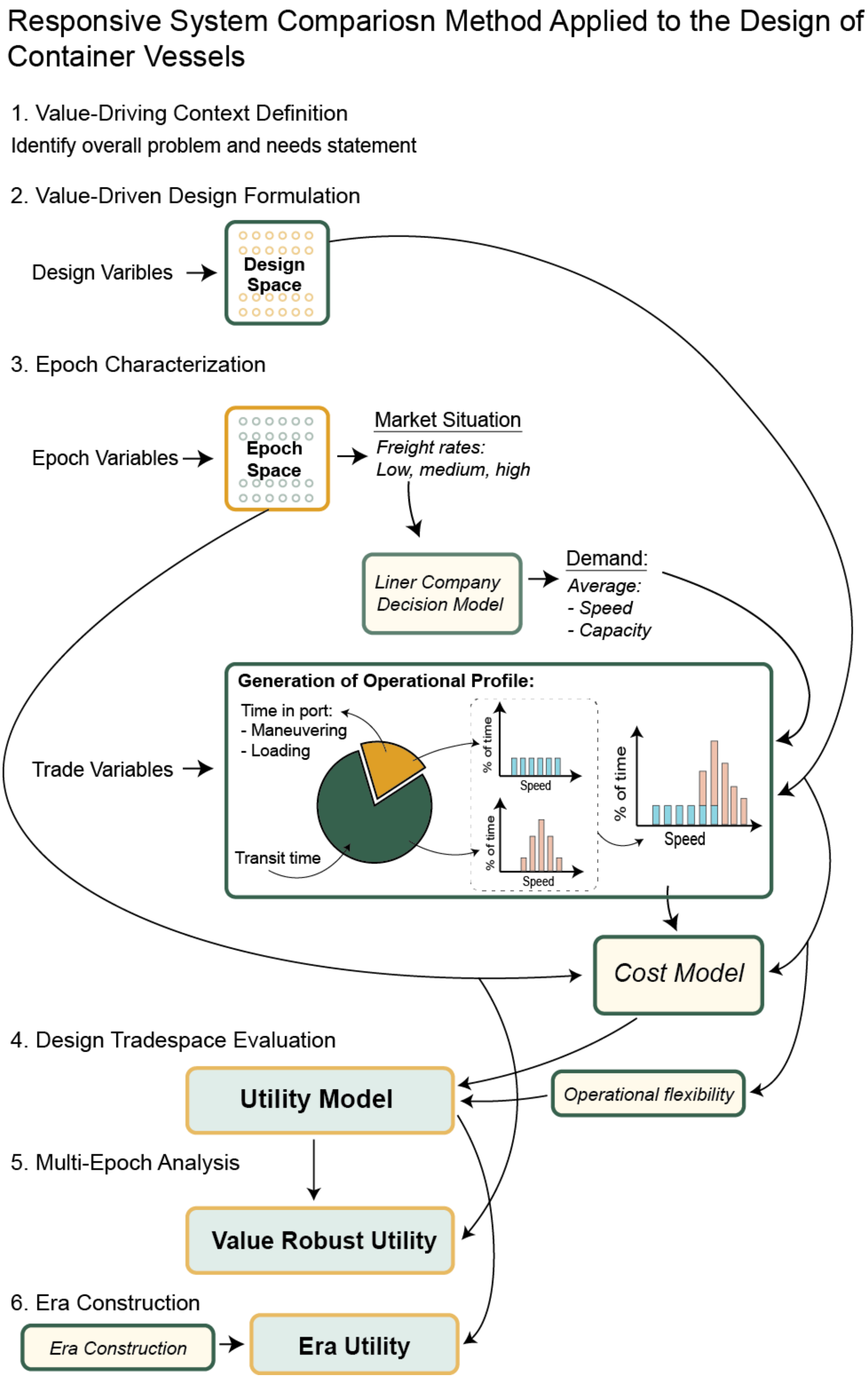


Figure 7-2: Principal methodology used in the case study

7.3 Responsive System Comparison Method Applied to Case Study

7.3.1 Value-Driving Context Definition

The view point is from an independent ship-owner operating in the charter market (see figure 7-1). The challenge for the tonnage providers in the container industry is that they do not know what liner company will end up chartering the vessel when the order is placed. During the lifecycle the vessel can be chartered to various liner companies and deployed in a wide range of trades.

The problem is to design, or rather decide, the principal characteristic of a value robust container vessel. The vessel must be attractive for a range of trades and liner companies and at the same time remain cost effective.

7.3.2 Value-driven design formulation

The second process of the RSC method consists of two main parts:

1. Identify and quantify performance attributes
2. Generation of overall system architecture and related design variables

Performance attributes

Based on the context definition we have formulated two main performance attributes (table 7-1)

Table 7-1: Performance attributes selected for the container vessel

Performance attribute	Unit	0 % utility	100 % utility	Weight
Unit transportation Cost	[USD/TEU]	Epoch min	Epoch max	0.75
Port flexibility	[-]	~ULCS	~Panamax	0.25

The unit transportations cost is selected based on the goal of having a cost competitive vessel. The cost per TEU transported is used as a measure of the competitiveness.

The port infrastructure have been identified as the main restriction on operational flexibility. Both the length, breadth and draft can potentially limit the access to a given port. The draft have been selected as the main limiting particular. Based on regression analysis a function to estimate the draft based on the cargo capacity was used as the utility function for this performance attribute (See appendix D for definition of the utility function).

Design Variables

Table 7-2: Design variables for the container vessel

Design variable	Unit	Min	Max
Capacity	[TEU]	3500	22750
Speed	[Knots]	15	25
Machniery Arrangement	[-]	0	3

We have selected three main design variables: The cargo defined by the number of TEUs, the design speed and the machinery arrangement.

Some of the variables presented in table 7-2 are description of functions rather than form. On the lowest level all design decisions are taken in the form-representation. The capacity is a result of design decisions related to the principal dimensions (length, breadth etc.) and the hull form. We chose the high-level functional design variables as we believe they are more accessible to a wider range of decision makers. To paraphrase Per Olaf Brett, deputy managing director at Ulstein International: *"A ship-owner doesn't care about the length, breadth or other particulars. He wants to know how much ship he can get for the money".*

The RSC framework offers flexibility in the choice of methods applied at the different steps. As part of the form-function mapping a parametric design study was applied. The basis for the study was a dataset containing all container vessels built after 2000 still in service from the IHS Fairplay database (*IHS Fairplay*, 2016).

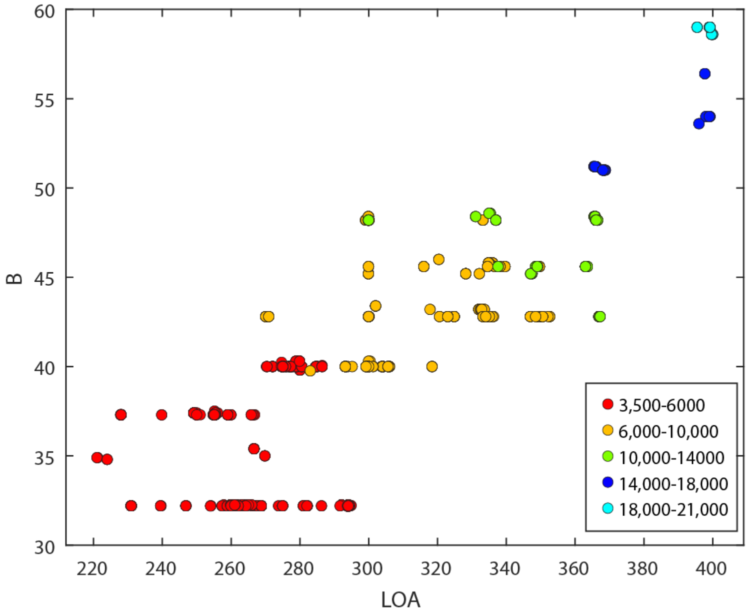
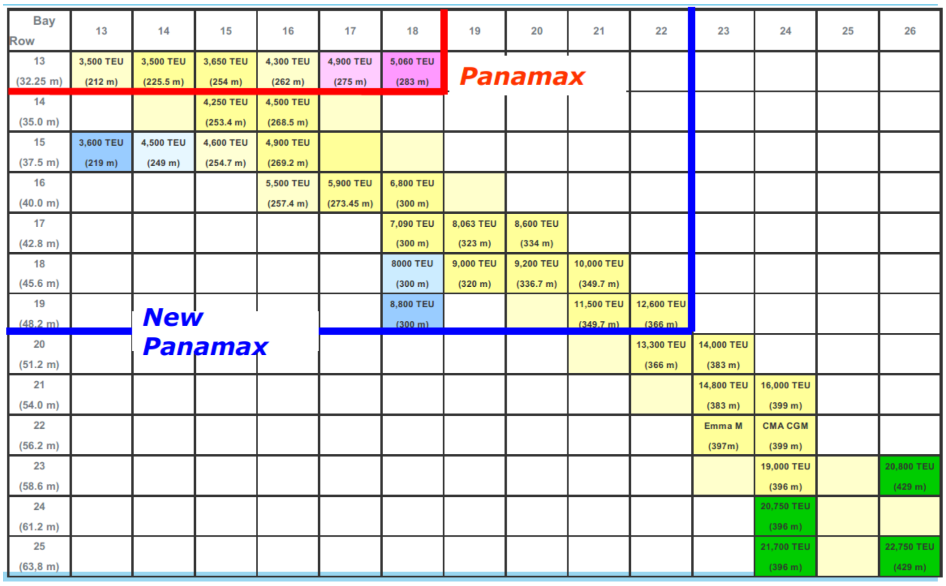


Figure 7-3: TEU vs length and breadth (based on *IHS Fairplay* 2016))

The physical size of the cargo unit, the container, impacts the design space. From figure 7-3 it is possible to identify certain bands of length and breadth that most designs follow. The breadth increases in increments of roughly 2.5 meters, the same as the width of standard ISO freight container (2.44 meters). Although not as clear, a similar tendency can be observed with the length, were especially the larger vessels have an incremental size increase of about 15 meters. The standard 40-foot container have length of 13.72 meters. As a result the design space with regard to capacity can be directly parametrized. This allows for a mapping from the capacity design variables to the principal length and breadth.



Bay Row	13	14	15	16	17	18	19	20	21	22	23	24	25	26
13 (32.25 m)	3,500 TEU (212 m)	3,500 TEU (225.5 m)	3,650 TEU (254 m)	4,300 TEU (262 m)	4,900 TEU (275 m)	5,060 TEU (283 m)								
14 (35.0 m)			4,250 TEU (253.4 m)	4,500 TEU (268.5 m)										
15 (37.5 m)	3,600 TEU (219 m)	4,500 TEU (249 m)	4,600 TEU (254.7 m)	4,900 TEU (269.2 m)										
16 (40.0 m)				5,500 TEU (257.4 m)	5,900 TEU (273.45 m)	6,800 TEU (300 m)								
17 (42.8 m)						7,090 TEU (300 m)	8,063 TEU (323 m)	8,600 TEU (334 m)						
18 (45.6 m)						8000 TEU (300 m)	9,000 TEU (320 m)	9,200 TEU (336.7 m)	10,000 TEU (349.7 m)					
19 (48.2 m)						8,800 TEU (300 m)			11,500 TEU (349.7 m)	12,600 TEU (366 m)				
20 (51.2 m)										13,300 TEU (366 m)	14,000 TEU (383 m)			
21 (54.0 m)											14,800 TEU (383 m)	16,000 TEU (399 m)		
22 (56.2 m)											Emma M (397m)	CMA CGM (399 m)		
23 (58.6 m)												19,000 TEU (396 m)		20,800 TEU (429 m)
24 (61.2 m)												20,750 TEU (396 m)		
25 (63,8 m)												21,700 TEU (396 m)		22,750 TEU (429 m)

Figure 7-4: Discrete design space. Capacity as function of length and breadth
Bergman (2014)

Based on the analysis of the existing fleet and figure 7-4 the dimensions shown in table table 7-3 was as a mapping from the capacity function to the principal length and breadth dimensions.

Table 7-3: Length, breadth and capacity defining the design space

Capacity [TEU]	Length [m]	Breadth [m]
3,500	212	31.5
4,250	253	35
1,900	269	37.5
5,900	273.5	40
7,090	300	42.8
9,000	320	45.6
11,500	350	48.5
13,300	366	51.2
14,800	383	54
18,000	399	56.2
19,000	399	58.6
20,750	399	61.2
22,750	430	63.8

The machinery arrangement area based on the strategies to comply with the sulphur emission regulations in the emission control areas (SECA). We have focused on the following three strategies:

1. Conventional two stroke slow speed engine with scrubber system to remove sulphur oxides and particles from the exhaust when operating inside ECA zones. Runs on heavy fuel oil (HFO) outside of emission zones.
2. The second option considered is to use a dual fuel engine that runs on HFO outside of ECA-zones and marine gas oil (MGO) inside. MGO is a fuel destilate with low sulphur and particle content.
3. The third option is LNG dual fuel engine, running on LNG in the ECA-zones. Outside HFO will still be the primary fuel.

Each of the options have their advantages and drawbacks. The scrubber options allows to use the historically cheaper low quality HFO all the time, but comes at the expense of increased capital cost for the scrubber as well as increased maintenance. MGO is historically the most expensive marine fuel type, making the fuel cost an important factor when spending a significant portion of the time inside emissions control zones. LNG has the potential to be a environmental conscious choice, as the SO_x, NO_x and particle emissions are reduced significantly. On the other hand does the LNG tanks require large volume, in addition to other equipment, reducing the cargo capacity. Details of the modelling of the various engine configurations is included in appendix C. The investment cost is presented in the following section.

Cost Model

As part of step two of the RSC method it is necessary to formulate the relationships and dependencies between the performance attributes and design variables. For a ship-owner the design decisions are in essence investment decisions. It is necessary to build a cost model to model the influence the design decisions have on the estimated building cost and operational expenses.

It is common to separate the cost of operating a vessel in three categories: (1) capital cost, (2) operating cost and (3) voyage cost. These main cost components are used to describe the operation of a container vessel in several publications (Culinane & Khanne, 1998; Gkonis & Psaraftis, 2010; Merk, Buxquet, & Aronietis, 2015). Figure 7-5 illustrate the principal cost model used for the analysis.

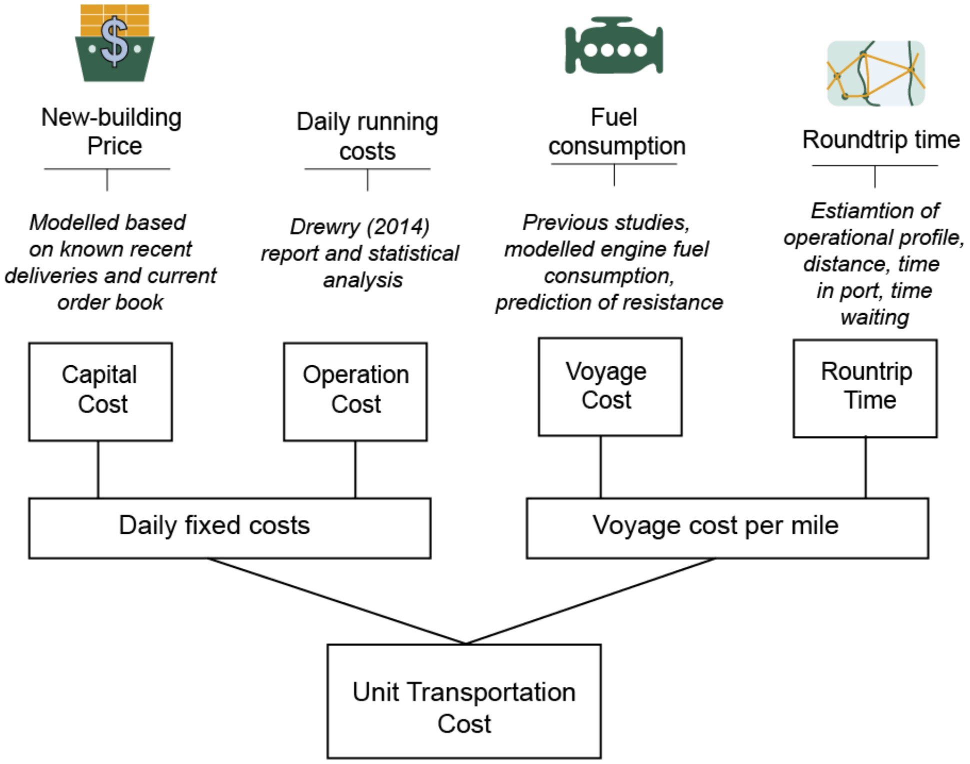


Figure 7-5: Principal cost model used in case study

Capital Expenditures

The capital expenditure (CAPEX) is a function of the investment cost of a new vessel. We assume that the investment cost is given by the installed power and the size of the vessel as expressed by equation 25.

$$C^{C} = f(N^{TEU}) + \ g_{i}(KW) \tag{25}$$

Where $f(Cap)$ is the building cost as a function of capacity, and $g_i(KW)$ is the cost of machinery configuration i as a function of installed power. The investment cost of the machinery configurations presented in table 7-4 are based on Rehn, Haugsdal, and Erikstad (2016)

Table 7-4: Investment costs of the engine configurations (Based on Rehn et al. (2016))

Configuration	Cost function: $g_i(KW)$ [USD]
HFO + Scrubber	$7850 \cdot KW^{0.693} + 28700 \cdot KW^{0.51}$
Dual Fuel HFO + MGO	$(7850 \cdot KW^{0.693}) \cdot 1.4$
Dual fuel: HFO + LNG	$(7850 \cdot KW^{0.693}) \cdot 1.4 ++33300 \cdot KW^{0.521}$

The building cost is estimated based on regression analysis of recent new orders from (Clarkson Research, 2015).

$$f(N^{TEU}) = (15 + 0.007 \cdot N^{TEU}) \text{ [mUSD]} \tag{26}$$

Where N^{TEU} is the capacity given in TEU.

