NTNU – Trondheim
Norwegian University of
Science and Technology

Designing Flexible Offshore Construction Vessels to Handle Future Uncertainty

Sigurd Solheim Pettersen

Marine Technology
Submission date: June 2015
Supervisor: Stein Ove Erikstad, IMT

Norwegian University of Science and Technology
Department of Marine Technology

NTNU – Trondheim
Norwegian University of
Science and Technology

Masters Thesis in Marine Systems Design
for
Stud. techn. Sigurd Solheim Pettersen
Designing Flexible Offshore Construction Vessels to Handle Future Uncertainty
Spring 2015

Background

Offshore Construction Vessels (OCVs) are increasingly used in the development of subsea oil and gas fields. The operations OCVs perform range from deployment and installation of subsea modules, to well intervention tasks and inspection, maintenance and repair of subsea structures. The diversity of the possible missions, creates a need for many different functionalities.

As the future operating context is uncertain, the functionalities of the initial design do not necessarily match the requirements set by subsequent contracts. There is also significant uncertainty in the economic, technical and environmental operating context of the vessel. This creates a need for flexible design solutions that can continue to deliver value in many alternative operating contexts, both by exploiting the opportunities and mitigate the risks represented by this uncertainty.

Overall aim and focus

The overall objective of this thesis is to identify valuable functional flexibilities in the design of OCVs subject to changing and uncertain future operating contexts, and to assess how flexibility can contribute to more cost-efficient designs.

Scope of work

The candidate should presumably cover the following main points:

1. Describe the operating context of the OCVs.
2. Create a high-level functional breakdown for OCVs.
    a. Describe the functional requirements of different market segments and propose possible equipment configurations.
    b. Identify equipment that may be regarded as optional.

3. Describe how uncertainty regarding future operating context affecting the value of OCVs can be treated by introducing flexibility, under the existing paradigms for decision making under uncertainty.
4. Describe and compare existing methodologies that can be used to identify and assess the value of flexibility.
5. Develop a realistic case study in which an OCV is subject to future market uncertainty, where:
    a. A platform OCV with functional flexibility is considered.
    b. Multiple market segments and vessel functionalities are considered.
6. Develop a quantitative model based on one of the methodologies in (4), for evaluating the design case in (5).
7. Discuss and conclude how flexibility affects the performance of OCVs.

Modus operandi

Professor Stein Ove Erikstad will be the responsible supervisor from NTNU.

The MSc project is within the topic area of the SIMOSYS project, and is thus eligible for traveling grants from this project.

The candidate will collaborate with Ulstein International during the work with this thesis. The contact person at Ulstein International will be Andre Keane. To the extent that the candidate will use data and material from Ulstein International that they consider sensitive, this must be presented in an anonymized or aggregated form that is acceptable to Ulstein International.

The work shall follow the guidelines made by NTNU for thesis work. The workload shall correspond to 30 credits, which is 100% of one semester.

Stein Ove Erikstad
Professor/Main Supervisor

Preface

This thesis is a part of the Master of Science degree in Marine Technology with specialization in Marine Systems Design at the Norwegian University of Science and Technology. The thesis was written in its entirety during the spring of 2015, and the work load is equivalent to 30 ECTS. The thesis focuses on applications of Epoch-Era Analysis and Real Options Analysis to handle future uncertainty in ship design, with offshore construction vessels (OCVs) used as a base case.

I would like to thank several people for their help and guidance throughout the process of writing this thesis. First, I would like to thank my supervisor Stein Ove Erikstad for pointing me towards literature on uncertainty and flexibility in systems, for valuable discussions throughout the semester and for providing traveling grants through the SIMOSYS project.

I would also like to thank the team at Ulstein International for their hospitality during my stays in Ulsteinvik. I want to thank Andre Keane for his help with defining a case and for comments on the Epoch-Era Analysis, Jose Jorge Agis for helping me understand OCV functions and operations, and Per Olaf Brett for providing insights in the overall industrial context of OCVs.

Trondheim, June 9, 2015

Sigurd S Pettersen

Sigurd Solheim Pettersen

Abstract

This thesis investigates how uncertainty in marine systems design can be handled through designing more flexible vessels. For multi-functional vessels not mainly doing transportation tasks, such as offshore construction vessels, there is a large potential in being able to take contracts not necessarily accounted for in the initial specification. Thus, there is a need to identify and value functional flexibility in offshore construction vessel designs, and to evaluate the existing methodologies for decision making under uncertainty that can be applied. We want to evaluate modifications of the vessel, through removing obsolete systems and installing systems adhering to current requirements. The primary research question for the thesis is therefore: *How do we identify and value functional flexibility in offshore construction vessel designs, subject to uncertain future operating contexts?* Secondary, the thesis also seeks to answer an additional research question: *Which methodologies exist for decision making under uncertainty that can be successfully applied in marine systems design, and how do they guide stakeholders towards great decisions?*

We argue that there are several paradigms for decision making that may be applied, each emphasizing different aspects of uncertainty and the notion of value. Novel systems engineering methods applied, such as Epoch-Era Analysis and the Responsive Systems Comparison method has a wide approach to value, accounting for stakeholder perception and context under uncertainty. The Responsive Systems Comparison method can be applied as a complete design methodology under uncertainty. Real Options Analysis from the financial paradigm treats value in a solely monetary way, and represents techniques for valuing flexibility. However, applying financial techniques in engineering systems poses a challenge. Monte Carlo Simulation solves some of the issues with real options in systems, but not the issue of actually identifying what system elements constitute interesting real options. For this, we introduce rules for transitioning between alternative concepts in the design space.

To test whether the Responsive Systems Comparison method and the Real Options Analysis with Monte Carlo Simulation are good approaches to answering the research questions, we develop a case study. The case study concerns an offshore construction vessel that can compete in four markets with developing contract requirements and economic uncertainty. The aim is to enable stakeholders to select a design that not only provides value at the first contract, but remains valuable throughout its lifetime, if necessary by altering the design itself. The model consists of the steps of the Responsive Systems Comparison method, with Monte Carlo Simulation for Real Options Analysis in the final step.

The results show that flexibility generate added value, both through reducing the downside risk and increasing the upside. We obtain flexible strategies that show us possible ways to transition the design towards alternative solutions, that are able to comply with the requirements of more valuable contract opportunities. This analysis is based on the Real Options Analysis using purely monetary measures of value, while the earlier Epoch-Era Analysis base value on the system capabilities in an engineering fashion. This causes some divergence in the results, as different conclusions regarding what constitutes a good design can be reached according to which of the analyses we apply. The divergence may not be a drawback, but may actually constitute an advantage as it facilitates a very broad discussion on the value of designs under uncertainty.

While the results indicate that flexibility is valuable, there are drawbacks related to the exercise of flexibility in ships, that are not accounted for in the modeling. An important risk that is not considered, is associated to shipbuilding projects. There are many other sources of uncertainty in marine systems that needs to be explored, and are not properly assessed by this model. Another need for further work exists in integrating Real Options Analysis into the Responsive Systems Comparison method, especially with respect to the question of how to properly quantify system value and performance under uncertainty.

Sammendrag

Denne oppgaven undersøker hvordan usikkerhet i marin prosjektering kan håndteres ved å utforme mer fleksible fartøy. For multifunksjonelle fartøy som ikke hovedsakelig driver med transportoppgaver, herunder offshore konstruksjonsfartøy, eksisterer det et stort potensiale i å kunne ta kontrakter som ikke nødvendigvis omfattes av den opprinnelige kravspesifikasjonen. Dermed oppstår det et behov for å identifisere og verdsette funksjonell fleksibilitet i design av offshore konstruksjonsfartøy, og å vurdere de eksisterende metoder for beslutningstakning under usikkerhet. Vi vurderer endringer i fartøyet, gjennom fjerning av systemer som ikke lenger behøves og installasjon av systemer som følger nye krav, eller tilpasser skipet til nye markeder. Den primære problemstillingen for oppgaven er derfor: *Hvordan kan vi identifisere og verdsette funksjonell fleksibilitet i design av offshore konstruksjonsfartøy, hvor fremtidige operasjonelle kontekster er usikre?* Sekundært søker oppgaven også å svare på problemstillingen: *Hvilke metoder finnes for beslutningstakning under usikkerhet som kan anvendes i marin prosjektering, og hvordan kan de bidra til gode beslutninger?*

Vi argumenterer for at det finnes flere paradigmer for beslutningstakning under usikkerhet som kan brukes, hver med vekt på ulike aspekter av usikkerhet og med ulik oppfatning av verdi. Nyere systems engineering-metoder som er benyttet, Epoch-Era-analyse og Responsive Systems Comparison-metoden, har en bred tilnærming til verdi, og tar hensyn til interessenters oppfatning av verdi og systemets kontekst under usikkerhet. Responsive Systems Comparison-metoden kan brukes som en komplett designmetodikk når det er usikkerhet. Realopsjonsanalyse fra det finansielle paradigmet behandler verdi på en utelukkende økonomisk måte, og presenterer teknikker for verdsetting av fleksibilitet. Anvendelse av finansielle teknikker på tekniske systemer er en utfordring. Monte Carlo-simulering løser noen av problemene med realopsjoner i systemer, men identifiserer ikke hvilke systemelementer som faktisk utgjør interessante realopsjoner. For dette innfører vi regler som definerer fartøyets mulighet til å omformes til andre designalternativer.

For å teste om Responsive Systems Comparison-metoden og realopsjonsanalyse med Monte Carlo simulering er gode tilnærminger til å besvare problemstillingen, utvikler vi et case-studie. Case-studiet gjelder et offshore konstruksjonsfartøy som kan konkurrere i fire markeder med kontraktskrav som endres over tid, og økonomisk usikkerhet. Målet er å hjeple beslutningstakere med å velge et design som ikke bare gir verdi gjennom den første kontrakten, men som vil være verdifullt gjennom hele levetiden, om nødvendig ved å endre designet selv. Modellen består av trinnene i Responsive Systems Comparison-metoden, med Monte Carlo-simulering for realopsjonsanalyse i det siste trinnet.

Resultatene viser at fleksibilitet genererer merverdi, både gjennom å redusere nedsiderisikoen og øke den økonomiske oppsiden. Fleksible strategier genereres og viser oss mulige måter å tilpasse designet til alternative designløsninger, som er i stand til å overholde kravene til mer verdifulle kontrakter. Denne analysen er basert på realopsjonsanalysen som bruker rene monetære verdimål, mens Epoch-Era-analysen som utføres tidligere benytter designets egenskaper som kilder til verdi. Dette fører til noe divergens i resultatene, og gir ulike konklusjoner om hva som utgjør et godt design. Divergensen er ikke nødvendigvis en ulempe, men kan faktisk utgjøre en fordel, da det muliggjør en meget bred diskusjon om hvilke designaspekter som skaper verdi i en usikker kontekst.