Operational Expenditures

The operating costs are all expenses involved in the day-to-day running, and can mostly be regarded as independent of the specific trade the vessel is engaged in (Stopford, 2009). Lubricating oil, manning and maintenance (including dry docking) are the biggest single cost components of the operating costs. The principal components and the major cost drivers of each is illustrated in figure 7-5.

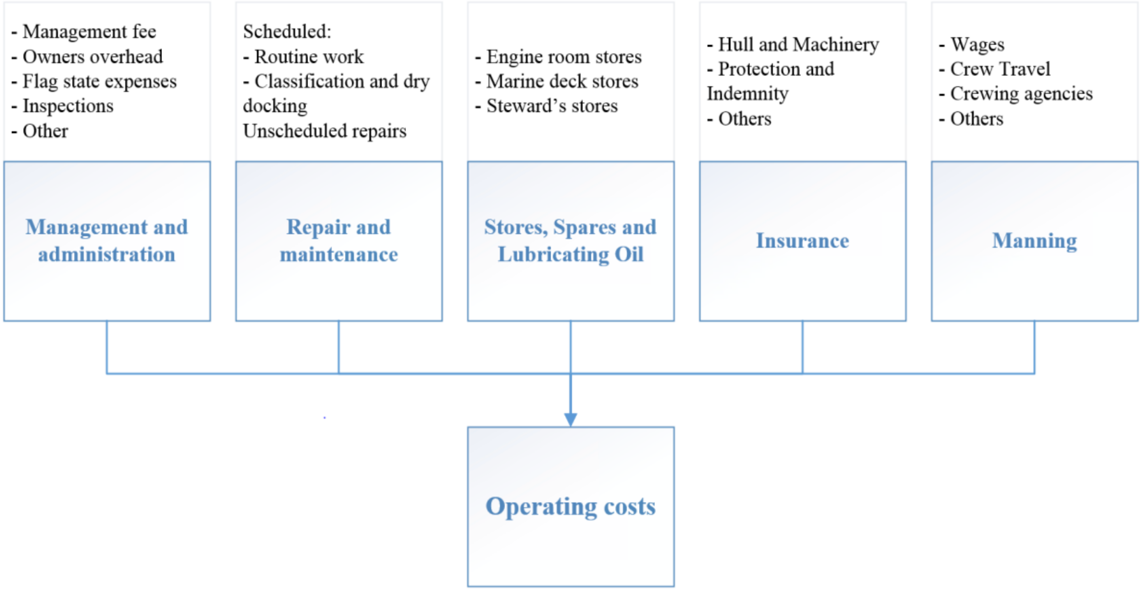


Figure 7-6: Principal components of the operating expenditures, based on Drewry Shipping Consultant (2015)

Some of the cost components will vary based on the size and value of the vessels, such as the consumption of lube oil and insurance. Figure 7-6 illustrate how the cost varies with size.

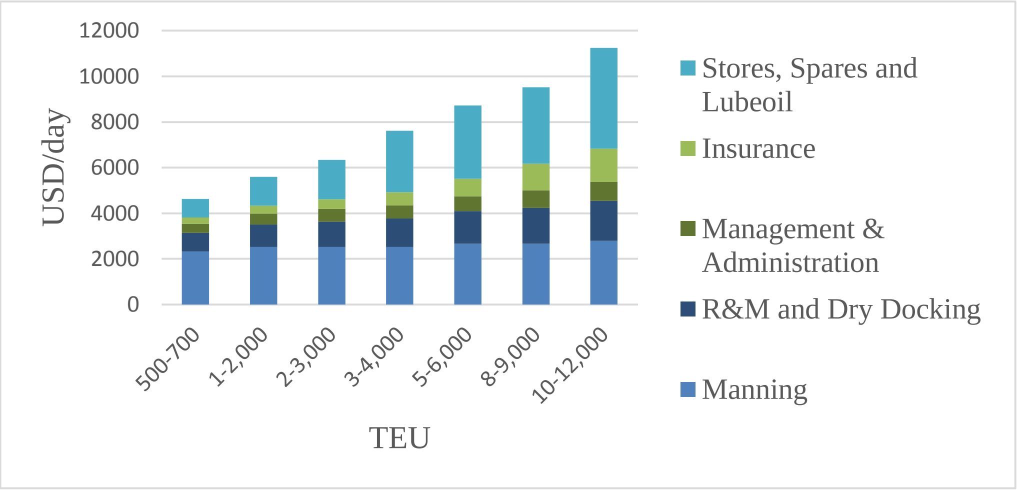


Figure 7-7: Operating costs for container vessels. Adapted from Drewry Shipping Consultant (2015).

We assume that the same trend can be used to estimate larger ships. Based on regression analysis equation 27 is used for the operating expenditure as a function of capacity.

$$OPEX(cap) = 495 \cdot (N^{TEU})^{0.334} \text{ [USD/day]} \tag{27}$$

Voyage Expenditures

The bunker, or fuel, cost is the main part of the fuel cost, and likely to be the main single cost driver for a shipping operation.

The fuel consumption is often regarded to be a function of the sailing speed and the size of the vessel. The sailing speed has the most significant impact on the fuel consumption, and a cubic relationship between sailing speed and fuel consumption is widely accepted in the literature (Corbett, Wang, & Winebrake, 2009; Fagerholt, Laporte, & Norstad, 2010; Khor, Døhlie, Konovessis, & Xiao, 2013; Lindstad, Asbjørnslett, & Jullumstrø, 2013; Psaraftis & Kontovas, 2013; Stopford, 2009). Wang and Meng (2012) did a regression analysis based on historical sailing data for container vessels ranging from 3000 to 8000 TEUs. The results showed that the fuel consumption varied as a function of the speed to the power of 2.7 to 3.3. This supports the assumption that a cubic relationship can be used to estimate fuel consumption as a function of speed for container vessels.

The fuel consumption as a function of size will vary depending on design features. Figure 7-8 show the relationship between size and fuel consumption based on data published by several sources. All the data was normalized to a speed of 20 knots using the cubic relationship.

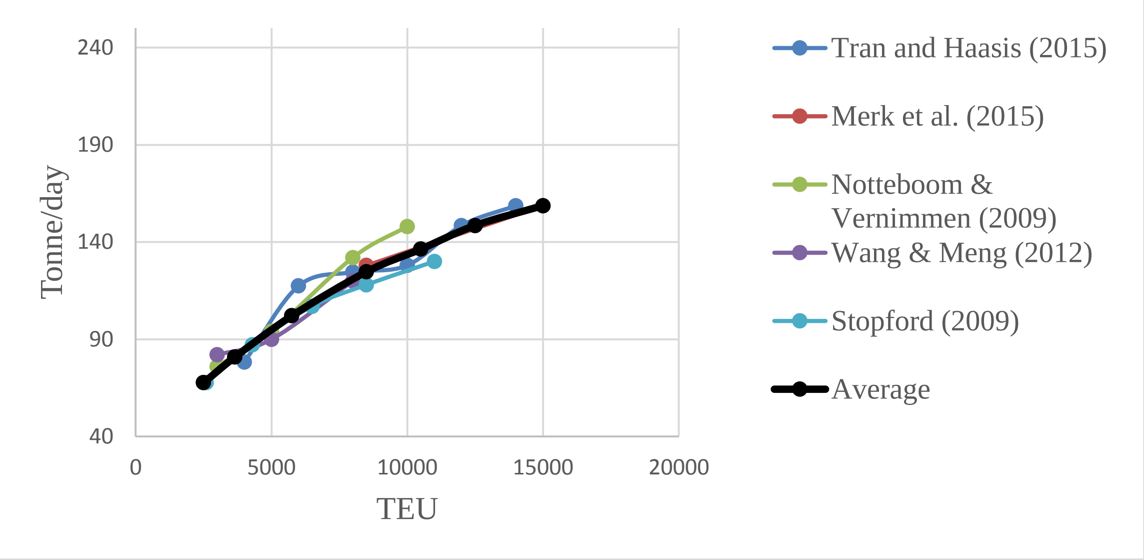


Figure 7-8: Fuel consumption as function of cargo capacity

Based on regression analysis of the average value, equation 28 is used to calculate daily fuel consumption, C^F. The same relationship is also used as a basis for calculating the required propulsion power.

$$C^F = 1.64 \cdot (N^{TEU})^{0.48} \text{ [tonne/day]} \tag{28}$$

7.3.3 Epoch Characterization

Figure 7-6 show the epoch variables used to parametrize the range of expected future scenarios. The trade specific variables describe particular of the various trades under consideration.

Table 7-5: Epoch characterization

		Range	No. of levels
World Market Development	GDP-growth	-4 - 12%	5
	GDP-multiplier	1 - 3 %	3
	Fleet growth	2-10	3
	HFO price	3-15 USD/mBTU	3
	MGO price	5-25 USD/mBTU	3
	LNG price	4-12 USD/mBTU	3
	% in ECA	0-30 %	3
Liner Company (Endogenous)	Trade	1-3	Table 7-6
	Average speed		
	Average capacity		

World Market Development

GDP Growth

Gross domestic product (GDP) measures the total production of goods and services in an economy. It is a common measure for the economic performance of a country, region or the world. (Begg et al., 2014).

GDP-multiplier

The container market is close to the costumer, and the demand for cargo have followed the economic development, while historically at a higher pace. The ration between the percentage increase in GDP and the increase in containerized cargo is known as the GDP multiplier.

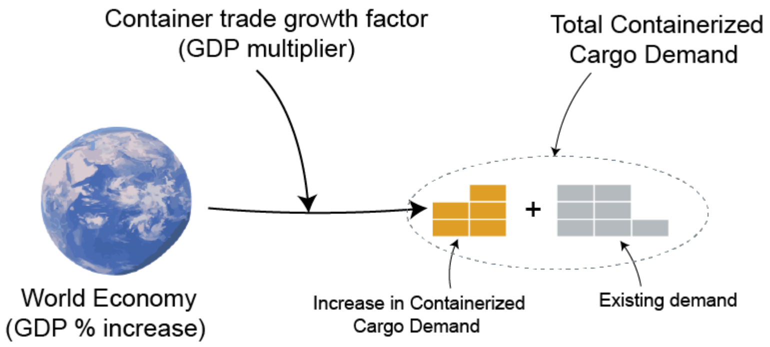


Figure 7-9: Container demand model

Fleet Growth

This is a measure of the net capacity growth, expressed as newbuilding in number of TEU subtracted the scrapped capacity.

Fuel Prices

In the model we include three alternative types of fuel, heavy fuel oil (HFO), marine gas oil (MGO) and liquefied natural gas (LNG). The prices of these will influence the voyage expenditures and the price difference is important to determine the value of the various machinery alternatives.

Trade Specific factors

In this study we focus on the three east-west mainlane trades. In table 7-6 the three main trades are summarized.

Table 7-6: Trade-specific factors (Clarkson Research, 2015; *IHS Fairplay*, 2016)

Trade	Distance [nm]	Port Calls	Est bound [million TEU]	West bound [million TEU]
Far East - Europe	12,000	13	4.52	9.19
Europe - U.S East Coast	7000	7	2.07	2.64
Far East - U.S West Coast	6,000	4	7.72	3.5

Endogenous Variables

The endogenous variables are not defined as an epoch variable. These variables reflect operational choices made by the liner companies. They are estimated based on the market- and trade epoch variables.

The liner companies face extremely complex strategic and operational challenges when designing the liner network and the vessel mix on each loop. Most of the literature on this topic have focused on operational research and optimization procedures to determine optimal network configuration and fleet mix. See e.g. (Christiansen et al., 2007; Hsu & Hsieh, 2007; Wang & Meng, 2012). These type of studies are far outside the scope of this thesis. We will instead develop some fundamental relationship to use a basis for the model.

First, let us observe the roundtrip time, T_r, for one vessel is given by equation 29.

$$T_r = \sum_{i=1}^{n} T_{pi} + \frac{D}{V \cdot 24} \tag{29}$$

Where T_{pi} is the time in port in days, n is the number of port calls, V is the speed of the vessel in knots and D is the roundtrip distance in nautical miles.

The reliability and predictability of the liner services to maintain a fixed schedule is one important success factor. The liner service frequency is given by the number of calls per week by any vessel in each port. With a given roundtrip time the service frequency is given by the number of vessels.

$$T_r \leq \frac{N \cdot 7}{F} \tag{30}$$

Equation 30 express the roundtrip time threshold, where F is the service frequency (calls per week in each port) and N is the number of vessels in use on the given loop.

By combining equation 29 and 30 we get the following relationship between minimum required speed, distance and number of vessels for a given service frequency:

$$V = \frac{D}{\frac{N \cdot 7}{F} - \sum_{I=1}^{n} T_{pi}} \tag{31}$$

Based on the relationship outlined in equation 29-31 and the application of production theory presented in section 3.5 in we can qualitatively identify the effect any change in epoch variables have on the liner companies decision.

Table 7-7: Qualitatively relationship between epoch variables and change in liner network configuration

Results in / Increase in	Average Speed	Average Capacity
Fuel Price	-	+
Fleet Growth	-	(+)
GDP	+	+
GDP multiplier	+	+
Route length	+	+
No. of port calls	+	-

The freight rate level is an important factor influencing the liner companies decisions. The GDP growth and GDP multiplier is used to assess the change in demand and the fleet growth the change in supply. Based supply-demand dynamics presented in section 3.7 we determine the freight levels based on the relative change in the supply and demand.

Table 7-8: Qualitatively relationship between epoch-variables and freight rates

Cargo volume growth	Fleet growth	Results in: **Freight rates**
High	Low	**High**
High / (Low)	High / (Low)	**Neutral**
Low	High	**Low**

The quantitative model used to predict the freight rates are based on Luo et al. (2009).

The freight rates, route length and fuel prices are used as input to resolve the uncertainty relating to the liner companies decisions. We have constructed a simple model where all the factors are given equal weight.

Operational Profile

To relate the epoch variables to the design variables we will as part of step 3 develop operational profiles. The output from the liner companies decision is used as the average speed during the transit leg and the average demand for cargo capacity. The speed-profile during transit is based on a normal distribution centred around the average. The time in port is given by the cargo volume. The manoeuvring time is a function of the number of port calls on the route. All the individual parts of the journey are added together to make up one roundtrip.

7.3.4 Design Tradespace evaluation

In the fourth step we use the relationships and models presented in the two previous steps in order to evaluate the design space. The deign space is evaluated based on the cost and utility. The principal process is outlined in figure 7-10.