Mens resultatene tyder på at fleksibilitet er verdifullt, er det ulemper knyttet til å benytte seg av fleksibiliteten i skipsdesign, som ikke er redegjort for i modelleringen. En viktig risikofaktor som ikke er vurdert, er knyttet til skipsbygging. Det finnes mange andre kilder til usikkerhet i marine systemer som må utforskes, og som ikke er vurdert i denne modellen. Et annet behov for videre arbeid er å integrere realopsjonsanalysen i Responsive Systems Comparison-metoden. Dette gjelder spesielt spørsmålet om hvordan man skal kvantifisere systemets verdi og ytelse under usikkerhet.

Contents

1 Introduction 1
1.1 Background . . . 1
1.2 Research Question . . . 2
1.3 Literature Review . . . 2
1.4 Structure of the Report . . . 5

2 Paradigms for Decision Making 7
2.1 Understanding Uncertainty . . . 7
2.2 Defining Flexibility . . . 8
2.3 Flexibility In Systems Engineering . . . 9
2.3.1 Quantification of Changeability . . . 11
2.4 Flexibility In Finance: Real Options . . . 12
2.4.1 Financial Options and Traditional Real Options . . . 12
2.4.2 Real Options *In* Systems . . . 13
2.5 Flexibility In Operations Research . . . 14
2.5.1 Stochastic Programming . . . 14

3 Methodologies for Achieving Flexibility 17
3.1 The Responsive Systems Comparison Method . . . 17
3.1.1 Epoch-Era Analysis . . . 17
3.1.2 The Seven Steps of the Responsive Systems Comparison Method . . . 19
3.2 Real Options Analysis . . . 23
3.2.1 Central Stochastic Processes . . . 23
3.2.2 Binomial Options Pricing . . . 24
3.2.3 Monte Carlo Simulation for Real Options Analysis . . . 25

4 Offshore Construction Vessels 29
4.1 Contextual Aspects of Offshore Construction Vessels . . . 29
4.1.1 Main Commercial Drivers in Offshore Construction . . . 29
4.1.2 The Phases of Offshore Construction . . . 30

4.1.3 Some Geographic Market Aspects 30
4.1.4 Main Players in the Offshore Construction Market 31
4.2 The Operations of Offshore Construction Vessels 31
4.2.1 Inspection, Maintenance and Repair 32
4.2.2 Subsea Installation, Umbilicals, Risers and Flowlines 34
4.2.3 Light Well Intervention 34
4.2.4 Diving Support 35
4.3 Functional Breakdown for Offshore Construction Vessels 35
4.3.1 Ship-Related Functions 35
4.3.2 Task-Related Functions 36
4.4 Uncertainties Faced by Offshore Construction Vessels 38
4.5 Identifying Sources of Flexibility 40
4.5.1 The Role of Modularization 40
4.5.2 Real Options and Offshore Construction Vessels 40

5 Case Study **43**
5.1 Case Description 43
5.1.1 The Future Expectations of the Ship Owner 44
5.2 Selecting a Design Methodology for Flexibility 45
5.3 Modeling With the Responsive Systems Comparison Method 45
5.3.1 Value-Driving Context Definition for the Offshore Construction Vessel . . . 45
5.3.2 Value-Driven Design Formulation for the Offshore Construction Vessel . . . 46
5.3.3 Epoch Characterization for the Offshore Construction Vessel 54
5.3.4 Tradespace Evaluation for the Offshore Construction Vessel 58
5.3.5 Multi-Epoch Analysis for the Offshore Construction Vessel 59
5.3.6 Era Construction for the Offshore Construction Vessel 60
5.3.7 Life Cycle Path Analysis for the Flexible Offshore Construction Vessel 61
5.4 Model Assumptions 65

6 Results and Discussion **67**
6.1 Tradespace Exploration 67
6.2 Multi-Epoch Analysis 70
6.3 Life Cycle Path Analysis with Flexibility 74
6.3.1 Life Cycle Path Analysis for Design 1 75
6.3.2 Life Cycle Path Analysis for Design 11 78
6.3.3 Life Cycle Path Analysis for Design 51 82
6.4 Discussion 85

7 Conclusions **89**
7.1 Further Work 90

Bibliography **91**

A Acronyms **i**

B Economic Data for the Case Study **iii**

C Era Construction for the Case Study **v**

D Offshore Construction Vessel Configurations **vii**

E MATLAB Code **ix**
E.1 MATLAB Files for the Responsive Systems Comparison Method ix
E.2 MATLAB Files for Life Cycle Path Analysis with Flexibility xxxii

List of Figures

2.1 Flexible versus robust design (Saleh, 2001). 9
2.2 Framework for handling uncertainty, based on McManus and Hastings (2006). . . 10
2.3 Five aspects of complexity in ship design (Gaspar, 2013), with future uncertainty represented by the temporal aspect. 11
2.4 Transition paths allowed for designs in a tradespace (Ross et al., 2008b). 11

3.1 Example era with an unchangeable design. The colors indicate the context of the epoch (Ross et al., 2008a). 18
3.2 Example era with a changeable design. The colors indicate the context of the epoch (Ross et al., 2008a). 19
3.3 Flowchart for the Responsive Systems Comparison method (Ross et al., 2009). . . . 20
3.4 Tradespace with some designs along the Pareto front highlighted (Gaspar et al., 2012). 21
3.5 Alternative eras on a two-dimensional epoch space (Gaspar et al., 2015). 22
3.6 Binomial lattice, based on Cox et al. (1979). 24
3.7 Binomial lattice with Geometric Brownian Motion sample path (Wijst, 2013). . . . 25
3.8 Flowchart for Monte Carlo Simulation (Rader et al., 2010). 26
3.9 Example of a target curve or cumulative distribution of value (de Neufville et al., 2007). 26

4.1 Players in the offshore construction market (RS Platou, 2014). 32
4.2 Functional breakdown of cargo spaces in offshore construction vessels. 37
4.3 Functional breakdown of systems for lifting and construction tasks in offshore construction vessels. 37
4.4 Functional breakdown of systems for diving tasks in offshore construction vessels. 38
4.5 Sankey diagram mapping the influence of some economic, technical, political and physical uncertainties on the supply and demand of oil. 39
4.6 Matrix explaining the physical relationships between important topside systems in an offshore construction vessel. Read from the rows to the columns. 42

5.1 Sankey diagram mapping the value attributes explained in the value proposition, to performance attributes, design variables and epoch variables. 47
5.2 The influence of epoch variables and design variables on the requirements, availability and the probability of winning contracts. 57
5.3 Tradespace exploration for a single epoch. The Pareto front is highlighted in red, while the color coding is presented in Table 5.7. 59

6.1 Tradespace for Epoch 3. The Pareto front is shown in red. The colors adhere to the legend in Table 5.7. 68
6.2 Vessel Configuration for Design 51. 69
6.3 Vessel Configuration for Design 106. 69
6.4 Pareto trace for the whole enumerated design space. Frequency refers to the share of epochs in which the design is Pareto optimal. 71
6.5 Multi-epoch tradespace exploration. Pareto front shown in red. Colors according to Table 5.7. 72
6.6 Vessel Configuration for Design 1. 72
6.7 Vessel Configuration for Design 11. 73
6.8 Vessel Configuration for Design 13. 73
6.9 Cumulative NPV distribution for Design 1. Red curves show inflexible design NPV, while green show flexible design NPV. Vertical lines illustrate expected NPV. 76
6.10 NPV distribution for inflexible Design 1. 77
6.11 NPV distribution for flexible Design 1 78
6.12 Cumulative NPV distribution for Design 11. Red curves show inflexible design NPV, while green show flexible design NPV. Vertical lines illustrate expected NPV. . 79
6.13 NPV distribution for inflexible Design 11. 80
6.14 NPV distribution for flexible Design 11. 81
6.15 Cumulative NPV distribution for Design 51. Red curves show inflexible design NPV, while green show flexible design NPV. Vertical lines illustrate expected NPV. . 82
6.16 NPV distribution for inflexible Design 51. 83
6.17 NPV distribution for flexible Design 51. 84

B.1 Costs for investment in systems iii

D.1 Vessel Configuration for Design 16 vii
D.2 Vessel Configuration for Design 21 viii
D.3 Vessel Configuration for Design 36 viii
D.4 Vessel Configuration for Design 61 viii

List of Tables

2.1 Exercise time for options. 13
2.2 Defining call and put options. 13
2.3 Financial options versus real options (based on Alizadeh and Nomikos (2009) and Wijst (2013)). 13
2.4 Real options *in* systems versus real options *on* projects. 14

4.1 Factors of the shipping market model of Stopford (2009). 29
4.2 Phases in the lifetime of an oil field (based on Ulstein International (2015)). 30
4.3 Offshore region description (based on RS Platou (2014)). 31
4.4 Defining well stimulation and scale squeeze operations. 33
4.5 Examples of maritime uncertainties, based on Erikstad and Rehn (2015). 38
4.6 Uncertainties faced by offshore construction vessels, based on Gaspar (2013). . . . 38

5.1 Performance attributes for the offshore construction vessel. 47
5.2 Design variables for the offshore construction vessel. 50
5.3 Accommodation and deck area needed for the installation of specific systems. . . 51
5.4 Minimum requirements for the initial operating context. 52
5.5 Components of the operational expenditures. 54
5.6 Epoch variables selected for the analysis. 55
5.7 Tradespace coloring legend, based on total deck area. This legend applies to all tradespaces. 58
5.8 Conditions for making a transition between two designs. 64

6.1 Comparing key tradespace data for Design 51 and Design 106 in Epoch 3. 68
6.2 Vessel - contract match in Epoch 3. 69
6.3 Average utility for each era, compared to the average utility from the multi-epoch and multi-era analysis. 74
6.4 Reviewing the contribution to value robustness. 75
6.5 NPV data for Design 1. 76
6.6 Possible flexible design strategy for an initial Design 1 in Era 1. 77

6.7 Set of real options for transition between Design 1 and Design 36. 78
6.8 NPV data for Design 11. 79
6.9 Possible flexible design strategy for an initial Design 11 in Era 1. 81
6.10 Set of real options for transition between Design 11 and Design 61. 81
6.11 NPV data for Design 51. 84
6.12 Possible flexible design strategy for an initial Design 51 in Era 1. 85
6.13 Set of real options for transition between Design 51 and Design 21. 85

B.1 Initial day rates and stochastic process parameters for contracts iv

C.1 Epoch progression of Era 1 v
C.2 Epoch progression of Era 2 v
C.3 Epoch progression of Era 3 vi
C.4 Epoch progression of Era 4 vi
C.5 Epoch progression of Era 5 vi

Chapter 1

Introduction

1.1 Background

When designing ships and other complex marine systems there is a lot of uncertainty related to the future operating context. Ship design approaches based on the tradition of the design spiral of Evans (1959), has focused mostly on technical aspects, not taking future uncertainty into account. To ensure that ships continue to add value throughout their lifetime, it is becoming more important to consider future uncertainty, both in the technical, commercial and operational aspects.

Design under uncertainty is becoming ever more relevant as new ship types emerge, that are not meant primarily for transportation tasks. For multi-functional vessels such as offshore construction vessels (OCVs) that potentially can perform a large variety of tasks ranging from offshore construction to well intervention, inspection, maintenance and repair, the objective changes from fulfilling static stakeholder requirements to matching the right vessel with the right mission (Gaspar et al., 2015). Considering that these missions are continuously changing, with offshore operations diverging with regards to system requirements, it becomes necessary to find the balance between optimizing the vessel for its initial contract, and investing in capabilities that allow it to be successful at a later time (Erikstad and Rehn, 2015).

By designing for flexibility, we enable the vessel to perform missions previously outside their scope of operations. Flexibility thus facilitates multi-functionality in vessels, while helping us avoid "multi-uselessness", as it is coined in Gaspar et al. (2015) and Ulstein and Brett (2015). In more general terms, flexibility allows us to capture upside potential, while reducing the downside. Flexibility is in this respect the desired outcome (McManus and Hastings, 2006), when we mitigate risks and exploit opportunities stemming from changes in the context, through actively modifying the vessel.

1.2 Research Question

The goal of this thesis is to investigate how uncertainty can be handled in marine systems by using flexibility. While there may be many ways to handle uncertainty, most engineering methods have been focused with mitigating risks, without capturing the upside potential (McManus and Hastings, 2006). For this reason, there is a need for investigating further how we can capture potential opportunities as well. The original research question thus becomes:

> *How do we identify and value functional flexibility in OCV designs, subject to uncertain future operating contexts?*

Identification of functional flexibility is difficult to do, before the role of the various subsystems in an OCV is clearly understood, as well as the interaction between them. To analyze flexibility in design, we first must know what alternative system configurations exist and how these provide value given future uncertainty. The initial research question forces us to go further. A second research question related to the more general problem of decision making under uncertainty, can be defined:

> *Which methodologies exist for decision making under uncertainty that can be successfully applied in marine systems design, and how do they guide stakeholders towards great decisions?*

The research questions presented here, represents an extension of the ship design problem. Thus we concentrate on these extensions. We will not deal primarily with engineering analysis in this thesis, but with approaches that provide continued value to the stakeholders in a marine system under uncertain future conditions.

1.3 Literature Review

To answer the research questions, the literature presented in this chapter has been useful. The reviewed literature for this thesis can be categorized in the following way. First, we go through recent ship design research pointing to the need for handling uncertainty. Next, we present research from the three central decision making paradigms (systems engineering, finance and operations research).

Erikstad and Rehn (2015) is a recent example presenting the state-of-the-art on uncertainty in marine systems design. Herein, real options and stochastic programming are investigated as methodologies for handling uncertainty. Gaspar (2013) discusses ship design as a complex problem, using a five aspects taxonomy presented in Rhodes and Ross (2010). Complexity is decomposed into the structural, behavioral, contextual, temporal and perceptual aspects. The traditional ship design domain is represented by the structural and behavioral aspects that can be handled by approaches such as the system-based design of Levander (2012) and Erikstad and Levander (2012), or the set-based design of Singer et al. (2009). To tackle future uncertainty we should increasingly account for the context (the contextual aspect), the stakeholder perceptions (the perceptual aspect), and the changes in these (the temporal aspect). The Ship Design and Deployment Problem (SDDP) is introduced in Erikstad et al. (2011), and formulated as an optimization problem. The SDDP seeks to further the understanding of how we should design a non-transport vessel that can match the requirements of both the current and future contracts, thus handling the contextual aspect of complexity. In the further work section, Erikstad et al. (2011) recommends an extension of the problem towards a stochastic programming formulation, as a way to account for future uncertainty, and thus the temporal aspect. Further insights in the handling of contextual aspects is found in Ulstein and Brett (2012) which emphasizes understanding of operational and commercial aspects to the same degree as technical aspects in ship design. They present the Accelerated Business Development as an example of a specific consulting process in which the complexity of marine decision making processes is accounted for. Their thoughts of what constitutes value, is outlined in a more recent paper, Ulstein and Brett (2015), exemplified through several performance perspectives. In Gaspar (2013), future uncertainty exists as the temporal aspect and is mitigated through the use of novel systems engineering techniques.

The approach of Gaspar (2013) was poineered by researchers at the Systems Engineering Advancement Research Initiative (SEARI) at the Massachusetts Institute of Technology (MIT), mostly in non-maritime applications. To obtain insight in the theory and methodology developed through that initiative, several SEARI papers have been reviewed. McManus and Hastings (2006) provides a sound systems engineering framework for handling uncertainty, and puts forth examples of how "-ilities" mitigate and exploit uncertainties. Ross et al. (2008b) focuses specifically on "-ilities" within the umbrella term changeability, and clarifies the differences between several related concepts, such as flexibility and adaptability. Ross et al. (2008b) also introduce concepts related to changeability, such as transition paths and filtered outdegree. Ross and Rhodes (2008) and Ross et al. (2008a) introduce Epoch-Era Analysis (EEA) as a way to parametrize the future uncertainty on the form of static epochs, which are combined to dynamic eras, used to evaluate system performance when subjected to uncertainty. Ross et al. (2008a) and Ross et al. (2009) introduce Responsive Systems Comparison (RSC) as a methodology incorporating EEA in a framework with increased emphasis on the value proposition of the stakeholders. Gaspar et al. (2012) exemplify the use of the RSC method in marine systems design, using a anchor handling vessel as a case. Gaspar et al. (2015) shows how EEA can be used to evaluate the value robustness in ship design, using an Ulstein platform supply vessel as a case.

Real options originate from the early work on options pricing in finance, in Black and Scholes (1973), Merton (1973) and Cox et al. (1979). Real options are increasingly used in systems design, as pointed out in Ross et al. (2008b). de Neufville (2003) argues that a real options approach is useful when designing flexible systems. Identification and evaluation of real options *in* systems, is contrasted with real options *on* projects, in Wang and de Neufville (2004) and Wang and de Neufville (2005). The main emphasis of these work, is to point out the need for methods dealing with real options *in* complex systems, as standard options pricing methods fall short. An application of real options *on* projects, is the combination carriers case presented in Sødal et al. (2008), which applies an analytical solution of the mean-reverting process to find the option value associated with market switching. Wijst (2013) and Alizadeh and Nomikos (2009) give further insight on real options *on* projects, using binomial lattices to a large extent. Hassan et al. (2005), de Neufville et al. (2007) and Lin et al. (2013) provides good examples of how real options *in* systems can be valued by Monte Carlo Simulation, comparing the Value-at-Risk, target curves or cumulative net present value distributions of flexible and inflexible versions of similar systems. These ideas are further outlined in de Neufville and Scholtes (2011). Another interesting example using a real options thinking is Baldwin and Clark (2002), who show that modular systems provide flexibility as modules allow us to replace functionalities easily. The modular approach of the system-based design of Erikstad and Levander (2012) and Levander (2012) is thus set into a flexibility context.

Stochastic programming is presented thoroughly in King and Wallace (2012) and Higle (2005). Differences between stochastic programming and real options as a means to assess flexibility are pointed out in King and Wallace (2012). Wang and de Neufville (2004) uses stochastic programming to value and plan how to exercise real options. Diez and Peri (2010) applies a robust stochastic programming approach to a bulk carrier design, subject to uncertain operating conditions.

1.4 Structure of the Report

The structure of this report is laid out in the following way:

- **Theory**
  Chapter 2 defines the concepts of uncertainty and flexibility, before detailing three paradigms for decision making under uncertainty, and how these paradigms treat flexibility. The decision making paradigms are systems engineering, finance and operations research.

- **Methodology**
  Chapter 3 presents the main methodologies that will be used for the analysis. Epoch-Era Analysis and the Responsive Systems Comparison method is presented first. Thereafter we present Real Options Analysis, as a good approach to evaluate flexibility in the context of a life cycle path analysis (which is a part of the RSC method). The binomial lattice approach that is often applied is introduced as it is often applied for valuing real options *on* projects. Monte Carlo Simulation is next presented as a more versatile approach to flexibility in systems.

- **Case study**
  In Chapter 4, we give an introduction to OCVs, their market, the operations and functionalities of this ship type. In Chapter 5, a specific case study is presented. We model and analyze this case using the Responsive Systems Comparison method.

- **Results and discussion**
  Finally, Chapter 6 details the results. We compare the results from the analysis, and evaluate the relevance of the results. In Chapter 7 we conclude and give recommendations on further work to be done on this topic.

Chapter 2

Paradigms for Decision Making

In this chapter, we set the stage by defining future uncertainty, and introduce flexibility as a way to handle this uncertainty. Further, the theoretical background for the three paradigms for decision making under uncertainty is presented.

2.1 Understanding Uncertainty

In this thesis, the word *uncertainty* refers to the fact that the future is inevitably unpredictable. The operating context of the system may change, and we are never completely aware of what exact changes will happen. Decisions have to be made before all the relevant facts are known with certainty. McManus and Hastings (2006) define uncertainty as "things that are not known, or only known imprecisely".

We need to consider the future as unknown to us. In some cases, it is tempting to consider only a *most-likely* scenario, or using mean values in the forecasts. Such forecasting neglects that future trends and fluctuations in central variables such as prices may be distributed in a variety of ways, or that disruptive events or trend-breakers may occur (de Neufville et al., 2007). The non-linear influence of uncertainty on system performance, is captured in Jensen's Inequality, which states that (de Neufville and Scholtes, 2011):

$$f(E[\mathbf{x}]) \leq E[f(\mathbf{x})] \tag{2.1}$$

Here, **x** is a vector of input variables. In other words, average value inputs may not produce the average performance level as output. Neglecting the existence of Jensen's Inequality may lead to bad decision making. Instead one should attempt to account for uncertainty by assessing a "wide range of possible futures and design our projects to deal effectively with these scenarios" (de Neufville and Scholtes, 2011). The degree to which one can manage uncertainty through design varies. Lin et al. (2013) group types of uncertainties according to how they can be influenced. Consequently the modeling approach needed will also change. The uncertainty categorization is presented below:

- **Exogenous uncertainty**
  Uncertainty that are independent of the decision making process. This includes market factors, such as the future day rates of vessels and the fuel prices (Erikstad and Rehn, 2015), as well as the demand for vessels in a market.