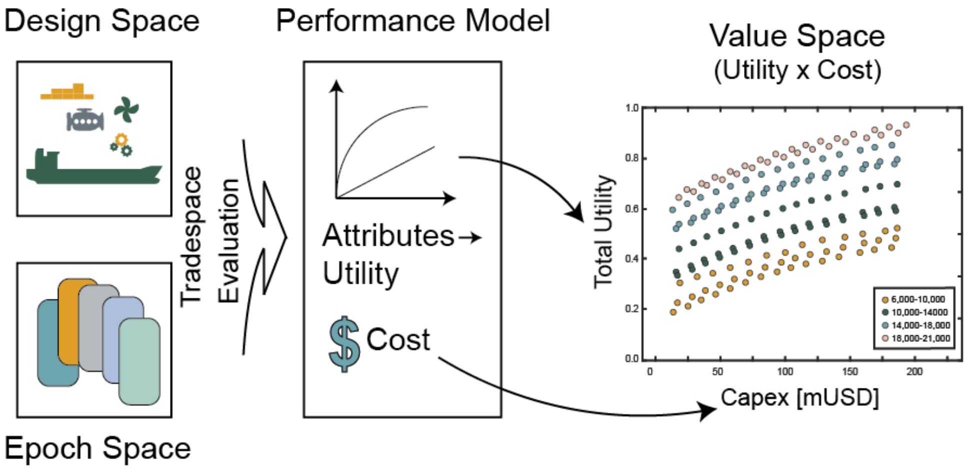


Figure 7-10: Principal procedure for tradespace evaluation (Adapted from Gaspar et al. (2015) and Ross et al. (2009))

Figure 7-11 illustrates a typical utility plot for one epoch. Each point represents a unique vessel design. The colours are used to group the designs based on the capacity as given by table 8-2.

The multi attribute utility is based on the unit transportation cost and the operational flexibility. In the cost model we have included an penalty of 100 USD for every potential demand of container transportation that is not fulfilled.

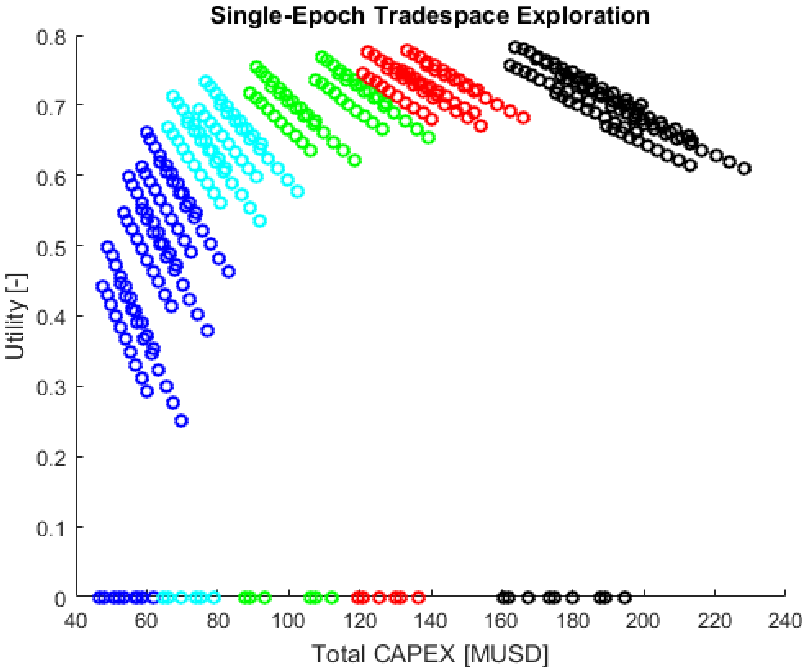


Figure 7-11: Example of tradespace evaluation for one epoch

Based on the evaluation we can identify the don-dominated designs along the Pareto frontier. They are the designs that deliver the highest utility at the lowest cost. While identifying the most valuable designs in a single epoch can be useful, it does not account for uncertainty or value robustness.

7.3.5 Multi-Epoch Analysis

The goal of the Multi-Epoch analysis is to apply techniques to identify passive value robust designs. We will calculate the average utility of each design across the epoch space. When calculating the average utility, the epochs could be weighted according to reflect stakeholders' expectations of the likelihood of the development reflected by the epochs. In this analysis all the epoch was weighted equally.

An alternative complementary approach is to calculate the Pareto Trace, as suggested by Ross et al. (2009) to assess cross-epoch value.

7.3.6 Era Construction

An era is a time ordered sequence of epochs. Each era represents one possible realization of the future context. A full enumeration of the era space is likely to be computational expensive. It can further become complex to formulate the necessary relationships to ensure logical continuation between the epochs.

We have chosen to construct eras based one the narrative approach used by H. M. Gaspar, S. O. Erikstad, et al. (2012). The eras are constructed based on expectations and causal relationships identified by stakeholders. Based on these expectations we handpick the set of epochs that captures the development.

Each epoch represents a one year period. This is on the upper end of the timescale for operational descisions. We assume that during this time the market and liner companies have time to respond the contextual changes. Further, is each era made up of 5 epochs, representing 5 years of operation. This in in the timeframe for strategic decisions used for investment decisions in the shipping industry.

Era 1
Moderate economic growth of 4 % GDP increase each year. The container segment will continue to grow at 2 times the GDP growth yearly. Fuel prices will remain low for the first half, than increase to a moderate level as defined by the last ten year average. Fleet growth are expected to be below volume growth for the first two periodsyears, than increase slightly above for the remaining time.

Era 2
We will experience zero economic growth for the first peride, which will gradually increase by an average of two percent each year. The container growth will follow the GDP at the same pace as today for the first thee years, than increase slightly. After two years OPEC will reinstate its cartel position and the oil prices will increase rapidly and remain high for the remaining time. The low demand for cargo will be met by a high newbuilding

activity as the liner companies seek to improve their margins by using larger and more efficient vessels. The fleet growth will fall after the two first years, and as market is moving into equilibrium the growth will increase again in the final period

Era 3

The economic growth will start at todays level, gradually weakening and reaching zero in the final two years, than drop to zero growth for the last. Increase reshoring of production will result in a decrease of the GDP-multiplier from today's level. Oil prices will increase moderately for the first couple of years, and then remain constant. We will see extensive scrapping of older and smaller vessels. The newbuilding activity will follow a cyclical pattern, starting of low, than increasing to a moderate level, before dropping again in the final period.

A detailed breakdown of the epoch variables in each epoch of the various eras is included in appendix E.

7.3.7 Life Cycle Path Analysis

In the life cycle path analysis, we will qualitatively discuss design strategies based on the multi-epoch and era analysis. In this study this is not explicitly included as a separate section, while topics typically addressed in the life cycle analysis is discussed along with the results from the multi-epoch and multi-era analysis.

8 Results

In this chapter we will present the results and comment on possible interpretation. Critical discussion regarding the validity of the results are saved for chapter 9.

The results can be separated into two main categories:

1. The results from the development of the methodology
2. The results from the case study

In accordance with the objectives for the thesis, the development of the framework and methodology to address uncertainty and complexity in the conceptual design of transportation vessels was a main goal of the thesis. Our approach was to combine traditional methods for conceptual design with emerging systems engineering techniques. In table 8-1 the main methods used have are related to the systems engineering complexity framework and to the overall RSC method as well as the four steps of the classical design loop.

Table 8-1: Summary of the framework used in the case study.

RSC	Classical design	Aspect of complexity	Method Used
1. Value Driving context definition	Needs analysis	Perceptual	Interview of key stakeholder
2. Value-Driven Design formulation	Generate	Structural / Behavioural	Decomposition through System Based ship design, and encapsulation through statistical analysis and parametric equation.
3. Epoch-Characterization	Analysis	Contextual	Decompose mission to operational profile. Economic production theory and freight rate forecasting principles to determine liner companies' response to contextual changes.
4. Design Tradespace Evaluation	Analysis / Evaluate	Contextual /Behavioural	Analytical modelling of the utility. Multi attribute utility.
5. Multi-Epoch Analysis	Evaluate	Temporal	Multi utility weighting
6. Era Construction	Evaluate	Temporal	Stakeholder interview to quantify expectations for future development
7.Lifecycle Path Analysis	Evaluate / Decide	Temporal / Perceptual	

8.1 Tradespace Exploration

For each epoch we calculated the multi attribute utility value for all designs. The value space is visualized by plotting the utility vs costs for all designs for every epoch. Each point of the scatter plot represents a feasible design combination. By grouping the designs according to some characteristic, it is possible to include more information. In the figure 8-1 the designs have been grouped according to the cargo capacity as defined by table 8-2

Table 8-2: Colour legend for tradespace representation grouped after cargo capacity

Capacity [TEU]	Colour
>5,000	Blue
5,000-8,000	Cyan
8,000-12,000	Green
12,000 – 18,000	Red
>18,000	Black

The results from the tradespace exploration is as many value space representations as the number of epochs. To illustrate the results we will present some valuespace representations for various epochs. The epoch shown in figure figure 8-1 is characterized by a high demand for cargo and a high average speed. The high average speed is the reason for the large number of designs with zeros utility, as all design unable to operate at the full range of the operating states is assigned zero utility. With the high demand for cargo their seem to exist economics of scale outweighing the diseconomies related to the flexibility. However, the return is strongly diminishing, with little increase in utility for additional capacity after 12,000 TEU.

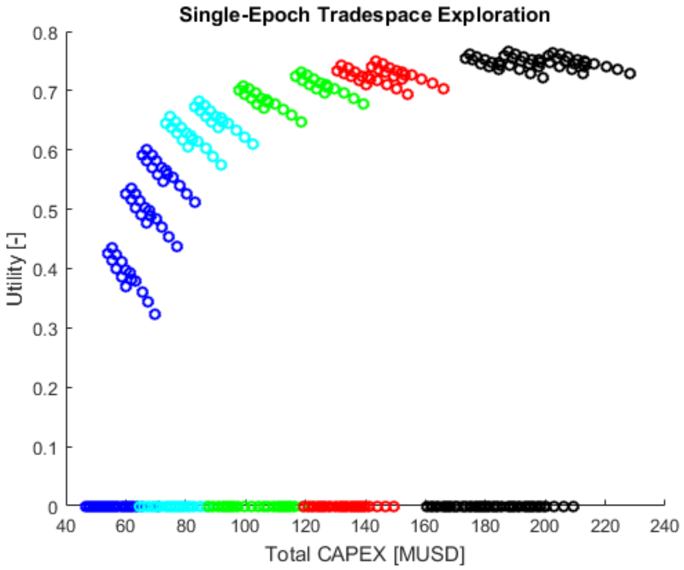


Figure 8-1: Single epoch tradespace exploration for high demand epoch, grouped after capacity.

Figure 8-2 illustrates the tradespace for another epoch, where the demand for cargo and speed is lower. As a result, the Pareto front does not cover the most expensive alternatives.

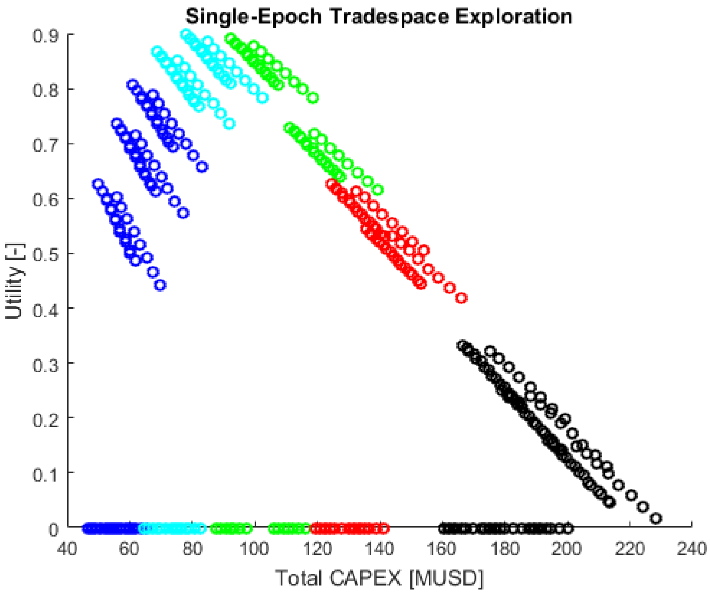


Figure 8-2: Single tradespace exploration for low demand epoch, grouped after capacity.

The designs can be grouped after other metrics than the capacity. In figure 8-3 the colour represents the machinery type, where blue is HFO + Scrubber, cyan is dual fuel MGO and green is dual fuel LNG.

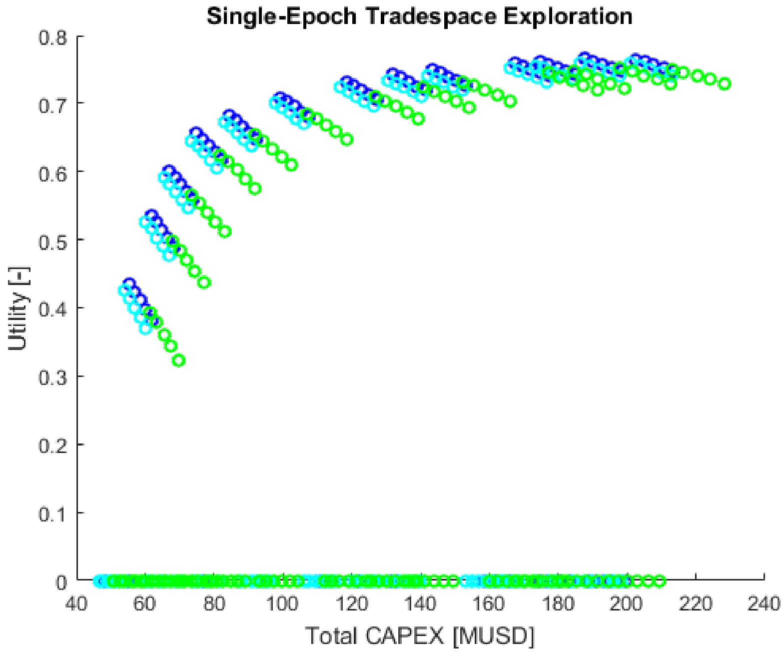


Figure 8-3: Single epoch tradespace exploration, grouped after machinery configuration.

In the epoch above the LNG price was marginally less than the MGO price. The MGO option has a lower investment cost for small engine sizes, while higher voyage expenditures for most fuel price combinations. As a result both the MGO and the HFO option in included in the Pareto front. The marginally lower LNG price was not sufficient to make the LNG dual fuel option optimal in this epoch, and all designs with LNG propulsion is Pareto dominated.

Figure 8-4 shows the tradespace grouped after machinery type for another epoch. Here the LNG cost was significantly less than the HFO and MGO price. For the larger vessels, the price difference makes it worthwhile to invest in LNG propulsion.

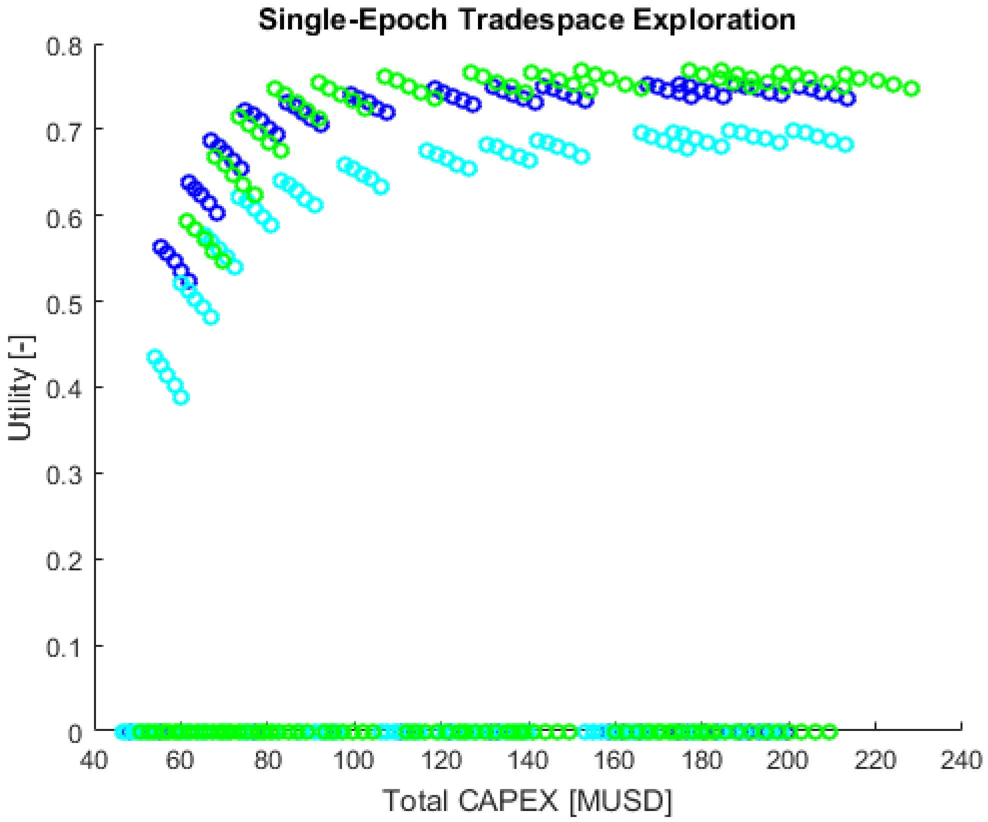


Figure 8-4: Single epoch tradespace exploration, grouped after machinery configuration

The capacity, machinery type and speed was the three design variables. In figure 8-5 the designs have been grouped based on the design speed in accordance with table 8-3.