- **Endogenous uncertainty**
  Uncertainty that can be managed actively by decision makers. An example may be to maximize the operability of a vessel, through installing a better dynamic positioning system, thus actively reducing the risk of not being able to operate.

- **Hybrid uncertainty**
  Uncertainty that can be partially influenced by decision making. An example is the ability of a vessel to win a contract, which is partially dependent on the capabilities of the vessel.

2.2 Defining Flexibility

McManus and Hastings (2006) mentions flexibility as one of several ways to deal with uncertainty, both by exploiting opportunities and mitigating risks in the design of engineering systems. In the words of de Neufville and Scholtes (2011), "flexible design enables the system to avoid future downside risks and take advantage of new opportunities". To specify exactly what we mean by flexibility, we present some definitions:

- **Saleh (2001)**
  "We define flexibility of a design as the property of a system that allows it to respond to changes in its initial objectives and requirements - both in terms of capabilities and attributes - occurring after the system has been fielded, ie. is in operation, in a timely and cost-effective way."

- **Ross and Rhodes (2008)**
  "Flexibility is the ability of a system to be changed by a system-external change agent."

- **McManus and Hastings (2006)**
  "Ability of the system to be modified to do jobs not originally included in the requirements definition."

Flexibility in engineering design allows systems to be modified as a response to changes from outside the system boundaries (Ross and Rhodes, 2008). Response to system-internal changes, is called adaptability (Ross et al., 2008b). Saleh (2001) mentions the importance of cost-effectiveness and timeliness, which can be seen as conditions for exercising flexibility. Flexible designs are often contrasted with both robust designs and optimized designs as illustrated by Figure 2.1. While robust designs "withstand random events", flexible systems "accommodate random events" (King and Wallace, 2012). However, flexibility can often be enabled by making some subsystems more robust. Diez and Peri (2010) points out that by making robust initial design decisions, the system may become more flexible at later stages.

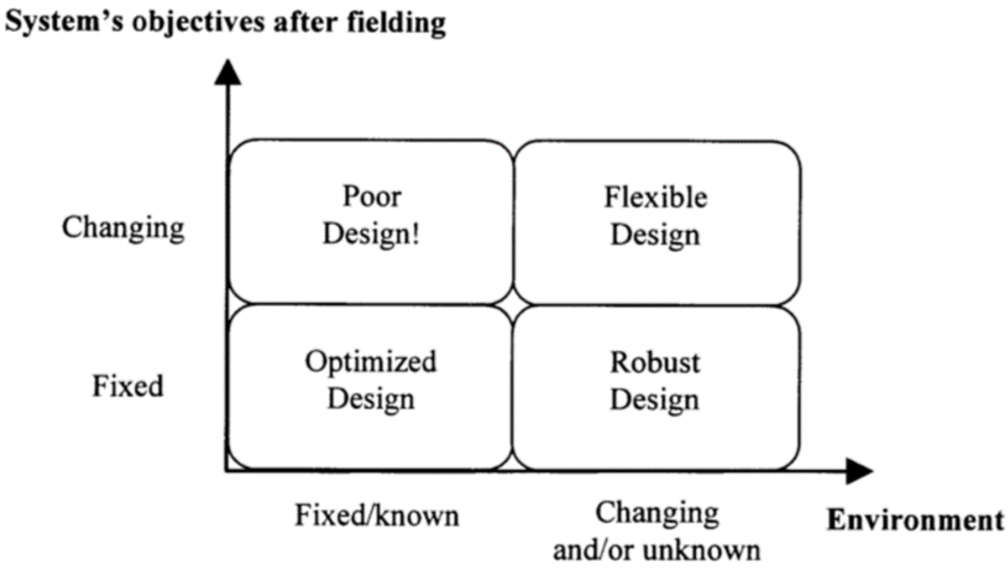


Figure 2.1: Flexible versus robust design (Saleh, 2001).

2.3 Flexibility In Systems Engineering

Systems engineering is a field that generally takes a broad view to the engineering and design of complex systems. Traditionally, systems engineering has treated system requirements and constraints relating to the operating context as constant (de Neufville and Scholtes, 2011). This has also been the case in ship design in the tradition of Evans (1959). When considering the full life cycle of a system, this assumption can not be considered valid. As Figure 2.1 shows, the objectives of the system may change, creating a need for flexibility.

The most common treatment of future uncertainty in the engineering disciplines have been risk analyses (McManus and Hastings, 2006). These focus on how to mitigate risks (negative uncertainties), often of disastrous proportions, either by introducing risk reducing measures, or by including design margins and redundancy in the design. Typically, one hopes to achieve system reliability and robustness (McManus and Hastings, 2006), and not flexibility. The focus has thus been on designing systems that succeed in trimming away the downside uncertainties in a cost efficient manner. Recently, the exploitation of upside uncertainty, is becoming more important as well, as exemplified by the research of the Systems Engineering Advancement Research Initiative (SEARI). The framework of McManus and Hastings (2006) illustrated in Figure 2.2 puts an equally large emphasis on exploiting opportunities, as reducing risks.

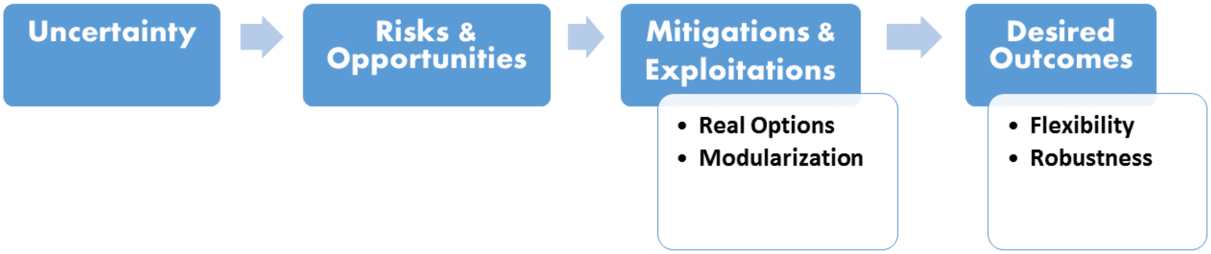


Figure 2.2: Framework for handling uncertainty, based on McManus and Hastings (2006).

Further understanding of future uncertainty can be understood in relation to the five aspects of complexity. Rhodes and Ross (2010) decompose complex systems into five aspects. While the structural and behavioral aspects can be handled by traditional engineering methods, the contextual, temporal and perceptual aspects require more novel approaches. An example of how these five aspects can be accounted for in ship design, is given in Figure 2.3.

Especially important for the discussion of uncertainty is the temporal aspect, as the system exists in an uncertain environment where the context and stakeholder needs change. The temporal aspect characterizes these changes over time (Rhodes and Ross, 2010). Time-based system properties that exploit and mitigate uncertainty can best be understood through the temporal aspect.

To handle the uncertainties that are manifested in the temporal aspect, we aim for designing value robust systems. A value robust system has the ability to "continue to deliver stakeholder value in the face of changing contexts and needs" (Ross and Rhodes, 2008). Value robustness is a broader concept than traditional robustness as it also allows the system to be changed as a response to uncertainty. The term value robustness encompasses much of the same function as the desired outcomes, mentioned in McManus and Hastings (2006). Flexibility is an example of a system property contributing towards active value robustness. Traditional robustness is called passive value robustness. The concept of value robustness also goes wider than purely monetary measures of success. The notion of value facilitates a wider discussion on which system performance attributes should be considered important, thus taking stakeholder preferences into account.

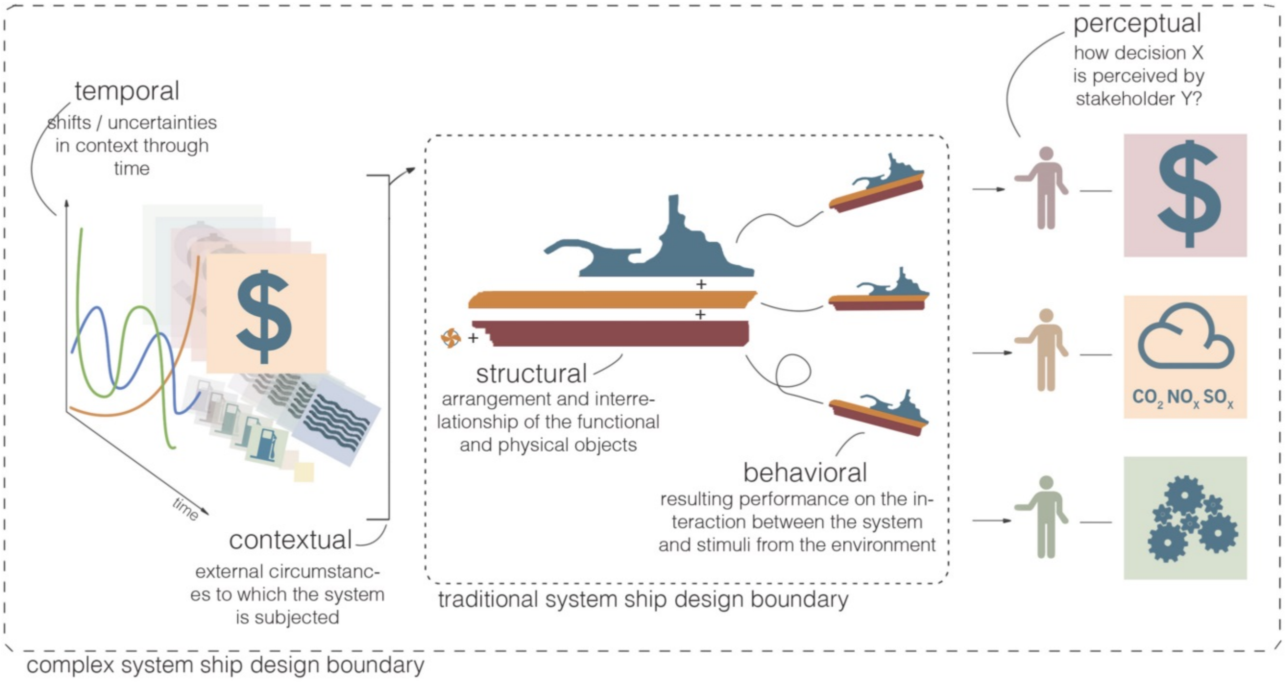


Figure 2.3: Five aspects of complexity in ship design (Gaspar, 2013), with future uncertainty represented by the temporal aspect.

2.3.1 Quantification of Changeability

Changeability is sometimes used as an umbrella term for system properties relating to changing the system, such as flexibility and adaptability. Ross et al. (2008b) present some means to quantify the level of changeability. By generating all possible designs, plotting them in a utility-cost tradespace we get an understanding of what constitutes a good design. According to the properties of each design alternative, it may be possible for a design to transition into another design. That is, the system is initially configured as a Design A, but it is allowed to change into Design B. Whether a given transition is allowed, must be determined by applying a transition rule. Figure 2.4 illustrates the feasible transitions in a tradespace.

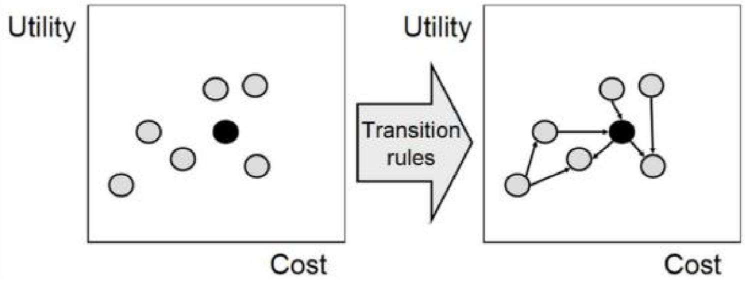


Figure 2.4: Transition paths allowed for designs in a tradespace (Ross et al., 2008b).

By counting the number of outgoing arcs from one point design in the tradespace we obtain the outdegree. However, not all outgoing arcs will be cost-beneficial. By removing the transition paths with costs found unacceptable according to some stakeholder, the filtered outdegree is obtained. This is a measure of the changeability of a design. To measure the flexibility of a system, we count only the changes occurring due to external stimuli (Ross et al., 2008b). Through this procedure it is possible to identify how system elements are altered according to the transitions, thus this process screens the design space for interesting sources of flexibility. The information obtained by evaluation of a whole design space, is hailed as the possibly most valuable insight from using set-based ship design (Singer et al., 2009), as it can be used in seeing what will provide flexibility when the system environment changes.

Ross et al. (2008b) considers changeability quantification to be a complementary approach to real options, which will be discussed next. Several other works within the SEARI literature propose to use real options. Within the framework of McManus and Hastings (2006) real options is classified as a technique for mitigation and exploitation of uncertainty. Real options is also mentioned as a good approach for valuing flexibility in Ross and Rhodes (2008).

2.4 Flexibility In Finance: Real Options

Real options has its background in the financial options theory of Black and Scholes (1973), Merton (1973) and Cox et al. (1979), and began as a tool for including managerial flexibility in investment decisions. Real options is also increasingly used to achieve flexibility in systems. According to de Neufville (2003), real options "refer to elements of a system that provide 'rights, not obligations' to achieve some goal or activity." By speaking of "elements of a system", de Neufville (2003) introduces the possibility to implement changes to the system itself. Wang and de Neufville (2005) sees the real option as the base unit of flexibility.

2.4.1 Financial Options and Traditional Real Options

An option is defined as "a security giving the right to buy or sell an asset, subject to certain conditions, within a specified period of time" (Black and Scholes, 1973). It is important to notice that options do not give an obligation to buy or sell. An implication of the "right, but not an obligation" to buy or sell, is that options have a limited downside, while the upside is potentially unlimited. Option values generally increase with volatility, and options on risky assets can therefore be more valuable. Classification of different types of options are presented in Table 2.1 and Table 2.2.

Table 2.1: Exercise time for options.

American	**European**
Any	At maturity

Table 2.2: Defining call and put options.

Call	**Put**
Right to buy	Right to sell

The Black-Scholes formula of Black and Scholes (1973) and Merton (1973) provides a closed-form solution to the problem of valuing European options. The formula assumes that stock prices move according to a random walk or Geometric Brownian Motion (GBM). The GBM assumes that the current movement is independent from previous states. Cox et al. (1979) extends the principles described by the Black-Scholes formula to American options, and proposes a discrete binomial lattice model for pricing options. Naturally, investments in financial assets such as stocks have different properties from real options, in which the investment decision concerns a physical object. Table 2.3 points out some important distinctions that typically separate real options from financial options.

Table 2.3: Financial options versus real options (based on Alizadeh and Nomikos (2009) and Wijst (2013)).

Financial Options	**Real Options**
Widely replicated	Unique
Tradeable in markets	Not tradeable
Short time to maturity	Long time to maturity
Well-defined characteristics	Unclear characteristics
Value more exogenous	Value more endogenous

2.4.2 Real Options *In* Systems

As we wish to discuss flexibility in systems, it is most relevant to restrict the field of real options to real options *in* projects, rather than real options *on* projects (Wang and de Neufville, 2004). While a real option *on* a project could be a decision to buy a vessel at the right time, a real option *in* a project could be a decision to install a new crane in an existing vessel. The first example only times an investment decision while treating technology as a black box (Wang and de Neufville, 2005), exerting no influence on the uncertainty. On the other hand, the real option *in* a system exerts an influence on the effects of uncertainty, by changing the system. Real options *in* systems will often require other solution techniques than real options *on* projects, for this reason. Table 2.4 presents the difference between real options *on* and *in* projects.

Table 2.4: Real options *in* systems versus real options *on* projects.

In	***On***
Path-dependent	Path-independent
Less endogenous	More endogenous
Flexible system components	Flexible investment decisions
Requires technical understanding	Technology is "black box"

Thus, we can separate into three types of options; financial options, real options *on* projects and real options *in* systems. In this work the focus will be on real options *in* systems. Still, it is important to recognize that to have optionality regarding the system as a whole, as an object of investment, may also have large value to the stakeholders.

2.5 Flexibility In Operations Research

In operations research, stochastic programming has emerged as the proper way of dealing with uncertainty. Normally, mathematical programs are post processed by a sensitivity analysis to check the effect of changes in the parameters. However, sensitivity analyses are only fit for analyzing deterministic problems (King and Wallace, 2012), as it neglects the future uncertainty, and considers that all decisions are taken at the same time. In stochastic programming, we separate the decisions taken at different times, through defining decision *stages*.

2.5.1 Stochastic Programming

In a two-stage stochastic program, the decisions that must be taken are divided into two sets. The first set are the decisions taken before the future uncertainty is resolved, in other words at Stage 1. The second set are the decisions taken when the uncertainty has been resolved, that is at Stage 2. These second stage variables are called recourse variables, as they have a dependency on the decisions that were taken in the first stage, and on the uncertainty that has now been resolved. A generic two-stage problem can be stated on the following form (Higle, 2005):

$$Min \quad cx + E[h(x,\omega)] \tag{2.2}$$

$$s.t. \quad Ax \geq b \tag{2.3}$$

$$x \geq 0 \tag{2.4}$$

Here, the element $E[h(x,\omega)]$ refers to the following second stage problem:

$$h(x,\omega) = Min \quad g_\omega y \tag{2.5}$$

$$s.t. \quad W_\omega y \geq r_\omega - T_\omega x \tag{2.6}$$

$$y \geq 0 \tag{2.7}$$

For the first stage, costs c should be minimized for decisions x, subject to constraints given by A and b. For the second stage we wish to minimize costs g under scenario ω by selecting recourse variables y. The constraint refers to a recourse relationship given by parameters W_ω, T_ω and r_ω that determine the possible values the second stage decision can take.

A drawback of stochastic programming, is that the computational burden quickly increases when considering a large number of possible scenarios (Higle, 2005). If the problem is multi-stage, consisting of more than two decision making stages, the complexity increases even further (King and Wallace, 2012). Another drawback with the attempt to optimize when there is uncertainty, is that the stochastic program will give us one solution. There is no immediate discussion of tradeoffs between different objectives or measures of value, as a single optimal solution is presented. For these reasons, we will not consider stochastic programming further in this work, but end the discussion of this topic with a comment on how real options are treated in stochastic programming.

Real Options In Stochastic Programming

An important distinction between operations research and real options theory, is that the options theory asks "what is it worth" instead of "what shall we do" (King and Wallace, 2012). While real options theory only values known options, stochastic programming can be used to decide what to do. The exercise of options on the form of recourse variables, can thus be a part of the solution to a stochastic program, but the value of the individual options are not obtained.

Chapter 3

Methodologies for Achieving Flexibility

In this chapter, we present the methodologies that will be used for analysis later. The Responsive Systems Comparison method constituting a framework for Epoch-Era Analysis, (EEA) and Real Options Analysis (ROA) are here seen as complementary approaches for finding flexible design solutions and strategies for handling future uncertainty.

3.1 The Responsive Systems Comparison Method

We use the Responsive Systems Comparison (RSC) method as an overall design methodology in this thesis. The RSC method is a structured methodology for analyzing system performance in a large variety of possible future scenarios. It considers changes in user needs and expectations, the context surrounding the system and changes in the system itself (Ross et al., 2008a). The RSC method incorporates EEA and tradespace exploration to provide the designer with quantitative comparisons between alternative system designs. The objective of the RSC method is stated in Rhodes and Ross (2010) with the following words:

> *"The goal of the method is to generate knowledge about tradeoffs, compromises, and risks to a system development project, and identify system concepts that are actively and/or passively value robust. The strength of the method is that it enables dialogue and knowledge building among system designers and stakeholders."*

3.1.1 Epoch-Era Analysis

Epoch-Era Analysis is an emerging approach to handling uncertainty, developed by the systems engineering community at MIT. EEA represents a structured analysis of the contextual and temporal aspects of complexity (Gaspar, 2013). Thus, EEA constitutes a promising methodology for handling uncertainty, and achieving flexibility in design.

The basic elements of the EEA, are the concepts epoch and era. An epoch is a static, fixed set of characteristics (Ross and Rhodes, 2008), both contexts and expectations, defined over a time interval. Each epoch will normally consist of a set of parametrized contextual factors (Gaspar, 2013), called epoch variables, each signifying an element of uncertainty. By combining several epochs in a consecutive order, an era is constructed. Eras are used to analyze the dynamic performance of designs over a longer time period, for example the system life cycle. Each era is effectively a kind of scenario, as it represents a possible realization of the future.