Table 8-3: Colour legend for tradespace value plot grouped after design speed.

Speed [knots]	Colour
15-17	Blue
18-19	Cyan
20-21	Green
22-23	Red
24-25	Black

Figure 8-5 illustrates the tradespace for an epoch with medium demand for capacity and a relatively low average speed. As a result, the designs with a relatively low installed power and speed makes up the Pareto front. For an epoch were he demand for speed was higher the vessels with a low design speed would not be able to maintain the desired port frequency and would therefore have zero utility, while vessels with relatively large propulsion power would be the better choice.

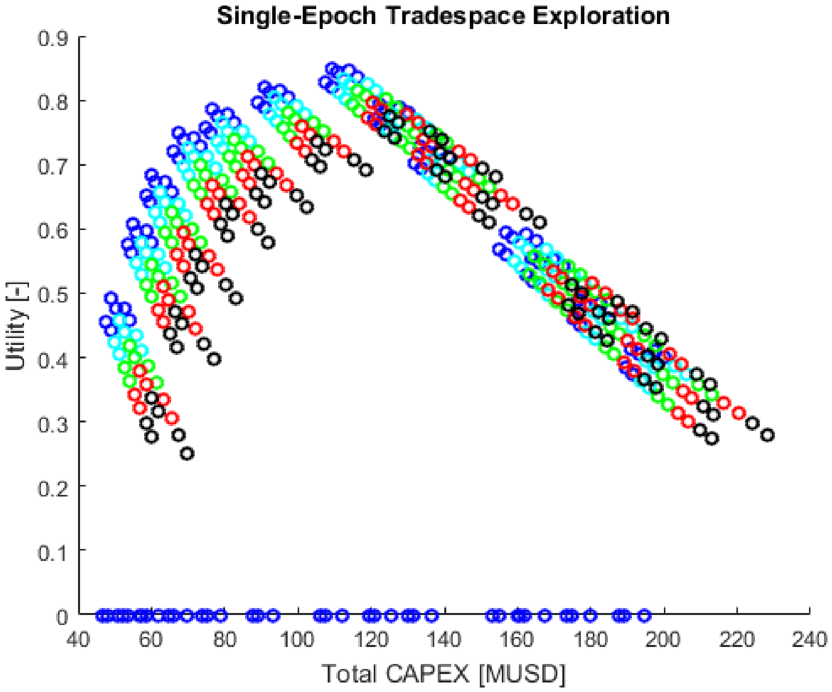


Figure 8-5: Single epoch tradespace exploration grouped after design speed.

The result from the single epoch valuations comes perhaps as no surprise: what is considered the *best* design is influenced by the operating context. By comparing results from single epochs it is possible to gain an understanding of how changes in context influences the design value and trade-offs. It is important to note how the utility is relative to each epoch, and cannot be compared directly across epochs. To assess value robustness we must apply systematic techniques to analyse cross-epoch performance. This is done in the multi-epoch analysis.

8.2 Multi-Epoch Analysis

The trade space evaluation results in a large amount of data. The goal of the multi era analysis is process this information to identify designs that continue to deliver value across changing contexts.

By calculating the average utility across all epochs we can produce a value space similar to the one use for the single epoch tradespace evaluation. The utility shown in figure 8-6 is the average utility value when all epochs are weighted equally.

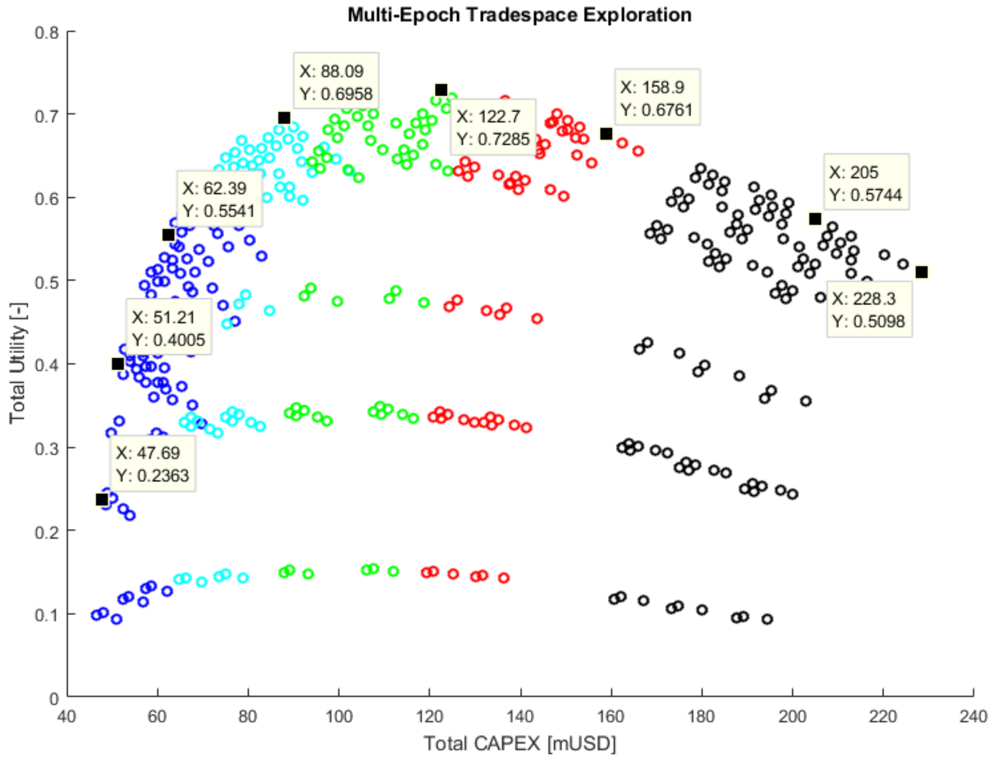


Figure 8-6: Multi-Epoch tradespace exploration

In figure 8-6 some of the designs are labelled. From left to right, the five firsts designs are along the Pareto front. Design number 5 is the global maximum. The three designs represent local maximum if only considering the trade space to the right of each design. Details of each design is presented in table 8-4.

Table 8-4: Design variables for key designs identified in the multi-epoch analysis

Design	Multi epoch utility [-]	CAPEX [mUSD]	Capacity [TEU]	Design speed [kn]	Machinery type [-]
1	0.24	48	3500	16	Dual fuel MGO
2	0.40	51	3500	19	Dual fuel MGO
3	0.55	62	4900	19	Dual fuel MGO
4	0.70	88	7090	23	HFO scrubber
5	0.73	123	11500	23	HFO scrubber
6	0.57	205	20750	23	Dual fuel LNG
7	0.51	228	22750	25	Dual fuel LNG

Although one should be careful to make any conclusions based on a limited selection of data points, it is possible to see some tendencies based on the designs presented in table 8-4. The machinery type that yields the highest utility seems to be dependent on the size of the vessel. For smaller vessels the dual fuel MGO option is preferred, for medium sized vessels the conventional slow speed HFO engine with scrubber is preferred, and for the largest vessels the dual fuel LNG seems the best option. Further, the design speed of the Pareto optimal designs seems to increase with increasing size.

Again, the grouping of designs can be based on any of the design metrics. Figure 8-7 and figure 8-8 show the Multi-Epoch trade space grouped after machinery type and design speed, respectively. The colour scheme is the same as used in the previous section. The cross metric, multi-epoch value plots confirms some of the tendencies observed based on the selection of designs. For lower speeds the HFO + Scrubber, and MGO dual fuel machinery configurations are both dominating the LNG dual fuel engine. For the larger designs with a capacity in excess of about 14,000 TEU the larger investment cost of the LNG engines can be justified based on the expected fuel cost savings. The design speed separates the tradespace in bands with similar utility. The range from 20 to 25 knots is alternating as the optimal choice based on the size.

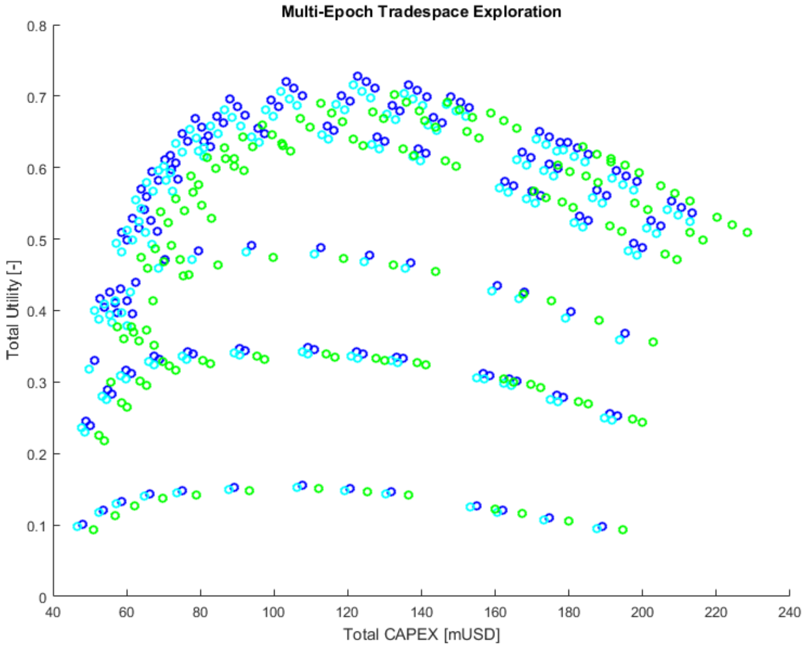


Figure 8-7: Multi-Epoch tradespace exploration grouped after machinery configuration

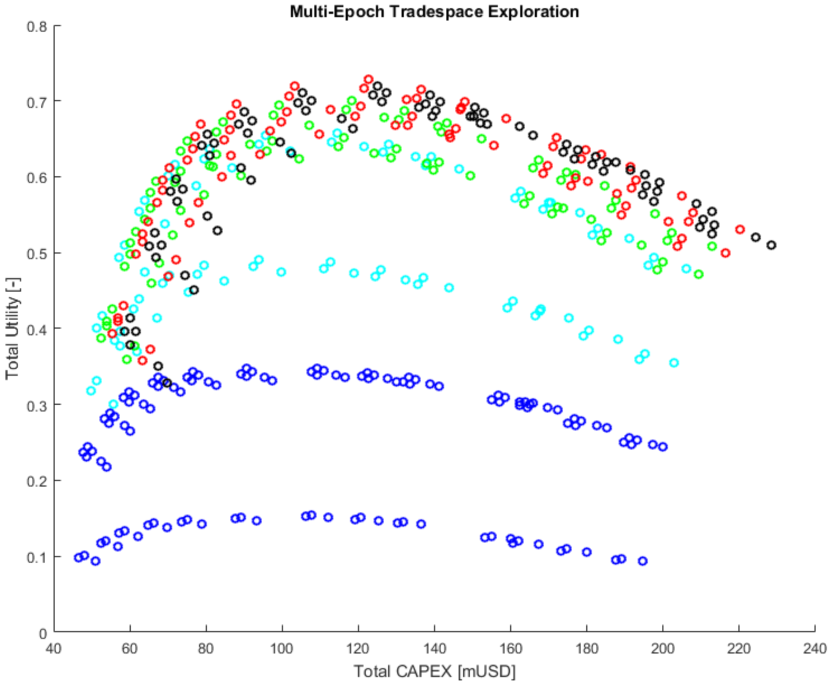


Figure 8-8: Multi-Epoch tradespace exploration grouped after design speed

An alternative measure of value robustness is the pareto trace. The pareto trace value is the frequency of which the given design is included in the pareto front when summed over all, or some of, the epochs. We have used the multi epoch utility rather than the Pareto trace to assess value robustness. The Pareto trace effectively ignores any designs that are not optimal in a given epoch, excluding the possibility that a

8.3 Era Analysis

Based on stakeholders expectations a number of timelines, eras, have been constructed by combining several epochs.

At this stage we wish to make some clarification regarding the contextual epoch parameters and the trade-specific parameters. The epoch parameters describe a simplified picture of the world-trade and economic situation, regulations and the global fleet development. The trade-specific parameters describes characteristics such as length and number of port calls for three different trades. For a set of context parameters, all the three trades are available.

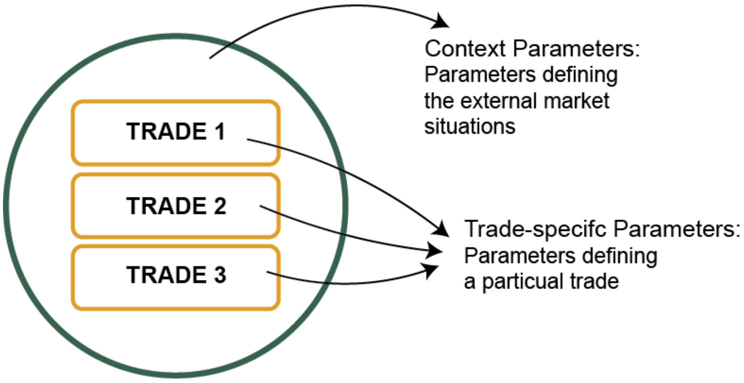


Figure 8-9: Context- and trade parameters

Figure 8-10 illustrates how the epochs is used as building blocks top construct eras. It further illustrates how each design can have various utility for the different trades within a single epoch. The trade-off between single or multi trade perspective is important. Is the design presented in figure 8-10 a good design since it delivers a relatively high average utility for trade 1, or is it undesired since it is unable to meet the minimum requirements for two of the trades in two epochs.

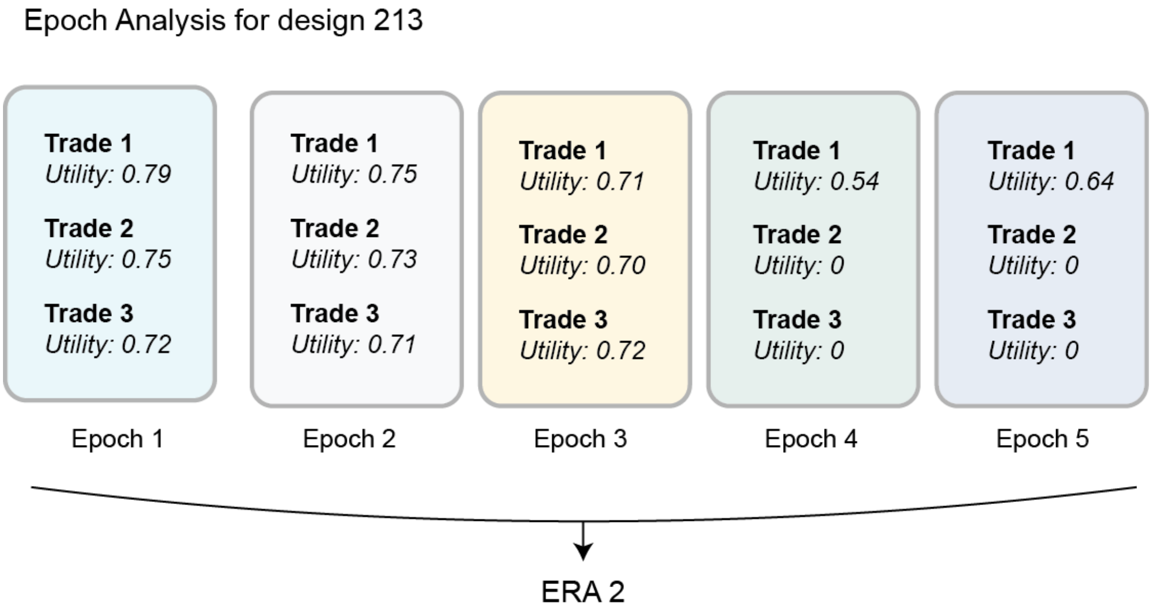


Figure 8-10: The construction of eras and the relationship between trades and epochs

In table 8-5 we present the results of the multi era analysis for the same designs as considered during the multi-epoch analysis.