Figure 3.1 shows the progression of an inflexible system through an era consisting of five consecutive epochs. Figure 3.1 shows that the system performs above its expectations for the three first epochs, before falling under the level of performance that is required. The color coding separates different contexts, so from Epoch 2 to Epoch 3, only expectations change. By allowing systems to transition into other point designs on a tradespace, we enable systems to maintain or even increase performance in the likely event that the context should change. Figure 3.2 shows the same system as Figure 3.1, the only difference being the inclusion of flexibility. From Figure 3.2, we see that the trajectory of system performance over time is altered, as the system adapts to the new expectations.

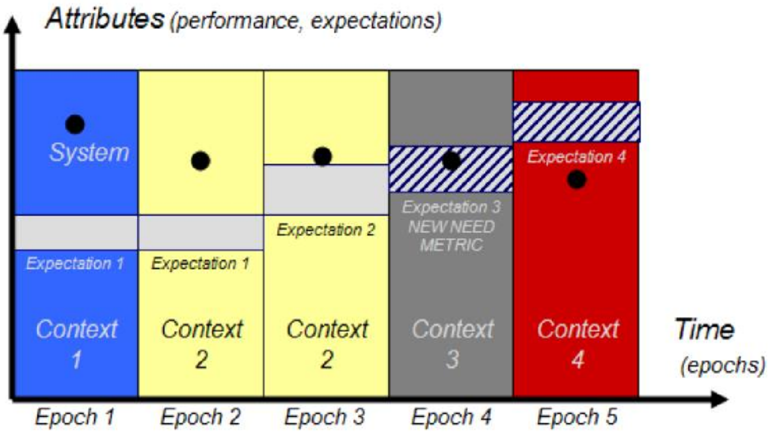


Figure 3.1: Example era with an unchangeable design. The colors indicate the context of the epoch (Ross et al., 2008a).

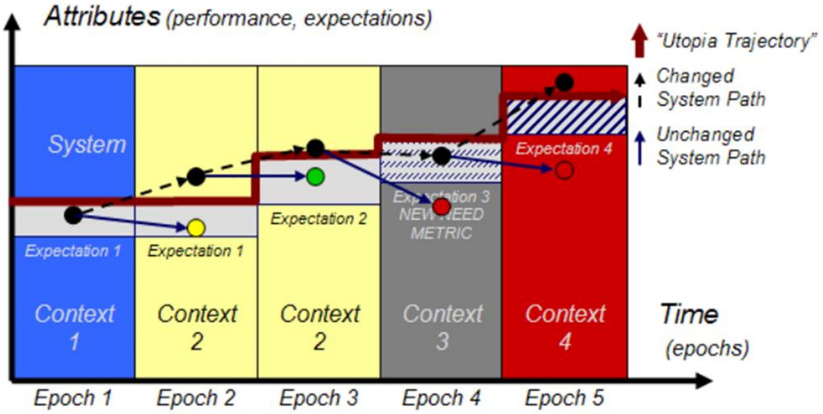


Figure 3.2: Example era with a changeable design. The colors indicate the context of the epoch (Ross et al., 2008a).

3.1.2 The Seven Steps of the Responsive Systems Comparison Method

In this section, we present the step-to-step approach of the Responsive Systems Comparison method. A flowchart outlining the process is given in Figure 3.3.

Step 1: Value-Driven Context Definition

In this first step in the RSC method, the aim is to identify the overall problem, and formulate a value proposition. The fundamental question is to select a system architecture maximizing the chances that the stakeholders remain satisfied, thus providing "the highest degree of value robustness" (Ross et al., 2008a). Key decision makers and other stakeholders need to be defined, and their perception of the value must be mapped.

Step 2: Value-Driven Design Formulation

Based on the value proposition, the key performance attributes and the design elements that contribute to attaining these attributes, must be defined. Performance attributes are quantified by normalizing their utility. The design variables are generally defined as discrete variables. As a result, it is possible to totally enumerate the design space. Naval architects may contrast set-based design represented by this design space (Singer et al., 2009), with iterative design spirals as in Evans (1959). Further, mapping between the performance attributes and the design variables takes place as a part of this step, thus we can formulate utility functions for the design (Gaspar et al., 2012).

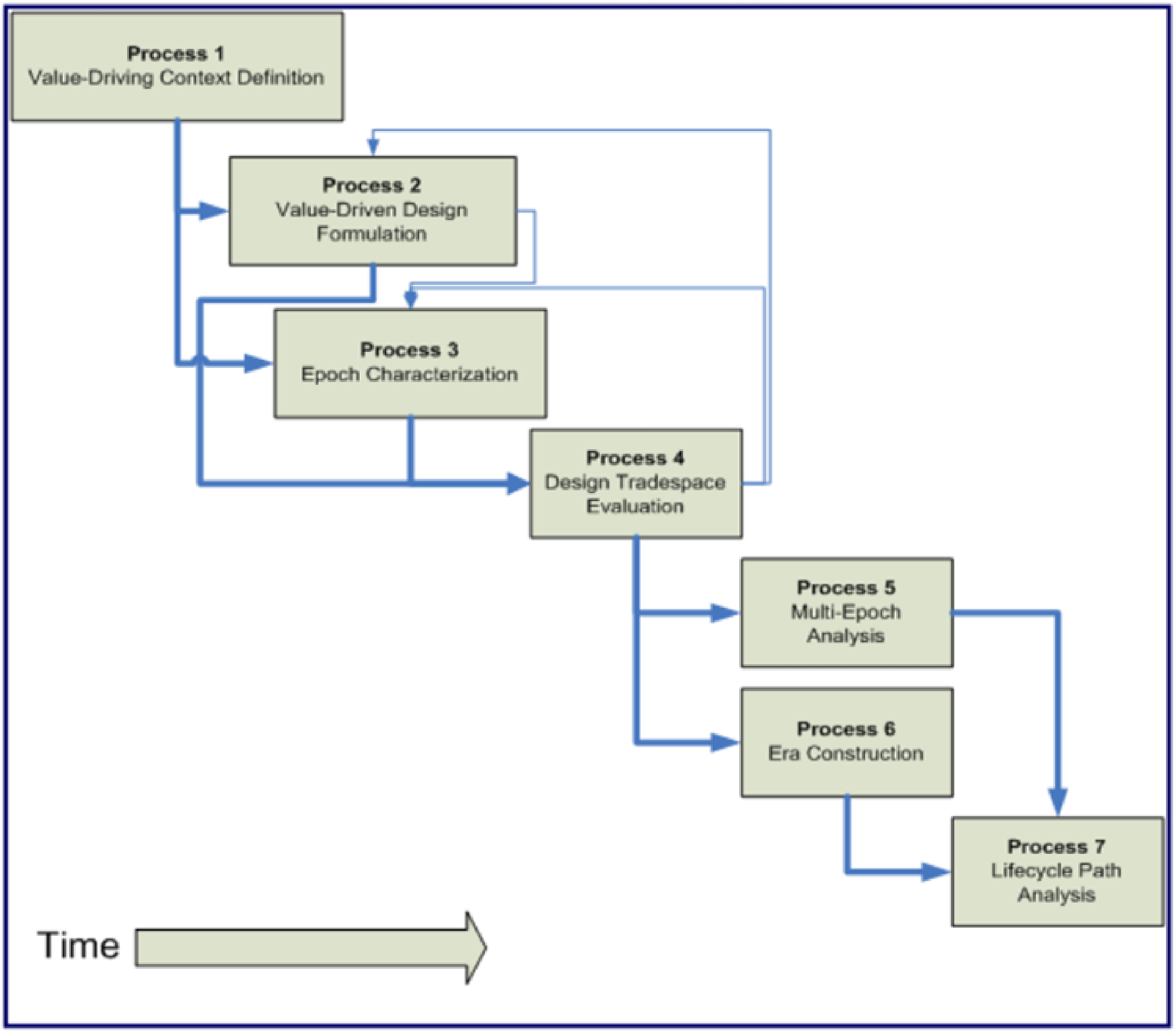


Figure 3.3: Flowchart for the Responsive Systems Comparison method (Ross et al., 2009).

Step 3: Epoch Characterization

Epoch variables are parameterizations of the stakeholders expectations of future uncertainties. Like the design variables, we treat epoch variables as discrete, so that total enumeration of the epoch space is possible. Considering that the system requirements may change from one epoch to the next, the performance of a system will be measured differently from epoch to epoch.

Step 4: Tradespace Evaluation

For each epoch, it is now possible to plot all individual designs in a tradespace. The tradespace provides the designer with an overview of existing tradeoffs between utility and cost. The tradespace evaluation allows us to limit the designs we analyze further. The Pareto front is often used as the criteria for analyzing designs further (Singer et al., 2009). The set of Pareto optimal designs are often referred to as non-dominated (Ross et al., 2008b), and consists of the designs that maximize the utility for each possible budgetary constraint. A tradespace example is shown in Figure 3.4.

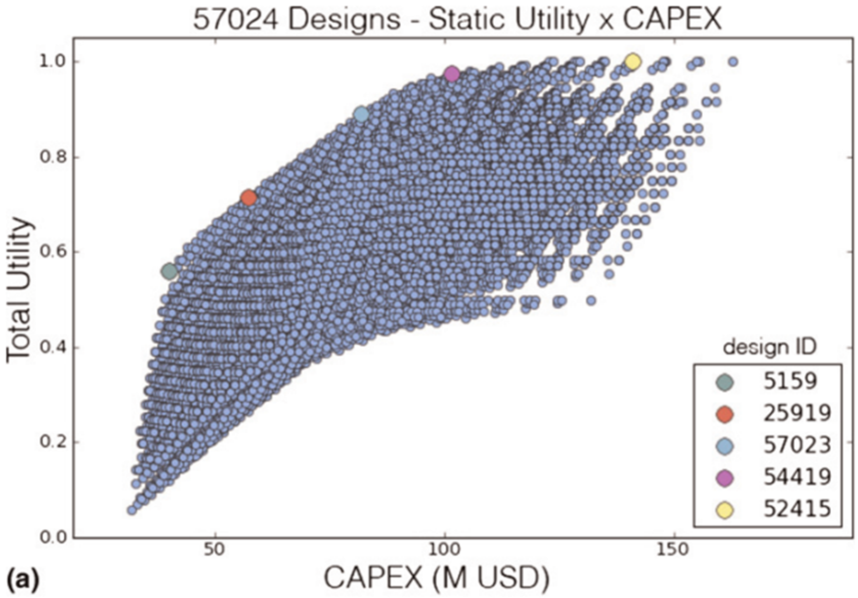


Figure 3.4: Tradespace with some designs along the Pareto front highlighted (Gaspar et al., 2012).

Step 5: Multi-Epoch Analysis

In this step, the goal is to identify the most passively value robust designs, by comparing many tradespace evaluations across epochs. The Pareto trace of a design measures the frequency with which a design occurs at the Pareto front (Ross et al., 2009). A high Pareto trace indicates that a design is passively value robust. An alternative approach to a multi-epoch analysis could be to calculate the weighted average utility of each design, across all epochs.

Ross et al. (2009) mentions changeability as a goal of the multi-epoch analysis, and the calculation of filtered outdegree. If this is included here we change the focus of the multi-epoch analysis from identification of passive value robustness to include active value robustness as well. However, in Gaspar et al. (2012) it is stated that the objective of the multi-epoch analysis is the identification of possible passively value robust designs. We therefore save the analysis regarding active value robustness, and thus flexibility, for Step 7 of the RSC method.

An alternative to a typical multi-epoch analysis, mentioned in the EEA framework presented in Curry and Ross (2015), is multi-era analysis. Instead of including all epochs in the analysis, we can limit our analysis to the epochs that are contained within an era. This assumes that we backtrack from Step 6 in the RSC, which is era construction. We can then apply the eras that were constructed there, for the multi-era analysis.

Step 6: Era Construction

Eras need to be constructed from the epochs defined, for example signifying the whole life cycle of a system. An illustrative example of how eras can be constructed from a set of epoch variables is shown in Figure 3.5.

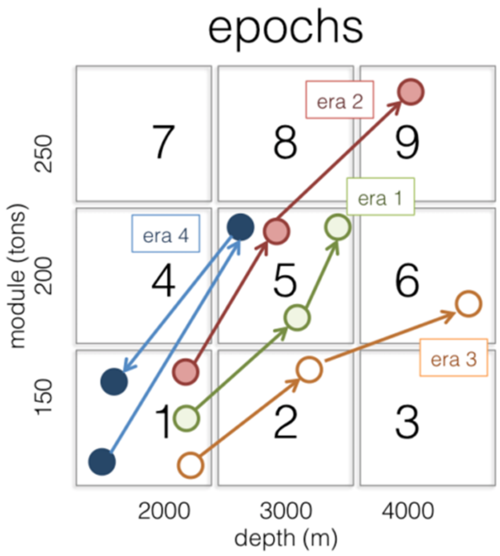


Figure 3.5: Alternative eras on a two-dimensional epoch space (Gaspar et al., 2015).

Eras can be constructed manually, formulated as possible stories that capture the expectations of the customer, or other stakeholders (Gaspar et al., 2012). When using a manual era construction approach we should be careful and avoid constructing eras based on wishful thinking (Rader et al., 2010). Alternatively, the era construction procedure can be automated through use of simulation according to some logical rules for era progression. The sequence of epochs should be constructed in a fashion that does not break chronology.

Step 7: Life Cycle Path Analysis

In the final step of the RSC method, we wish to enable the system to deliver value throughout its lifetime by developing designs and corresponding design strategies that tackle change and uncertainty. At this step in the RSC method it is possible to analyze the economics of a flexible design with some well-defined transition opportunities serving as options, while benchmarking against some inflexible version of the initial design. We can analyze which design variables should be changed to enhance the value of the vessel (Gaspar et al., 2012), thus seeing how value is enhanced when transition paths are enabled and real options in the system are exercised. This allows us to find strategies to cope with an uncertain future operating context. Next, we turn to Real Options Analysis to further investigate how to value such flexibility.

3.2 Real Options Analysis

Real options analysis is an umbrella term for several methodologies used for the valuation of real options. To understand the basics of ROA, we first look into some basic stochastic processes that are often applied in ROA. Thereafter we investigate binomial options pricing and ROA with Monte Carlo Simulation, and discuss these in light of the separation between real options *on* projects, and real options *in* systems. In the case study presented later, ROA will be applied as a part of the life cycle path analysis in the RSC method.

3.2.1 Central Stochastic Processes

Stochastic processes are often used for modeling the uncertain, fluctuating value of some asset or system over time. Stochastic processes are essential for understanding how options are priced. The Geometric Brownian Motion (GBM) is described by the following stochastic differential equation (Wijst, 2013):

$$dS_t = \mu S_t dt + \sigma S_t dW_t \tag{3.1}$$

Here, μ is the drift describing the long term movement, S_t refers to the stock price at time t, σ is the standard deviation, or volatility, of the stock price, while dW_t is the time-increment of a standard Wiener process. The Wiener process will often be implemented as a normally distributed random number with a mean of 0, and a standard deviation of σ. The GBM is path independent (Wang and de Neufville, 2004), meaning that the direction of the price motion will be independent of the current state. The popular Black-Scholes formula (Black and Scholes, 1973) is an example of an analytical options pricing method that uses GBM to value European options.

Alternatively, a mean-reverting process can be used for modeling such fluctuation. The mean-reverting process lets the motion revert back to a long term mean value (de Neufville and Scholtes, 2011). It is described by:

$$dS_t = \kappa(m - S_t)dt + \sigma dW_t \tag{3.2}$$

The same notation as for the GBM are used. In addition, for this mean-reverting process, we define the mean-reversion rate κ, and the mean long-term price m. The higher the κ, the faster the process will revert back to the mean. The application of mean-reverting processes instead of the GBM is recommended in de Neufville and Scholtes (2011) as it prevents the long term asset price from "blowing up", in assets where such behavior is illogical. It instead captures the logics of supply and demand, as a price rise may cause more supply to enter the market, again leading to falling prices. The mean-reverting process is thus path dependent, as the movement of the price depends on its previous state. An analytical solution to the mean-reverting process used to determine the value of market switching, is found in Sødal et al. (2008).

3.2.2 Binomial Options Pricing

For options analysis in finance and for real options *on* projects, a common approach is the use of the binomial lattice method of Cox et al. (1979). Figure 3.6 illustrates the binomial lattice. Here S is the initial asset price. For each time step the price can go either up,u, or down, d. The probability of an up-movement is q. By working recoursively through the binomial lattice, finding the expected value on each node for the predecessors, the option value will finally be found at the root node. Figure 3.7 shows a possible sample path for an asset price movement.

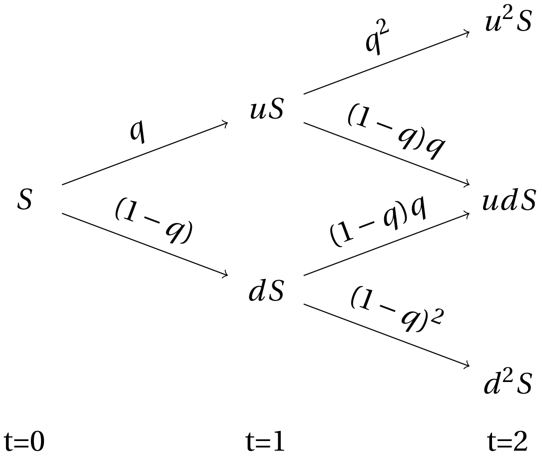


Figure 3.6: Binomial lattice, based on Cox et al. (1979).

From Figure 3.7, we easy that when the lattice is made finer, with smaller time-increments, the asset price movement will approach the movement described by a GBM process. Under the same assumptions and with very small time-increments, the results of the binomial lattice method will converge to the results of the Black-Scholes formula (Cox et al., 1979).

An observation about the binomial lattice model is that there is no randomness in the results themselves. The output is merely a single option value, which does not lend itself to discourse

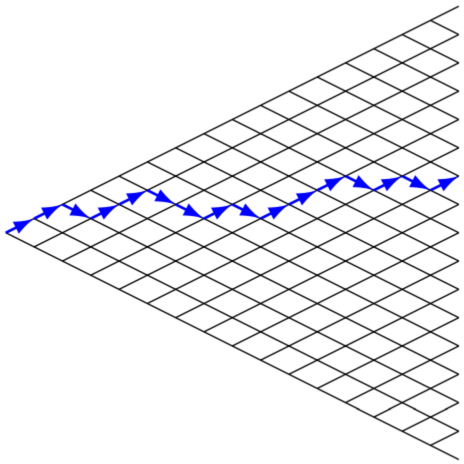


Figure 3.7: Binomial lattice with Geometric Brownian Motion sample path (Wijst, 2013).

surrounding the value of the design as such. Additionally, in Chapter 2, we introduced the distinction between financial options, real options *on* projects and real options *in* systems. A consequence of this distinction, is that financial approaches to options, such as the use of binomial lattice models becomes inappropriate. A number of reasons for this exist:

- Revenue is path dependent, thus typically not following the GBM (Wang and de Neufville, 2004), for example instead following a mean-reverting process. This means that the lattice will not recombine.
- Discrete uncertainties, often binary events, are not captured by the binomial lattice structure. Technical and regulatory uncertainties are often of this form (de Neufville et al., 2007).
- There are many interdependencies between the real options (design elements) in a system (Wang and de Neufville, 2005), leading to implications for the valuation. The effects on one real option, when an alternative real option is exercised, is not captured in the binomial lattice model.

To avoid the deficiencies of the options pricing methodologies for financial options and real options *on* projects such as the binomial lattice model, Monte Carlo Simulation methods can be applied instead, when we analyze real options *in* systems.

3.2.3 Monte Carlo Simulation for Real Options Analysis

Monte Carlo Simulation (MCS) is a tool that is often applied to analyze the value of systems subject to uncertainty. It is seen as the preferred method for analyzing system performance by de Neufville and Scholtes (2011). MCS is a method first described in Metropolis and Ulam (1949), in which random numbers are sampled from known probability distributions for each uncertain variable. These random numbers are then used as input for the calculations. Each run of the MCS model will represent a possible realization of the future, or a scenario. By running a large amount of simulations and storing the resulting output, one can obtain the distribution of possible outcomes. One can say that a MCS model is a "shape-in, shape-out" model (de Neufville and Scholtes, 2011). Figure 3.8 illustrates the main working principles of a MCS algorithm.