Table 8-5. Result of multi era analysis

		Design no.						
		1	2	3	4	5	6	7
Era 1	Trade 1	0.51	0.46	0.64	0.68	0.71	0.60	0.52
	Trade 2	0.28	0.43	0.61	0.65	0.71	0.69	0.65
	Trade 3	0	0.41	0.59	0.64	0.70	0.72	0.71
Era 2	Trade 1	0.31	0.43	0.62	0.70	0.77	0.48	0.39
	Trade 2	0.21	0.26	0.37	0.70	0.75	0.67	0.61
	Trade 3	0.1	0.25	0.36	0.71	0.74	0.73	0.70
Era 3	Trade 1	0.50	0.45	0.63	0.68	0.74	0.56	0.48
	Trade 2	0.26	0.42	0.60	0.66	0.72	0.67	0.62
	Trade 3	0.09	0.40	0.58	0.65	0.70	0.71	0.69
Average	**Multi era**	**0.25**	**0.39**	**0.56**	**0.67**	**0.73**	**0.65**	**0.60**
	Multi epoch	**0.24**	**0.40**	**0.55**	**0.70**	**0.73**	**0.57**	**0.51**

The average value across all eras are similar for most designs as the multi-epoch utility. With some few exceptions. Design 5 continues to deliver the highest utility across most of the trades and eras.

9 Discussion

Figure 9-1 illustrates the general principals of any analysis and can be used as a high-level illustration of the approach in this thesis. It is interesting to discuss how the input data and choice of method to model the problem affects the results and conclusion.

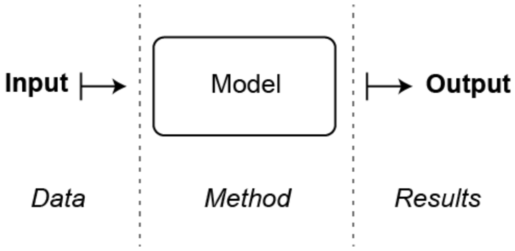


Figure 9-1: High level illustration of the analysis process

The word model implies some form of simplification and idealization. Statistician George Brox is generally attributed with the much-cited quote: *“Essentially, all models are wrong, but some are useful.*” Instead of asking if the model developed in this thesis is *correct* or *true*, we aim to discuss to what degree the model is *useful*.

The choice to use the responsive system comparison method as the overall framework is an important decision that warrants a discussion. The RSC share common characteristics in terms of approach and workflow with the traditional four step design loop. We have chosen to use the RSC method as a general framework rather than rigorous methodology. This provides us with the opportunity to integrate well-established methods. The initial enumeration of the design space are closely related to the set based design. A disadvantage of this approach is the form is specified early in the process. By integrating a function oriented approach as shown in the System Based Ship design methodology could increase the holistic thinking. Gaspar et al. (2015) showed how epoch-era analysis could be used for the design of marine machinery systems. By defining a set of subsystems based on their function and develop solutions for these independently could be a alternative approach. What is design variables for one subsystem would be outside the scope and could be treated as epoch-variables for another system. This would limit the design space for each subsystem, opening for more computational expensive evaluation methods.

The design- and epoch space grows rapidly with increasing number of variables and the discretization level. This limits the number of designs and contextual factors than can reasonably be considered. We chose to perform a complete multi epoch analysis, where the entire design space were evaluated for every epoch. This limited the option of methods available. An example of this is the estimation of propulsion power. There exist several models to predict the resistance of a vessel based on design particulars. From simple statistical methods used in this thesis, to more complex empirical models, CFD-analysis and model test. It is important to be critical to how the choice of methods influences the questions that can be asked the model. For instance, it is possible to increase the breadth of a vessel to maintain the same cargo capacity with a smaller length. Initially, this was one of the design options we wanted to include. However, as neither the cost- or the propulsion model includes the breadth of the vessel we could not expect the model to give any useful insight into this trade-off.

In order to limit the design space we used only a three level discretization for several of the variables, low, medium and high. This allowed us to consider a larger range of expected scenarios, while limiting the resolution. For the multi-epoch analysis, we believe this a reasonable trade-off, while for the construction of eras this became a challenge. Single epochs are the building blocks used to construct eras. The timelines is therefore limited by the epochs. With a low level of discretisation the jumps from one time period to the next became large, and limited the ability to accurately capture the stakeholders preferences.

After having discussed the limitations resulting from the computational cost of evaluating the large design- and epoch space it seems appropriate to discuss the implications of such an extensive multi-epoch evaluation. We have generated epochs with even density across the entire epoch-space. When weighting all epochs equally this can lead to too much emphasis being put on the extreme combinations of variables that in reality in unlikely to occur. This could be countered by weighting the epochs according to some probability or importance measure. Another approach is to generate more epochs cantered around the expected realization by varying the discretization level. The later approach would also overcome some of the challenges with the construction of coherent progression in eras. A similar approach could be done with the design space. Based on an initial broad search the design space could be refined around particular eras of interest. A two step approach, first going broad and then going deep, is an often mentioned concept in tradespace exploration. Given the computational challenges we believe that using dynamic discretization levels in combinations with a two-step exploration would be advantage to implement in the RSC method. After identifying certain value robust designs, it is possible to do a local search focusing on the trade space adjacent to selected design by refining the discretization level of the design variables in a range around the values of the identified design.

The construction of eras is in itself a key element worthy of discussion. In the case study we chose to handpick epochs to capture the development proposed by a narrative storytelling approach. This is a direct and transparent way to include stakeholders perception. The subjective approach put a lot of emphasis on the stakeholders assumption. There is a risk of stakeholders being systemically biased in overestimating the expected development based on wishful thinking. We have previously addressed how various forecasting models can be used to model the market dynamics and predict future development. We have used a simple model to predict the state of the market based on the stakeholders' expectations regarding cargo- and fleet growth. As the freight rates is an important factor in establishing the operational profile it is important to be critical of this process. We acknowledge that this is an element that could be improved by applying more sophisticated techniques. The simple model used in this thesis is more suited for illustrating the general procedure than actually being used as the basis for real-life decisions. The same is true for the liner company decision model. It is important to distinguish between the general approach and the actual results. We believe the two weak links addressed here devaluates the actual results, while not undermining the validity of the general approach.

Several cost aspects are not included in the model. The most noteworthy is the cargo handling cost. This includes the port and terminal handling costs and, feeder costs and further intermodal transportation. This is likely to be a major part of the total cost. When not including this cost it is done under the assumption that this will be given as a fixed cost for every container, and not alter the relative unit transportation cost between the designs. The unit transportation cost can therefore not be compared directly with the freight rates. We discussed how there is likely to diseconomies of scale related to the cargo handling cost. This would make the assumption of constant handling costs invalid. The operational flexibility utility is directly related to these diseconomies. By altering the modelling or weight of this utility it is possible to adapt the model to reflect this effect.

We have chosen include the effect of most design and epoch parameters in the cost model. It could be possible to take a more utility-based approach, by defining individual goals an utility for smaller subsystems. For instance, the machinery configuration could be seen as an independent utility attribute, where the stakeholders' preferences could be used to rank the options. The same could be done for design speed, capacity, emissions and other aspect. The reason why we have chosen a cost model rather than a purely utility model is that we believe this better captures the importance of being economically competitive. The is related to the design for *multi uselessness*, as a to large focus on specific features could cause a tendency towards over-engineering. It is common saying that engineers always wants to design a Rolce Royce, when a Toyota is probably the better choice for most.

We have used a static cost model, where the prices are assumed to be fiex. We know that the new building price is correlated with the market situations. In the eras were we predict a negative market development, the better choice might be to not invest at all, or wait until the market have weakened. This is an example of flexibility that have not been considered. There exist several other areas were the design decisions could have been adapted to facilitate for flexibility. One example is the LNG cargo tank. This is assumed to be a fixed says, adapted for the use in the ECA-zones only. By having a larger tank we could have used LNG on a larger part of the transit when price situation would favour this.

We have based several aspects of the modelling on statistical analysis, including regression analysis, of known designs. A common critic of this approach in design is that the designer locks himself based on what have been done before, and eliminates the opportunity for innovation. The goal of this thesis have however not been on innovating new design features and expansion of the design space. We have attempted to illustrate an approach to expand the boundaries of the design process itself.

10 Concluding Remarks and Further Work

We set of with an objective to investigate the concept of value robust design. The initial review of existing literature related to conceptual ship design supported the notion of this as a worthwhile area to investigate further. The review further revealed that there exist several mehods, concepts or ideas addressing this topic. The concept of vessel mission and design of the “right vessel to the right vessel” is an important as a basis and general idea. A common denominator among the existing method is to design for a fixed context with lmited attention to future uncertainties. To broaden the scope of conceptual ship design we looked to systems engineering. The application of the five-aspect taxonomy to conceptual ship design revealed that the traditional approaches focuses on the structural and behavioural aspects. The contextual, temporal and perceptual have generally received less attention.

The methodology and case study was developed based on the viewpoint of an independent ship owner chartering out vessels. Further adaptions have been made to address the specifics of the container market. Two main sources of uncertainties was identified: Aspects relating to the market situation, and the liner companies response to changes in the market. We have applied the Responsive System Comparison method with Epoch-Era analysis in combination with traditional marine design concepts to identify passive value robust container vessel designs. This represents a novel approach, that to our knowledge have not been applied to the design of traditional transportation vessels.

In this thesis we have successfully developed a framework to address value robustness in the design of transportation vessels. The trade specific utility is measured in monetary value by developing a cost model to link the design decisions with the market- and trade variables. The stakeholders perceived value is included with a multi attribute value function accounting for the operational flexibility. The actual results must be seen in light of the assumptions made. We believe the model represents a useful extension of the boundaries of the design process. At the same time it important to acknowledge how simplifications and idealization limits the direct real-life precision of the results.

10.1 Further Work

My greatest aspiration for this work would be to inspire someone to continue and explore strategies for conceptual design of transportation vessels. We believe that the trend towards a more holistic thinking in the early design phases will continue. However, the industry has yet to establish best practice methods to incorporate the extension of system boundaries called for in recent literature. Based on this work I believe Epoch-Era analysis can establish a new practise for extending the traditional scenario analysis. The Responsive system comparison method provides a useful framework for merging EEA with other methodologies. Further work should consider other techniques that can be applied within this framework. Including operations research could be interesting. One possible implementation is to formulate the liner companies' decision as a mathematical optimization model based on the epoch variables, and used this as input for the investment problem of the independent ship owner.

Another area that could justify further effort is the mapping between design and the performance space. The simplifications made in the fuel consumption and other modelling approaches limited the number of design parameters that could be evaluated. An alternative approach would be to use empirical formulas, such as Holtrop-Mennen or Hollenbach, to calculate the resistance and use this a basis for the fuel- and voyage expenditures calculations. This would allow for the inclusion of variation in principal dimensions, such as breadth and length, to achieve the same cargo capacity. Wide beam designs were the length is shorter and breadth is wider for the same cargo capacity, have become popular in the container industry in recent years. This development should be seen in connection with the widespread adoption of slow steaming, as wide beam designs are believed to be relatively more efficient at lower speeds and less at higher.

Flexibility in marine design have gained traction as a research area. Pettersen (2015) demonstrated how real option analysis and simulation could be utilized as part of the life cycle analysis step to value flexibility in the design of specialized offshore vessels. We believe there exist value in flexibility also in the design of merchant transportation vessels. The option to utilize various fuel types in response to changes in the market described in this work is an example of flexibility. The results could have benefitted by expanding the scope to formalize the valuation of this, as well as other areas of, flexibility. Simulation appears to be a powerfull tool for including emerging factors of complexity in ship design. It is possible to see Monte Carlo Simulation as an integrated tool in the RSC methodology. Further research is needed to establish procedures for the era generation, and using simulation to combine eras to represent the desired developments could be an interesting area for further research.

Bibliography

Andrews, D. (1981). Creative Ship Design *The Naval Architect*.

Andrews, D. (1985). *An Integraded Approach to Ship Synthesis*. London: Royal Institution of Naval Architects

BCG. (2015). The Transformation Imperative in Container Shipping.

Beenstock, M., & Vergottis, A. (1989a). An econometric model of the world market for dry cargo freight and shipping. *Applied Economics*, *21*(3), 339-356.

Beenstock, M., & Vergottis, A. (1989b). An econometric model of the world tanker market. *Journal of Transport Economics and Policy, 23*, 263-280.

Beenstock, M., & Vergottis, A. (1993). *Econometric modelling of world shipping*: Springer Science & Business Media.

Begg, D., Vernasca, G., Fischer, S., & Dornbusch, R. (2014). *Economics* Berskshire (UK): McGraw-Hill Education

Benford, H. (1967). *On the rational selection of ship size*: SNAME.

Bergman, J. (Producer). (2014, 10.11.2015). Bigger ships - Bigger challenges: The evolution of container ships size and it's impact on the industry [Conference presentation] Retrieved from https://www.iaph2015.org/downloads/Presentations/Dienstag_pdf/Presentation_Jost%20Bergmann.pdf

Birge, J. R., & Louveaux, F. (2011). *Introduction to stochastic programming*. New York: Springer Science & Business Media.

Bjerksund, P., & Ekern, S. (1992). *Prinsipper for opsjonsbaserte analyser innen shipping* (Vol. 13/92). Bergen: Stiftelsen for samfunns- og næringslivsforskning.

Black, F., & Scholes, M. (1973). The pricing of options and corporate liabilities. *The journal of political economy*, 637-654.

Brett, P. O., & Ulstein, T. (2012). *Critical Systems Thinking in ship deisgn approaches* Paper presented at the International Maritime Design Conference Glasgow.

Britannica Academic. (2015). economy of scale. from http://academic.eb.com/EBchecked/topic/178584/economy-of-scale

Caracostas, N. (1979). Containership Economics for Effective Decision-Making Analysis *Marine Technology*.

Christiansen, M., Fagerholt, K., Nygreen, B., & Ronen, D. (2007). Chapter 4 Maritime Transportation. In B. Cynthia & L. Gilbert (Eds.), *Handbooks in operations research and management science* (Vol. Volume 14, pp. 189-284): Elsevier.

Clarkson Research. (2015). Shipping Intelligence Network. Retrieved November 21, 2015, from Clarkson Research Services Limited https://sin.clarksons.net/

Collette, M., Bronsart, R., Chen, Y., Erikstad, S. O., Georgiev, P., Giuglea, V., . . . Zanic, V. (2015). *Proceedings of the 19th International Ship and Offshore Structures Congress : Vol. 1.* Paper presented at the International Ship and Offshore Structures Congress, Cascais, Portugal

Corbett, J. J., Wang, H., & Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment, 14*(8), 593-598. doi: http://dx.doi.org/10.1016/j.trd.2009.08.005

Cuesta, E. F., Grimstad, A., & Hagen, A. (2009). Integrating a Maritime Transport Chain Perspective into ship design Trondheim: DNV proNavis.

Culinane, K., & Khanne, M. (1998). Economies of Scale in Large Container Ships. *Journal of Transport Economics and Policy*, pp. 185-208.

De Weck, O. L., Roos, D., & Magee, C. L. (2011). Engineering Systems - Meeting Human Needs in a Complex Technological World: MIT Press.

Devanney, J. (2011). The impact of the energy efficiency design index on very large crude carrier design and CO2 emissions. *Ships and Offshore Structures, 6*(4), 355-368. doi: 10.1080/17445302.2010.546651

Dickens, M. (2015). *New Developments in Container Shipping.* NTNU, Trondheim.

Diez, M., & Peri, D. (2010). Two-stage Stochastic Programming Formulation for Ship Design Optimisation under Uncertainty. *Ship Technology Research, 57*(3), 172-181. doi: 10.1179/str.2010.57.3.003

Drewry Shipping Consultant. (2015). *Ship Operating Costs 2014/15: Annual review and Forecast* (N. Gardiner Ed.). London: Drewry Maritime Reasearch.

Dyer, M., & Stougie, L. (2006). Computational complexity of stochastic programming problems. *Mathematical Programming, 106*(3), 423-432. doi: 10.1007/s10107-005-0597-0

Erikstad, S. O. (1996). *A decision support model for preliminary ship design.* (PhD), NTNU, Trondheim.

Erikstad, S. O. (Producer). (2014a, 13 october 2015). Lecture Note: Ship, Size and speed. Retrieved from https://ntnu.itslearning.com/,

Erikstad, S. O. (Producer). (2014b, 13 october 2015). Lecture Notes TMR4115: Introduction to Marine Systems Design Models and Methods. Retrieved from https://ntnu.itslearning.com/,

Erikstad, S. O., & Rehn, C. F. (2015). *Handling Uncertainty in marine systems design - state-of-the-art and need for research.* Paper presented at the 12th international marine design conference

Evans, J. H. (1959). BASIC DESIGN CONCEPTS. *Journal of the American Society for Naval Engineers, 71*(4), 671-678. doi: 10.1111/j.1559-3584.1959.tb01836.x

Eyres, D. J. (2007a). 1 - Basic design of the ship *Ship Construction (Sixth Edition)* (pp. 3-9). Oxford: Butterworth-Heinemann.

Eyres, D. J. (2007b). 2 - Ship dimensions, form, size or category *Ship Construction (Sixth Edition)* (pp. 10-14). Oxford: Butterworth-Heinemann.

Ezekiel, M. (1939). Tanker Freight Rates and Tankship Building: An Analysis of Cyclical Fluctuations (Book Review) (Vol. 47, pp. 882-883).

Fagerholt, K., Laporte, G., & Norstad, I. (2010). Reducing fuel emissions by optimizing speed on shipping routes. *The Journal of the Operational Research Society, 61*(3), 523-529.

Gaspar, H. M. (2013). *Handling aspects of complexity in conceptual ship design.* (2013:319 Phd), Norwegian University of Science and Technology, Faculty of Engineering Science and Technology, Department of Marine Technology, Trondheim.

Gaspar, H. M., Balland, O., Aspen, D. M., Ross, A. M., & Erikstad, S. O. (2015). Assessing air emissions for uncertain life-cycle scenarios via responsive systems comparison method. *229*(4), 350-364. doi: 10.1177/1475090214522218

Gaspar, H. M., Erikstad, S. O., & Ross, A. M. (2012). Handling temporal complexity in the design of non-transport ships using Epoch-Era Analysis. *Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering, 154*(3), 109-119. doi: 10.3940/rina.ijme.2012.a3.230

Gaspar, H. M., Hagen, A., & Erikstad, S. O. (2016). On designing a ship for complex value robustness. *Ship Technology Research, 63*(1), 14-25. doi: 10.1080/09377255.2015.1119923

Gaspar, H. M., Rhodes, D., Ross, A., & Erikstad, S. (2012). Addressing Complexity Aspects in Conceptual Ship Design: A Systems Engineering Approach. *J. Ship Prod. Des., 28*(4), 145-159. doi: 10.5957/JSPD.28.4.120015

Gaspar, H. M., Ross, A. M., Rhodes, D. H., & Erikstad, S. O. (2012). *Handling Complexity Aspects in Conceptual Ship Design*. Paper presented at the Int'l Maritime Design Conference, Glasgow, UK.

Gkonis, K. G., & Psaraftis, H. N. (2010). *Some Key Variables Affecting Liner Shipping costs*. National Technical University of Athens Athens, Greece.

Hagen, A., & Grimstad, A. (2010). The extension of system boundaries in ship design. *Transactions of the Royal Institution of Naval Architects Part A: International Journal of Maritime Engineering, 152*(1), A17-A28. doi: 10.3940/rina.ijme.2010.a1.167

Hsu, C.-I., & Hsieh, Y.-P. (2007). Routing, ship size, and sailing frequency decision-making for a maritime hub-and-spoke container network. *Mathematical and Computer Modelling, 45*(7–8), 899-916. doi: http://dx.doi.org/10.1016/j.mcm.2006.08.012

IHS Fairplay. (2016).

Jansson, J. O., & Shneerson, D. (1982). The Optimal Ship Size. *Journal of Transport Economics and Policy, 16*(3), 217-238.

Khor, Y. S., Døhlie, K. A., Konovessis, D., & Xiao, Q. (2013). Optimum Speed Analysis for Large Containerships. *Journal of Ship Production and Design, 29*(3), 93-104.

Levander, K. (2012). *System Based Ship Design [Textbook]*. NTNU, Trondheim.

Lindstad, H., Asbjørnslett, B. E., & Jullumstrø, E. (2013). Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market. *Transportation Research Part D: Transport and Environment, 19*, 5-12. doi: http://dx.doi.org/10.1016/j.trd.2012.11.001

Lundgren, J., Ronnqvist, M., & Varbrand, P. (2010). *Optimization*.

Luo, M., Fan, L., & Liu, L. (2009). An econometric analysis for container shipping market. *The flagship journal of international shipping and port research, 36*(6), 507-523. doi: 10.1080/03088830903346061

MAN Diesel. (2016). Product Catalog: Man Diesel Two Stroke Low Speed ME-GI Marine engines, avalible from: http://marine.man.eu/two-stroke/2-stroke-engines/me-gi-engines.

Manzanero, L. D. A., & Krupp, K. J. (2009). *Forecasting container freight rates - an econometric analysis.* (M.Sc finance & strategic management), Copenhagen buisness school, Copenhagen.

McManus, H., & Hastings, D. (2005). *3.4. 1 A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems.* Paper presented at the INCOSE International Symposium.

Merk, O., Buxquet, B., & Aronietis, R. (2015). The Impact of Mega-Ships: International Transport Forum.

Notteboom, T., & Vernimmen, B. (2009). The effect of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography, 17*(5), 325-337. doi: http://dx.doi.org/10.1016/j.jtrangeo.2008.05.003

Nowacki, H. (2010). Five decades of Computer-Aided Ship Design. *Computer-Aided Design, 42*(11), 956-969. doi: http://dx.doi.org/10.1016/j.cad.2009.07.006

Papanikolaou, A., Levander, K., Singer, D. J., Vassalos, D., Andersen, P., Riska, H. O. K. K., . . . Vassalos, D. (2009). *State of the Art report on design for X*. Paper presented at the 10th international marine design conference

Pettersen, S. S. (2015). *Designing Flexible Offshore Construction Vessels to Handle Future Uncertainty.* (Masters), NTNU, Trondheim.

Phillips, F., & Srivastava, R. (1993). Committed Costs vs. Uncertainty in New Product Development.

Popela, P., Novotný, J., Roupec, J., Hrabec, D., & Olstad, A. (2014). Two-stage stochastic programming for engineering problems. *Eng. Mech, 21*(5), 335-353.

Powell, W. B., & Topaloglu, H. (2003). Stochastic programming in transportation and logistics. *Handbooks in operations research and management science, 10*, 555-635.

Psaraftis, H. N., & Kontovas, C. A. (2013). Speed models for energy-efficient maritime transportation: A taxonomy and survey. *Transportation Research Part C: Emerging Technologies, 26*, 331-351. doi: http://dx.doi.org/10.1016/j.trc.2012.09.012

Rehn, C. F., Haugsdal, A., & Erikstad, S. O. (2016). *Flexible Strategies for Maritime Sulphur Emission Regulation Compliance.* Paper presented at the PRADS, Copenhagen.

Rhodes, D. H., & Ross, A. M. (2010, 5-8 April 2010). *Five aspects of engineering complex systems emerging constructs and methods.* Paper presented at the Systems Conference, 2010 4th Annual IEEE.

Roberts, C. J., Richards, M. G., Ross, A. M., Rhodes, D. H., & Hastings, D. E. (2009). Scenario planning in dynamic multi-attribute tradespace exploration (pp. 366-371).

Rodrigue, J.-P., & Slack, C. C. B. (2013). *The geography of transport systems*. New York: Routledge.

Rosenman, R. D. C. M. A., Radford, A. D., & Gero, M. B. J. S. (1990). *Knowledge-Based Design Systems* Reading, Massachusetts: Addison Wesley

Ross, A. M. (2006). *Managing unarticulated value : changeability in multi-attribute tradespace exploration.* (PhD), Massachusetts Institute of Technology.

Ross, A. M., & Hastings, D. H. R. D. E. (2008). Defining Changeability: Reconciling Flexibility, Adaptability, Scalability, Modifiability, and Robustness for Maintaining System Lifecycle Value. *Systems engineering*(11).

Ross, A. M., McManus, H. L., Rhodes, D. H., Hastings, D. E., & Long, A. (2009). *Responsive systems comparison method: Dynamic insights into designing a satellite radar system.* Paper presented at the AIAA SPACE 2009 Conference & Exposition, Pasadena.

Ross, A. M., & Rhodes, D. H. (2008). *Architecting Systems for Value Robustness: Research Motivations and Progress*. Paper presented at the Systems Conference, 2008 2nd Annual IEEE.

Ross, A. M., & Rhodes, D. H. (2008). *Using Value-Centric Time Scales for Conceptualizing System Timelines through Epoch-Era Analysis*. Paper presented at the INCOSE International Symposium 2008, Utrecht, the Netherlands.

Ross, A. M., Rhodes, D. H., & Fitzgerald, M. E. (2015). Interactive Value Model Trading for Resilient Systems Decisions. *Procedia Computer Science, 44*, 639-648. doi: http://dx.doi.org/10.1016/j.procs.2015.03.035

Saleh, J. H. (2001). *Weaving time into system architecture : new perspectives on flexibility, spacecraft design lifetime, and on-orbit servicing.* (Ph.D), Massachusetts Institute of Technology.

Schaffner, M. A. (2014). *Designing Systems for Many Possible Futures: The RSC-based method for Affordable Concept Selection, with Mult-Era Analysis* (MSc), Massachusetts Institute of Technology Cambridge, Massachusetts, USA

Simon, H. A. (1962). The Architecture of Complexity. *Proceedings of the American Philosophical Society, 106*(6), 467-482.

Singer, D. J., Doerry, N., & Buckley, M. E. (2009). What Is Set-Based Design? *Naval Engineers Journal, 121*(4), 31-43. doi: 10.1111/j.1559-3584.2009.00226.x

Stopford, M. (2009). *Maritime Economics*. New York: Routledge.

Svensen, T., & DNV-GL. (2012). Hull design boosts fuel economy of ultra large container ships.

Titman, S., & Martin, J. d. (2010). *Valuation: The art and Science of corporate investment decisions* (Second ed.): Pearson Higher Education.

Tran, N. K., & Haasis, H.-D. (2015). An empirical study of fleet expansion and growth of ship size in container liner shipping. *International Journal of Production Economics, 159*, 241-253. doi: http://dx.doi.org/10.1016/j.ijpe.2014.09.016

Tvedt, J. (2003). Shipping market models and the specification of freight rate processes. *Maritime Economics & Logistics, 5*(4), 327-346.

Ulstein, T., & Brett, P. O. (2015). *What is a better ship? - it all depends...* . Paper presented at the 12th international maritime design conference Tokyo.

Wang, S., & Meng, Q. (2012). Sailing speed optimization for container ships in a liner shipping network. *Transportation Research Part E: Logistics and Transportation Review, 48*(3), 701-714. doi: http://dx.doi.org/10.1016/j.tre.2011.12.003

Appendix A: Acronyms

BCG	Boston Consulting Group
CAPEX	Capital expenditures
ECA	Emission Control Areas
EEA	Epoch-Era Analysis
GBM	Geometric Brownian Motion
GDP	Gross Domestic Product
HFO	Heavy Fuel Oil
LNG	Liquefied Natural Gas
MGO	Marine gas oil
OPEC	Organization of Petroleum Exporting Countries
OPEX	Operational expenditures
ROI	Return on Investment
RSC	Responsive systems Comparison
SECA	Sulphur Emission Control Areas
SFOC	Specific Fuel Oil Consumption
VOYEX	Voyage expenditures

Appendix B: Economic Data

A more detailed description of the economic data used and analysis done for construct the cost model.

B.1 Operational Expenses

Breakdown of the operational expenses based on vessel size from Drewry Shipping Consultants (2014):

Daily Operating Cost for Container Vessels [USD/Day]

Cost Component	Vessel Capacity [TEU]						
	500-700	1,000-2,000	2,000-3,000	3,000-4,000	5,000-6,000	8,000-9,000	10,000-12,000
Manning	2330	2530	2530	2530	2660	2660	2790
Repair and maintenance	810	980	1110	1240	1440	1570	1750
Management and administration	390	470	560	580	640	780	830
Insurance	280	350	410	570	770	1160	1460
Stores, spares and lubeoil	820	1270	1730	2690	3220	3350	4420
Total	4630	5600	6340	7610	8730	9520	11250

Power regression model:

$$f(x) = a \cdot x^b$$

Coefficients [95% confidence bounds]:

$$a = 494.9\ [250.2, 739.5]$$
$$b = 0.3341\ [0.2759, 0.3924]$$

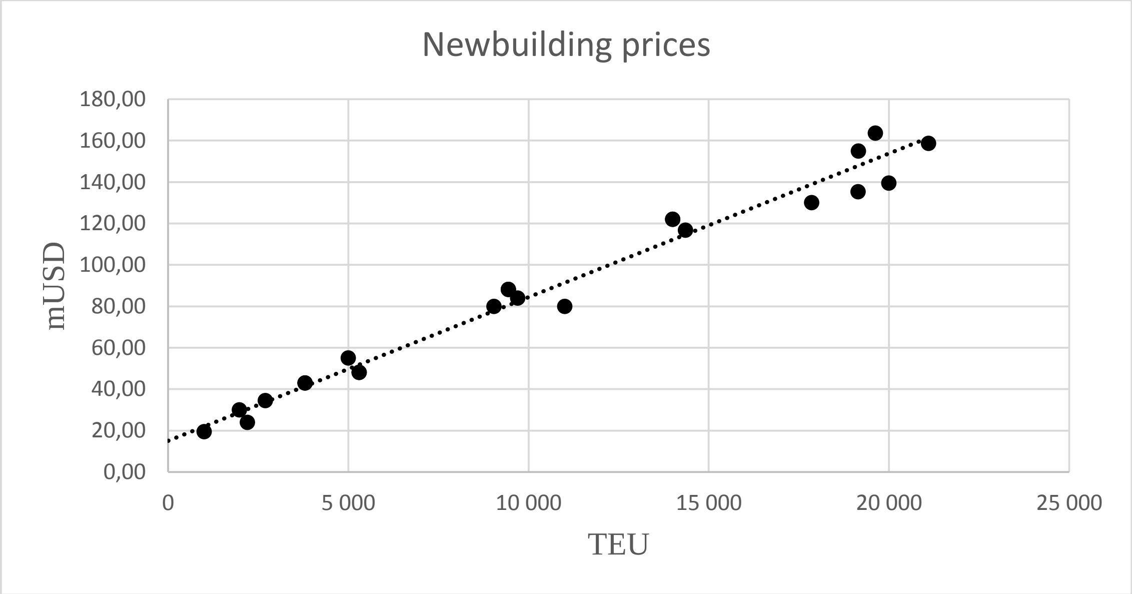
$$R^2 = 0.9858$$

B.2 Building Prices

Data for the newbuilding prices are based on data for vessels built or on order for 2015, 2016 and 2017. The dataset are form Clarksons (2015) and consists of 22 entries.

Type	Dwt [tonne]	Capacity [TEU]	Built	Builder	Owner	Price [mUSD]
Container	12 500	1 000	2016	Dae Sun S.B.	Nam Sung Shpg. Co.	19.5
Container	30 000	1 980	2015.9	STX Dalian	Unknown	30
Container	27 366	2 204	2015.9	Zhejiang Yangfan	Deutsche Afrika	24
Container	37 000	2 700	2017.2	Jiangsu New YZJ	Lomar Shipping	34.5
Container	55 000	3 800	2017	Jiangsu New YZJ	Hamburg-Sud	43
Container	65 000	5 300	2017	Zhejiang Ouhua SB	Zodiac Maritime Agy	48
Container	111 349	9 040	2016.2	HHIC-Phil (Subic SY)	Ciner Denizcilik	80
Container	83 731	9 448	2016.3	STX SB (Jinhae)	Rickmers Reederei	88.15
Container	110 000	9 700	2017	Jiangsu New YZJ	Pacific Intl Lines	84
Container	150 000	14 000	2017.5	Hyundai HI	Maersk Line	122
Container	225 000	19 150	2018	Dalian COSCO KHI	COSCON	135.3
Container	230 000	19 630	2017.3	Daewoo (DSME)	Maersk Line	163.63
Container	83 731	9 448	2016.3	STX SB (Jinhae)	Rickmers Reederei	88.15
Container	151 796	14 354	2016.9	Samsung HI	Costamare Shipping	116.8

Container	250 000	21 100	2017.9	Samsung HI	OOCL	158.6
Container	126 368	11 010	2016.4	HHIC-Phil (Subic SY)	Costamare Shipping	80
Container	230 000	20 000	2018.2	Shanghai Waigaoqiao	COSCON	139.5
Container	197 850	19 154	2016.7	Samsung HI	Quantum Scorpio Box	155
Container	61 450	5 001	2016	Weihai Samjin SY	Unknown	55
Container	65 000	5 300	2017.6	Zhejiang Ouhua SB	Zodiac Maritime Agy	48
Container	55 000	3 800	2017.6	Jiangsu New YZJ	Hamburg-Sud	43
Container	150 000	14 000	2017.6	Hyundai HI	Maersk Line	122
Container	185 000	17 859	2016	Jiangnan Changxing	CSSC Shipping (HK)	130



$$f(x) = ax + b$$

Coefficients:

$$a = 0.0069$$

$$b = 15$$

$$R^2 = 0.9749$$

Appendix C: Fuel Data

Appendix A: Here the data used for the fuel consumption is presented. This includes the fuel consumption as function of capacity, the specific fuel consumption and fuel prices.

C.1 Fuel Consumption

	Tran and Haasis (2015)	Merk et al. (2015)	Notteboom and Vernimmen (2009)	Wang and Meng (2012)	Stopford (2009)
2,000-3,000					67.7
3,000-4,300	78.3		76	82	87.2
5,000-6,500	117.4		94	90	107.0
8,000-9,000	124.5	128	132	128	111.0
10,000-11,000	128.0		148		116.8
12,000-13,000	148.5				
14,000-16,000	158.7	158.7			

The following was obtained bas on a power regression of the average value:

$$f(x) = a \cdot x^b$$

Coefficients [95% confidence bounds]:

$$a = 1.637\ [1.255, 2.02]$$

$$b = 0.4771\ [0.4517, 0.5026]$$

$$R^2 = 0.998$$

C.2 Specific Fuel Consumption

The specific fuel consumption (SFOC) was obtained from (MAN Diesel, 2016). Data for HFO

% MCR:	50	55	60	65	70	75	80	85	90	95	100
SFOC [g/kWh]	170.9	169.7	168.7	168	167.7	168.2	168.9	169.9	171.1	172.4	173.9

The following was obtained based on polynomial regression:

$$f(x) = p_1 \cdot x^2 + p_2 \cdot x + p_3$$

Coefficients [95% confidence bounds]:

$$p_1 = 0.0068\ [0.0060, 0.0076]$$

$$p_2 = -0.9519\ [-1.072, -0.8314]$$

$$p_2 = 201.3\ [197, -205.7]$$

$$R^2 = 0.9866$$

C.3 Energy Density

Fuel type	Energy Content [MJ/kg]
HFO	40.5
MGO	42.7
LNG	45

C.4 Scrubber

Power Consumptoion	0.5 % of actual power
NaOH Consumption	7 % of SFOC – modelled as 20 percent increase in OPEX

C.5 LNG

Volume: 3 % of cargo capacity lost due to fuel tanks and other equipment

10 % Increased OPEX in maintenance costs

Appendix D: Ship Data

D.1 Draft vs TEU

Function to calculate the draft as function of TEU. Used as utility function for operational flexibility

$$f(x) = a * x^b + c$$

Coefficients:

$$a = -662$$

$$b = -5.686$$

$$c = 18.49$$

Appendix E: Era Construction

Era 1

Epoch	GDP Growth	GDP Multi	HFO Price	MGO Price	LNG Price	% Time in ECA	Fleet Growth
1	4	2	3	5	4	10	6
2	4	2	3	5	4	10	6
3	4	2	8	15	8	10	10
4	4	2	8	15	8	10	10
5	4	2	8	15	8	10	10

Era 2

Epoch	GDP Growth	GDP Multi	HFO Price	MGO Price	LNG Price	% Time in ECA	Fleet Growth
1	0	2	3	5	4	10	10
2	4	2	3	5	4	10	10
3	4	2	8	15	8	20	6
4	8	3	15	25	12	20	6
5	8	3	15	25	12	30	10

Era 3

Epoch	GDP Growth	GDP Multi	HFO Price	MGO Price	LNG Price	% Time in ECA	Fleet Growth
1	4	2	3	5	4	10	2
2	4	2	3	5	4	10	2
3	4	1	8	15	8	20	6
4	0	1	8	15	8	20	6
5	0	1	8	15	8	30	2

Appendix F: Matlab Code

F.1 ProdTheory.m

```
%This function calculates and plots the annual transportation capacity,
%total cost and profit based on economic production theory
%Inputs
L = 0.6; % Utilization factor
Tw = 2; %Waiting time per roundtrip
D = 5000*2; %Distance one way (*2 for roundtrip)
Rh = 300; %Unloading rate, containers / hour
OH=10; %Days off-hire during one year
SFC=0.000180;
FP = 350; % 350 USD/tonne for fuel
CRF = 0.15;
UnitRevenue = 0.000200; %100 USD/TEU;

V=[10:1:30]; %Range of speed to consider
q=[1000:1000:25000]; %Range of capacities to consider

Capex = zeros(length(V),length(q));
Q = zeros(length(V),length(q));
C = zeros(length(V),length(q));
P = zeros(length(V),length(q));
CF = zeros(length(V),length(q));
YearlyCost = zeros(length(V),length(q));
FuelCon = zeros(length(V),length(q));
R = zeros(length(V),length(q));

%loops through the designspace
for i=1:length(V)
    for j=1:length(q)
        TS = (D/(V(i)*24));
        TP = ((q(j)*L)/(12*Rh));
        T = TS + TP + Tw;
        Q(i,j) = (2*q(j)*L*(365-OH))/(((q(j)*L)/ ...
        (12*Rh))+(D/(V(i)*24))+(Tw));
        P(i,j) = 1.637*(q(j)^0.48)*((V(i)/20)^3)*(1/(SFC*24));
        Capex(i,j) = 0.000350*P(i,j)+15+0.0069*q(j); %mUSD
        FuelCon(i,j) = P(i,j)*SFC*(TS/T)*24*(365-OH);
        CF(i,j) = FuelCon(i,j)*FP*(1/1000000);
        YearlyCost(i,j) = Capex(i,j)*CRF + CF(i,j);
        R(i,j) = UnitRevenue*Q(i,j) - YearlyCost(i,j);
    end
end

%Plotting
figure(1)
[F,t] = contour(q,V,Q,10)
```

```
title('Isoquants')
xlabel('q [TEU]')
ylabel('V[kn]')

figure(2)
[X Y] = meshgrid(q,V);
surf(X,Y,Q)
title('3D surface plot (Transportation Capacity)')
xlabel('q [TEU]')
ylabel('V[kn]')

figure(3)
[F,t] = contour(q,V,YearlyCost,10)
title('ISOCOST')
xlabel('q [TEU]')
ylabel('V[kn]')

figure(4)
[F,t] = contour(q,V,R,10)
title('Revenue')
xlabel('q [TEU]')
ylabel('V[kn]')

figure(5)
[X Y] = meshgrid(q,V);
surf(X,Y,R)
title('3D surface plot')
xlabel('q [TEU]')
ylabel('V[kn]')
```

F.2 RSC.m

```
%This runs through the steps of the RSC method
clc
%%
%Design space enumeration
TradeSpace=tradespace();
%%

%%
%Estimate engine size as function of size and speed
TradeSpace=estimatekw(TradeSpace);
%%

%%
%Estimate CAPEX as function of capacity, installed power and en
  ine configuration
TradeSpace=CAPEX(TradeSpace);
%%

%%
```

```
    %Estimate the daily non-fuel OPEX [USD/day]
    TradeSpace=OPEX(TradeSpace);
    %%

    %%
    %Epoch space enumeration
    EpochSpace = epochs();
    %%

    %%
    %Calcualte current feight level based on epoch varialbe
    EpochSpace = freightrates(EpochSpace);
    %%

    %%
    %Liner company response
    EpochSpace = liner(EpochSpace);
    %%

    %%
    %Operational Profile
    [FuelCon,NoContainer,MCR,Penalty] = FuelCon(TradeSpace,EpochSpace);

    %%
    % Calculates yearly capital expenditures
    Capex = cost(TradeSpace,EpochSpace);

    %%
    %Calcualtes yearly fuel cost
    FuelCost = FuelCost(EpochSpace,TradeSpace,FuelCon);

    %%
    %Calculate yearly unit transportation cost
    [UnitCost,FuelUnitCost,OpexUnitCost,CapexUnitCost,PenaltyCost] = UnitCost(EpochSpace,TradeSpace,FuelCost,Capex,NoContainer,Penalty);

    %%
    %Calculates utility
    [Utility,CostUtility,UnitCost_min,UnitCost_max,FlexUtility,Draft] = Utility(UnitCost,TradeSpace,MCR);

    %%
    %Calcualtes avreage utility with equal weight on all epochs
    TotalUtility=MultiEpoch(Utility);


    %%
    %Generate the ERA space
    EraSpace=Era();

    %%
    %Multi era analysis
    [EraUtility_trade1, EraUtility_trade2, EraUtility_trade3] = MultiEra(Utility,EraSpace);
```

F.3 Tradespace.m

```
function [ DesignSpace ] = tradespace()

%%Function generates all feasible design based on input on design var
%% Import the data from excel spreadsheet
[~, ~, raw] = xlsread('Designvar.xlsx','Sheet1','A4:C16');

% Matrix of capacity, length and breadth
Cap = reshape([raw{:}],size(raw));

% Clear temporary variables
clearvars raw;

Speed = [15:1:25];

% Machinery configuration (1=HFO + Scrubber, 2 = dual fuel, 3 = dual fuel
% LNG]
Mach = [1:1:3];

%initializing
NoDesigns = length(Cap)*length(Speed)*length(Mach);
DesignSpace = zeros(NoDesigns,5);

%Define all possible combinations
n=1;
 for i=1:length(Cap)
    for j=1:length(Speed)
        for k=1:length(Mach)
            DesignSpace(n,1)=Cap(i,1);
            DesignSpace(n,2)=Cap(i,2);
            DesignSpace(n,3)=Cap(i,3);
            DesignSpace(n,4)=Speed(j);
            DesignSpace(n,5)=Mach(k);
        end
    end
 end
```

F.4 Estimatekw.m

```
function [TradeSpace] = estimatekw(tradespace)
%Function to estiamte the engine power as function of size and design
%speed.

%Specific fuel consumption, 180 g/kWh
```

```
SFC=0.000180;

%Initillizing
dailyfuelcons=zeros(length(tradespace),1);
InstalledKW20=zeros(length(tradespace),1);
InstalledKW=zeros(length(tradespace),1);

for i=1:length(tradespace)
    dailyfuelcons(i) = 1.64*((tradespace(i,1)^0.48));
    InstalledKW20(i) = dailyfuelcons(i)/(SFC*24);
    InstalledKW(i) = (InstalledKW20(i)*((tradespace(i,4)/20)^3))/0.70;
end

TradeSpace = [tradespace InstalledKW];
```

F.5 CAPEX.m

```
function [TradeSpace] = CAPEX(tradespace)
%Function to estiamte the building cost as function of size, KW and engine
%option

%Initillizing
capex=zeros(length(tradespace),1);

for i=1:length(tradespace)

    P=tradespace(i,6);

    if tradespace(i,5)==1 %HFO + Scrubber
        MachineryCost = 7850*P^(0.693)+28700*P^0.51;
    end
    if tradespace(i,5)==2 %Dual fuel MGO
        MachineryCost = 7850*P^(0.693)*1.4;
    end
     if tradespace(i,5)==3 %Dual fuel LNG
        MachineryCost = 7850*P^(0.693)*1.4 + 33300*P.^0.521;
     end

    BuildCost = tradespace(i,1)*0.007+15;

    capex(i) = MachineryCost*(1/1000000) + BuildCost;
end

TradeSpace = [tradespace capex];
```

F.6 OPEX.m

```
function [TradeSpace] = OPEX(tradespace)
% Calculates the non-fuel operational expenses, given in USD/day

%Initillizing
opex=zeros(length(tradespace),1);

for i=1:length(tradespace)
    opex(i)=495*(tradespace(i,1)^0.334);
end

TradeSpace = [tradespace opex];

end
```

F.7 Epochs.m

```
function [EpochSpace] = epochs()
%Generate the enumerated set of epoch (the epoch space)

%Epoch variables
GDP = -4:4:12;
GDP_multi=1:1:3;
HFOPrice = [3 8 15]; %USD/mBTU
MGOPrice = [5 15 25]; %USD/mBTU
LNGPrice = [4 8 12]; %USD/mBTU
FleetGrowth = [2 6 10];

%trade characteristics
Eca = 0:10:30; % % of route in ECA zone
RouteLength = [4000 7000 12000]; %Route length in nautical miles

n=1;
NoEpochs = length(FleetGrowth)*length(GDP)*length(GDP_multi)...
    *length(HFOPrice)*length(MGOPrice)*length(LNGPrice)...
    *length(Eca)*length(RouteLength);


EpochSpace = zeros(NoEpochs,8);

for a=1:length(GDP)
    for b=1:length(GDP_multi)
            for d=1:length(HFOPrice)
            for e=1:length(MGOPrice)
            for f=1:length(LNGPrice)
            for g=1:length(Eca)
            for h=1:length(RouteLength)
```

```
            for i=1:length(FleetGrowth)
                   EpochSpace(n,1)=GDP(a);
                   EpochSpace(n,2)=GDP_multi(b);
                   EpochSpace(n,3)=HFOPrice(d);
                   EpochSpace(n,4)=MGOPrice(e);
                   EpochSpace(n,5)=LNGPrice(f);
                   EpochSpace(n,6)=Eca(g);
                   EpochSpace(n,7)=RouteLength(h);
                   EpochSpace(n,8)=FleetGrowth(i);
            end
            end
            end
            end
            end
        end
    end
end
```

F.8 Freightrates.m

```
function [epochspace] = freightrates(EpochSpace)
%Calculates the freight level based on the economic situation and fleet
%growth

MarketLevel = zeros(length(EpochSpace),1);

for i=1:length(EpochSpace)
    ContainerGrowth = EpochSpace(i,1)*EpochSpace(i,2);

    ChangeRate = 5.9 + 4.3*ContainerGrowth - 3.54*EpochSpace(i,8);
    if ChangeRate <= -5
        MarketLevel(i) = 1;
    elseif  ChangeRate > -5 && ChangeRate <= 10
            MarketLevel(i)=2;
    elseif  ChangeRate > 10
            MarketLevel(i)=3;
    end

end
epochspace = [EpochSpace MarketLevel];
end
```

F.9 Liner.m

```
function [epochspace] = liner( EpochSpace )
%Calcualtes liner companies response to epoch variables

%Initlizing
Speed = zeros(length(EpochSpace),1);
Capacity = zeros(length(EpochSpace),1);

for i=1:length(EpochSpace)
    if EpochSpace(i,9) == 1
        MarketNorm = 0;
    elseif EpochSpace(i,9) ==2
        MarketNorm = 0.5;
    elseif EpochSpace(i,9) == 3
        MarketNorm = 1;
    end

    if EpochSpace(i,7) == 12000
        LengthNorm = 1;
    elseif EpochSpace(i,7) == 7000
        LengthNorm = 0.5;
    elseif EpochSpace(i,7) == 4000
        LengthNorm = 0;
    end

    if EpochSpace(i,3) == 3
        FPNorm = 1;
    elseif EpochSpace(i,3) == 10
        FPNorm = 0.5;
    elseif EpochSpace(i,3) == 15
        FPNorm = 0;
    end

    Speed(i) = 15 + 3.3*MarketNorm + 3.3*LengthNorm - 3.3*FPNorm;
    Capacity(i) =  5000 + 7000*MarketNorm + 7000*LengthNorm + 7000*FPNorm;

end

epochspace = [EpochSpace Speed Capacity];
```

F.10 FuelCon.m

```
function [YearFuelCon,NoContainer,MCR,Penalty] = FuelCon(TradeSpace,EpochSpace)
%Estimates the operational profile and fuel consumption based
%on the liner companies demand and design variables

YearFuelCon = zeros(length(EpochSpace),length(TradeSpace));
NoContainer = zeros(length(EpochSpace),length(TradeSpace));
MCR = zeros(length(EpochSpace),length(TradeSpace));
Penalty = zeros(length(EpochSpace),length(TradeSpace));

for i=1:length(EpochSpace)
    SpeedProfile = zeros(30,1);
    avg = round(EpochSpace(i,10)); %avg speed on trade
    if EpochSpace(i,7) == 12000
        PortCalls = 13;
    elseif EpochSpace(i,7) == 7000
        PortCalls = 4;
    elseif EpochSpace(i,7) == 4000
        PortCalls = 7;
    end

    TransitTime = ((EpochSpace(i,7))*2)/(avg); %Roundtrip time in hours

    %Hours per trip av various speeds (Transit)
    SpeedProfile(avg-3) = 0.05*TransitTime;
    SpeedProfile(avg-2) = 0.10*TransitTime;
    SpeedProfile(avg-1) = 0.15*TransitTime;
    SpeedProfile(avg) = 0.4*TransitTime;
    SpeedProfile(avg+1) = 0.15*TransitTime;
    SpeedProfile(avg+2) = 0.10*TransitTime;
    SpeedProfile(avg+3) = 0.05*TransitTime;

    %Maneouvering time in port
    PortTimeMan =PortCalls*2*8; %8 hour per port, roundtrip

    %Speed Profile Port Maneouvering
    SpeedProfile(12) = SpeedProfile(12) + 0.125*PortTimeMan;
    SpeedProfile(11) = SpeedProfile(11) + 0.125*PortTimeMan;
    SpeedProfile(10) = SpeedProfile(10) + 0.125*PortTimeMan;
    SpeedProfile(9) = SpeedProfile(9) + 0.125*PortTimeMan;
    SpeedProfile(8) = SpeedProfile(8) + 0.125*PortTimeMan;
    SpeedProfile(7) = SpeedProfile(7) + 0.125*PortTimeMan;
    SpeedProfile(6) = SpeedProfile(6) + 0.125*PortTimeMan;
    SpeedProfile(5) = SpeedProfile(5) + 0.125*PortTimeMan;


    for j=1:length(TradeSpace)

        %Number of containers per trip, based on demand from liner
        %companies and ship capacity
        if EpochSpace(i,11) >= TradeSpace(j,1)
```

```
            NoContainer(i,j) = TradeSpace(j,1);
            Penalty(i,j) = EpochSpace(i,11)-TradeSpace(j,1);
        else
            NoContainer(i,j) = EpochSpace(i,11);
        end

        PortTimeLoading = (NoContainer(i,j)*1.2)/200; %0.8 tilization one way, 0.4 other way. 200 containers per hour at port;

        FuelConTrip = 0;
        HoursYear = 8520; %10 days off-hire
        RoundTripsYear = HoursYear/(TransitTime+PortTimeLoading+PortTimeMan);
        NoContainer(i,j)=NoContainer(i,j)*RoundTripsYear;

        for k=1:length(SpeedProfile)

            if SpeedProfile(k) == 0
                continue %Skip to next iteration
            end

            KW = TradeSpace(j,6)*0.7*((k/(TradeSpace(j,4)))^3);
            MCR(i,j) = (KW/TradeSpace(j,6))*100;
            kWh = KW*SpeedProfile(k);

            FuelConTrip = FuelConTrip + kWh*((0.0068*MCR(i,j)^2)-(0.9519*MCR(i,j))+201.3)*(1/1000000);

        end
        YearFuelCon(i,j) =  FuelConTrip*RoundTripsYear;
    end

end
```

F.11 Cost.m

```
function [CAPEX1] = cost(TradeSpace,EpochSpace)
%Calcualtes the yearly cost for the Design and epoch combinations

%Economic information:
T_life = 25;
T_payback = 12;
%Risk adjusted discount rate:
r_discount = 0.1;

Cost=zeros(length(EpochSpace),length(TradeSpace));
CAPEX_equity = zeros(length(TradeSpace),1);
CAPEX_loan = zeros(length(TradeSpace),1);
CAPEX1 =  zeros(length(TradeSpace),T_life);
CAPEX=TradeSpace(:,7);
loan_remaining=zeros(1,length(TradeSpace));
```

```


for i=1:length(TradeSpace)

    CAPEX_equity(i) = 0.3*CAPEX(i);
  CAPEX_loan(i) = 0.7*CAPEX(i);
    loan_remaining(i) = CAPEX_loan(i);
    for t = 1:T_life
        %Calculating CAPEX paid per period as long as loan remains.
        if t <= T_payback
            CAPEX1(i,t) = CAPEX_equity(i)/T_life + ...
            CAPEX_loan(i)/T_payback + r_discount*loan_remaining(i);
            loan_remaining(i) = loan_remaining(i) - (1/T_payback)*loan_remaining(i);
        %Calculating CAPEX paid per period when loan is repaid.
        else
            CAPEX1(i,t) = CAPEX_equity(i)/T_life;
        end
    end

end

end
```

F.12 FuelCost.m

```
function [FuelCost] = FuelCost(EpochSpace,TradeSpace,FuelCon)
%Calculates yearly fuel cost
%   Detailed explanation goes here

FuelCost =zeros(length(EpochSpace),length(TradeSpace));

for i=1:length(EpochSpace)

    EcaShare = EpochSpace(i,6)/100;
    HFOPrice = EpochSpace(i,3)*39.5;
    MGOPrice = EpochSpace(i,4)*38.9;
    LNGPrice = EpochSpace(i,5)*38;

    for j=1:length(TradeSpace)

        if TradeSpace(j,5) == 1 %Scrubber
            FuelCost(i,j) = FuelCon(i,j)*HFOPrice;

        elseif TradeSpace(j,5) == 2 %MGO
            FuelCost(i,j) = (1-EcaShare)*HFOPrice*FuelCon(i,j)+(EcaShare*MGOPrice*FuelCon(i,j));

        elseif TradeSpace(j,5) == 3 %LNG
```

```
            FuelCost(i,j) = (1-EcaShare)*HFOPrice*FuelCon(i,j)+(EcaShare*LNGPrice*FuelCon(i,j));

        end

    end
end

end
```

F.13 UnitCost.m

```
function [UnitCost,FuelUnitCost,OpexUnitCost,CapexUnitCost,PenaltyCost]...
    = UnitCost(EpochSpace,TradeSpace,FuelCost,CAPEX,NoContainer,Penalty)
%Caluclates the unit transportaion cost [USD/TEU] on a yearly basis

UnitCost=zeros(length(EpochSpace),length(TradeSpace));
FuelUnitCost=zeros(length(EpochSpace),length(TradeSpace));
OpexUnitCost=zeros(length(EpochSpace),length(TradeSpace));
CapexUnitCost=zeros(length(EpochSpace),length(TradeSpace));
PenaltyCost=zeros(length(EpochSpace),length(TradeSpace));

for i=1:length(EpochSpace)
    for j=1:length(TradeSpace)

        if TradeSpace(j,5) == 1 %Scrubber
            YearlyCost = CAPEX(j,1)*1000000+...
            TradeSpace(j,8)*365+FuelCost(i,j);
            FuelUnitCost(i,j) = (FuelCost(i,j)*1.005)...
            /NoContainer(i,j);
            OpexUnitCost(i,j) = ((TradeSpace(j,8)*365)*1.1)...
            /NoContainer(i,j);
            CapexUnitCost(i,j) = (CAPEX(j,1)*1000000)...
            /NoContainer(i,j);
            UnitCost(i,j) = FuelUnitCost(i,j)...
            + OpexUnitCost(i,j) + CapexUnitCost(i,j);

        elseif TradeSpace(j,5) == 2 %MGO
            YearlyCost = CAPEX(j,1)*1000000+TradeSpace(j,8)...
            *365+FuelCost(i,j);
            FuelUnitCost(i,j) = FuelCost(i,j)/NoContainer(i,j);
            OpexUnitCost(i,j) = ((TradeSpace(j,8)*365))/...
            NoContainer(i,j);
            CapexUnitCost(i,j) = (CAPEX(j,1)*1000000)...
            /NoContainer(i,j);
            UnitCost(i,j) = FuelUnitCost(i,j) +...
            OpexUnitCost(i,j) + CapexUnitCost(i,j);

```

```
        elseif TradeSpace(j,5) == 3 %LNG
            NoContainer = NoContainer*0.97;
            YearlyCost = CAPEX(j,1)*1000000+TradeSpace(j,8)...
            *365+FuelCost(i,j);
            FuelUnitCost(i,j) = FuelCost(i,j)/NoContainer(i,j);
            OpexUnitCost(i,j) = ((TradeSpace(j,8)*365)*1.1)...
            /NoContainer(i,j);
            CapexUnitCost(i,j) = (CAPEX(j,1)*1000000)/...
            NoContainer(i,j);
            UnitCost(i,j) = FuelUnitCost(i,j) +
OpexUnitCost(i,j)...
            + CapexUnitCost(i,j);

        end
    end

end
```

F.14 Utility.m

```
function [Utility,CostUtility,UnitCost_min,UnitCost_max,...
FlexUtility,Draft] = Utility(UnitCost,TradeSpace,MCR)
%Calculates the utility based on the design and epcoh variables

%Initilizing
[NoEpochs, NoDesign] = size(UnitCost);
CostUtility=zeros(NoEpochs,NoDesign);
UnitCost_min = zeros(NoEpochs,1);
UnitCost_max = zeros(NoEpochs,1);
Draft = zeros(NoDesign,1);
FlexUtility=zeros(NoDesign,1);
Draft_min = 13;
Draft_max = 16;

Utility=zeros(NoEpochs,NoDesign);


for i=1:NoEpochs
        UnitCost_min(i) = min(UnitCost(i,:));
        UnitCost_max(i) = max(UnitCost(i,:));

end

for k=1:NoDesign

    Draft(k) = -662*TradeSpace(k,1)^(-0.5686)+18;49;

    if Draft(k) > 16
        Draft(k)=16;
    end
    if Draft(k) < 13
```

```
        Draft(k) = 13;
    end
end

for i=1:NoEpochs
    for j=1:NoDesign

        CostUtility(i,j) = 1-((UnitCost(i,j)-UnitCost_min(i))...
        /(UnitCost_max(i)-UnitCost_min(i)));
        FlexUtility(j) = 1-((Draft(j)-Draft_min))...
        /(Draft_max - Draft_min);
        Utility(i,j) = 0.75*CostUtility(i,j)+0.25*FlexUtility(j);
        if MCR(i,j) > 100
            Utility(i,j) = 0;
        end

    end
end

end
```

F.15 MultiEpoch.m

```
function [TotalUtility] = MultiEpoch(Utility)
%Calcultes the avreage utility across all epochs for all designs

[NoEpochs,NoDesign] = size(Utility);

TotalUtility=zeros(NoDesign,1);

for j=1:NoDesign
        TotalUtility(j) = sum(Utility(:,j))/NoEpochs;
end

end
```

F.16 Era.m

```
function [TotalUtility] = MultiEpoch(Utility)
%Calcultes the avreage utility across all epochs for all designs

[NoEpochs,NoDesign] = size(Utility);

TotalUtility=zeros(NoDesign,1);

```

```
8     for j=1:NoDesign
9             TotalUtility(j) = sum(Utility(:,j))/NoEpochs;
10    end
11
12    end
13
dbtype Era.m

1     function [Era_epochs] = Era()
2     %Function that generates era based on maunual selection of epochs
(based
3     %on stakeholderes expectations)
4
5
6     NoEra = 3; %Number of eras to consider
7     NoEpochEra = 5; % No epochs in each era
8     Era_epochs = zeros(NoEra,(NoEpochEra*3));
9
10
11    for i=1:NoEra
12        if i==1 %Era one
13            Era_epochs(i,1) = 6815;
14            Era_epochs(i,2) = Era_epochs(i,1)+3;
15            Era_epochs(i,3) = Era_epochs(i,1)+6;
16
17            Era_epochs(i,4) = 6815;
18            Era_epochs(i,5) = Era_epochs(i,4)+3;
19            Era_epochs(i,6) = Era_epochs(i,4)+6;
20
21            Era_epochs(i,7) = 7284;
22            Era_epochs(i,8) = Era_epochs(i,7)+3;
23            Era_epochs(i,9) = Era_epochs(i,7)+6;
24
25            Era_epochs(i,10) = 7284;
26            Era_epochs(i,11) = Era_epochs(i,10)+3;
27            Era_epochs(i,12) = Era_epochs(i,10)+6;
28
29            Era_epochs(i,13) = 7284;
30            Era_epochs(i,14) = Era_epochs(i,13)+3;
31            Era_epochs(i,15) = Era_epochs(i,13)+6;
32
33        elseif i==2 %Era two
34            Era_epochs(i,1) = 3900;
35            Era_epochs(i,2) = Era_epochs(i,1)+3;
36            Era_epochs(i,3) = Era_epochs(i,1)+6;
37
38            Era_epochs(i,4) = 6816;
39            Era_epochs(i,5) = Era_epochs(i,4)+3;
40            Era_epochs(i,6) = Era_epochs(i,4)+6;
41
42            Era_epochs(i,7) = 7292;
43            Era_epochs(i,8) = Era_epochs(i,7)+3;
44            Era_epochs(i,9) = Era_epochs(i,7)+6;
45
46            Era_epochs(i,10) = 11648;
47            Era_epochs(i,11) = Era_epochs(i,10)+3;
48            Era_epochs(i,12) = Era_epochs(i,10)+6;
```

```

        Era_epochs(i,13) = 11658;
        Era_epochs(i,14) = Era_epochs(i,13)+3;
        Era_epochs(i,15) = Era_epochs(i,13)+6;

    elseif i==3 %Era three
        Era_epochs(i,1) = 6814;
        Era_epochs(i,2) = Era_epochs(i,1)+3;
        Era_epochs(i,3) = Era_epochs(i,1)+6;

        Era_epochs(i,4) = 6814;
        Era_epochs(i,5) = Era_epochs(i,4)+3;
        Era_epochs(i,6) = Era_epochs(i,4)+6;

        Era_epochs(i,7) = 6320;
        Era_epochs(i,8) = Era_epochs(i,7)+3;
        Era_epochs(i,9) = Era_epochs(i,7)+6;

        Era_epochs(i,10) = 3404;
        Era_epochs(i,11) = Era_epochs(i,10)+3;
        Era_epochs(i,12) = Era_epochs(i,10)+6;

        Era_epochs(i,13) = 3412;
        Era_epochs(i,14) = Era_epochs(i,13)+3;
        Era_epochs(i,15) = Era_epochs(i,13)+6;

    end %if
end %for
end %function
```

F.17 MultiEra.m

```
function [ EraUtility_trade1, EraUtility_trade2, EraUtility_trade3] = MultiEra(Utility,EraSpace)
%Calculates the avreage utility for the epochs in each era


[NoEpochs, NoDesign] = size(Utility);
[NoEras, NoEpochEra] = size(EraSpace);
NoTrades = 3;

EraUtility_trade1 = zeros((NoEras),NoDesign);
EraUtility_trade2 = zeros((NoEras),NoDesign);
EraUtility_trade3 = zeros((NoEras),NoDesign);

for i = 1:NoEras

        EraUtility_trade1(i,:) = ((Utility(EraSpace(i,1),:))...
            +(Utility(EraSpace(i,4),:))+...
            (Utility(EraSpace(i,7),:))+(Utility(EraSpace(i,10),:))...
```

```
            +(Utility(EraSpace(i,13),:)))/5;

        EraUtility_trade2(i,:) = ((Utility(EraSpace(i,2),:))+...
            (Utility(EraSpace(i,5),:))+...
            (Utility(EraSpace(i,8),:))+(Utility(EraSpace(i,11),:))+...
            (Utility(EraSpace(i,14),:)))/5;

        EraUtility_trade3(i,:) = ((Utility(EraSpace(i,3),:))+...
            (Utility(EraSpace(i,6),:))+...
            (Utility(EraSpace(i,9),:))+(Utility(EraSpace(i,12),:))+...
            (Utility(EraSpace(i,15),:)))/5;
end

end %function
```