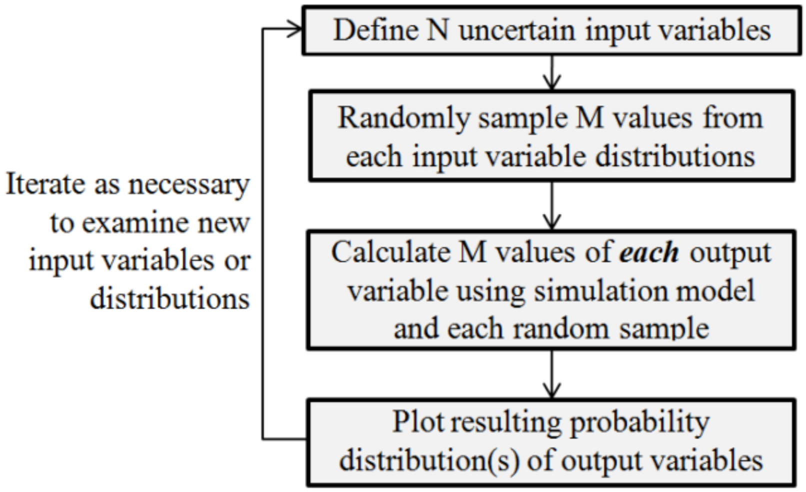


Figure 3.8: Flowchart for Monte Carlo Simulation (Rader et al., 2010).

The output of a MCS is typically on the form of a probability distribution. de Neufville and Scholtes (2011) often present this on the form of a cumulative distribution function called a target curve, or a Value-at-Risk curve in finance. The Value-at-Risk is defined as the probability of missing a profit target. An example of a target curve is shown in Figure 3.9.

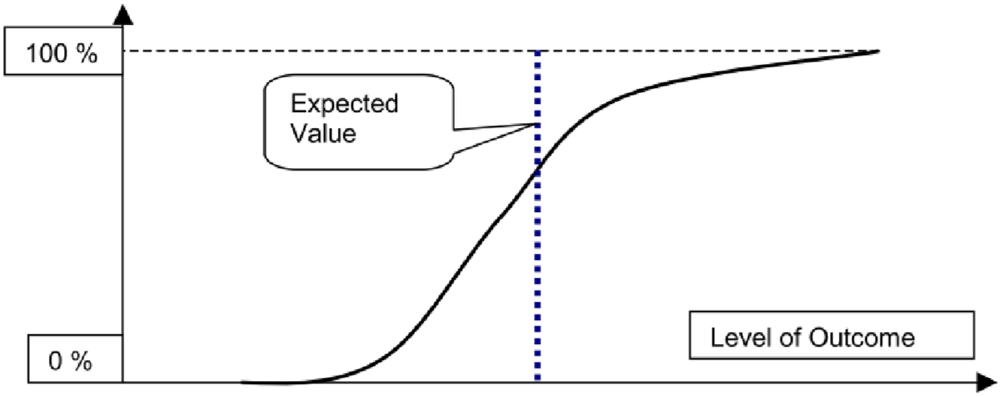


Figure 3.9: Example of a target curve or cumulative distribution of value (de Neufville et al., 2007).

The target curve provides a lot more information than we would get from an analysis that just finds a single point estimate, such as the binomial lattice. A large advantage of presenting results on this form, is that the upsides and downsides are clearly visible. While decision makers often want to select the design that maximizes the expected value, others may choose to select a design that minimizes the downside or maximizes the upside, depending on their risk attitudes. This way the use of distributions to illustrate outcomes fosters much of the same thinking about tradeoffs and compromises, as does the tradespace exploration.

Screening and Triggering Real Options

ROA only values options. It does not excel at real options identification. The design space is typically too large to efficiently explore all possible options in a complex system (Lin et al., 2013). By applying a screening model, we can identify the most interesting candidate flexibilities (de Neufville and Scholtes, 2011). Various sorts of screening models can potentially be applied. Wang and de Neufville (2004) propose the formulation and solution of mathematical programs, and subsequent sensitivity analyses as a screening method. Ross et al. (2008b) present concepts that may fulfill the functions of the real options screening procedure. By defining transition rules one can determine which system elements that may change, thus representing potential real options. Further, the filtered outdegree concept can eliminate the potential real options that do not seem to be sufficiently cost-beneficial.

After some screening procedure, it is necessary to formulate some decision making rules for triggering the real options. The triggering rules are conditions that define whether or not a system flexibility should be exercised or not (de Neufville and Scholtes, 2011). Triggering rules are in essence if-statements, letting the flexibilities in the system be exercised if some condition is met. For each realization of uncertainty, the simulation model must know what action to take (Lin et al., 2013). For example, if the value of the system over the rest of its lifetime will increase if the flexibility is triggered, it may be reasonable to exercise the flexibility.

The Value of Flexibility

The value of projects throughout their lifetimes are often found using a discounted cash flow analysis to obtain an estimate of the net present value (NPV). NPV is commonly defined as:

$$NPV = \sum_{t=0}^{N} \frac{I_t - C_t}{(1+r)^t} \tag{3.3}$$

In Equation 3.3, I is income, C is cost, r is the discount rate used, and t the time period. de Neufville and Scholtes (2011) expands NPV to include the exercise of flexibility, and uses simulation to obtain the NPV. Thus, we do not claim that a traditional, static discounted cash flow analysis is appropriate when analyzing a system that can be changed. However, if the cash flows and the parameters of the process are changed accordingly as the system changes, the analysis should still be valid. Equation 3.4 is presented in (Hassan et al., 2005) as an estimated expected value of flexibility, $E(V)$, as a function of the expected NPV (ENPV) of a flexible design, $E(NPV_{flex})$, and the ENPV of an inflexible design, $E(NPV_{rigid})$.

$$E(V) = E(NPV_{flex}) - E(NPV_{rigid}) \tag{3.4}$$

Chapter 4

Offshore Construction Vessels

Offshore construction vessels (OCVs) are vessels that perform a wide range of construction tasks, such as installation of subsea structures and flowlines, maintenance and repair, diving and well intervention. OCVs can therefore be regarded as multi-functional vessels. Here, we introduce the commercial context, before describing the operations. Then, a functional breakdown is presented. On this basis, we propose which main systems that can be seen as potential sources of flexibility, enabling the vessel to perform new operations. Chapter 4 serves as a basis upon which the case study in Chapter 5 will be built.

4.1 Contextual Aspects of Offshore Construction Vessels

4.1.1 Main Commercial Drivers in Offshore Construction

To understand how the commercial context of the offshore construction vessels work, we can start out by looking at a shipping market model for ordinary transportation vessels. Table 4.1 shows the main drivers for shipping markets considered by Stopford (2009).

Table 4.1: Factors of the shipping market model of Stopford (2009).

Demand	**Supply**
World economy	World fleet
Seaborne commodity trades	Fleet productivity
Average haul	Shipbuilding production
Random shocks	Scrapping and haul
Transport costs	Freight revenue

There is good reason to consider the factors on the supply side to be the same in offshore markets. On the demand side for OCVs, the mention of seaborne commodity trades, average haul and transport costs are not that relevant. In the formulation of the Ship Design and Deployment problem in Erikstad et al. (2011), the situation in offshore shipping is contrasted with that of other shipping markets, where optimization often takes the form of routing problems. OCVs however, mainly perform non-transportation tasks, so instead of routing, the problem rather becomes one of selecting the most suitable contract for the vessel. Rather than systems handling payload, OCVs have systems to perform specific tasks (Erikstad and Levander, 2012). It therefore becomes more important to consider demand drivers such as field development, the need for maintenance and other services in existing fields during their lifetime, and the oil price. Throughout this chapter we will see that the variety of demands for specific services in the offshore sector impacts the design and the options inherent in the design tremendously. The question of matching the right vessel to the right mission thus becomes extremely important.

4.1.2 The Phases of Offshore Construction

To assess the need for OCVs, it is important to have a general understanding of the phases of offshore construction. The different phases of the lifetime require different types of services. Table 4.2 shows the phases of the life of an oil field, with corresponding service need.

Table 4.2: Phases in the lifetime of an oil field (based on Ulstein International (2015)).

Lifetime phase	**Service need**
Field development	Seabed survey Installation Tie-in
Production	Maintenance and repair
Abandonment	Decommisioning

Especially for installation and decommisioning tasks, there is a large need for heavy lift vessels, rigs, pipe laying vessels and cable laying vessels. However, an increasing amount of work in all phases can be done by OCVs.

4.1.3 Some Geographic Market Aspects

The market for OCVs differ throughout the world. Differences in the geography itself exists, such as physical attributes related to water depth and wave characteristics, along with local political, regulatory and economic differences. The regions that are often considered, and some related characteristics, are given in Table 4.3.

In addition to these existing offshore region, there has been a push towards the Arctic regions. This seems to pose many new challenges as icing on surface structures would be a driver to move equipment to the sea floor. However, the economic significance of the Arctic seems limited

Table 4.3: Offshore region description (based on RS Platou (2014)).

Region	Characteristics
Gulf of Mexico	Deep water, existing infrastructure, short tie-ins
Brazil	Deep water, strong growth subsea, strict labor regulations
North Sea	Shallow water, existing infrastructure, strong demand for tie-ins
Mediterranean	Shallow water, but moving deeper
West Africa	Deep water, strong growth subsea, politically unstable
South East Asia	Shallow water, but moving deeper

compared to the development elsewhere. According to RS Platou (2014), the strongest growth will occur in the Southern hemisphere in places like Brazil, Africa and Australia.

4.1.4 Main Players in the Offshore Construction Market

Figure 4.1 defines the relationships between the central actors in the offshore construction market. The distinction is made between traditional shipping companies, subsea contractors of varying size, and the end clients which are the oil companies. The larger contractors can be involved in EPCI (Engineering, Procurement, Commissioning and Installation) contracts, which are often larger in scope, more complex and may have a larger risk and thus return than smaller projects (RS Platou, 2014).

The traditional shipping company charters out their vessels to both smaller subsea contractors and the larger EPCI-based contractors. The contracts can either be long term, or the vessels may compete on a day-to-day basis in a spot market. The contractors in the market charters in, or own vessels that are used for the tasks specified by the contract with the end client. Especially for the operations of larger EPCI contractors, the tasks become too complex for multi-functional OCVs, and require very specialized equipment. An example is laying rigid pipe, which are performed by pipe-lay vessels or barges (Ritchie, 2008). The further discussion will best fit the smaller vessels that do not compete for EPCI contracts. We use the distinction between operations performed by smaller OCVs, presented in the next section, to segment the market.

4.2 The Operations of Offshore Construction Vessels

We here look into typical operations performed by OCVs. It is necessary to decompose the OCV operations, due to the very diverse need for equipment. We use the distinction between IMR (Inspection, maintenance and repair), SURF (Subsea installation, Umbilicals, Risers and Flowlines), LWI (Light Well Intervention) and DSV (Diving Support Vessels). This is the distinction made by Ulstein International (2015).

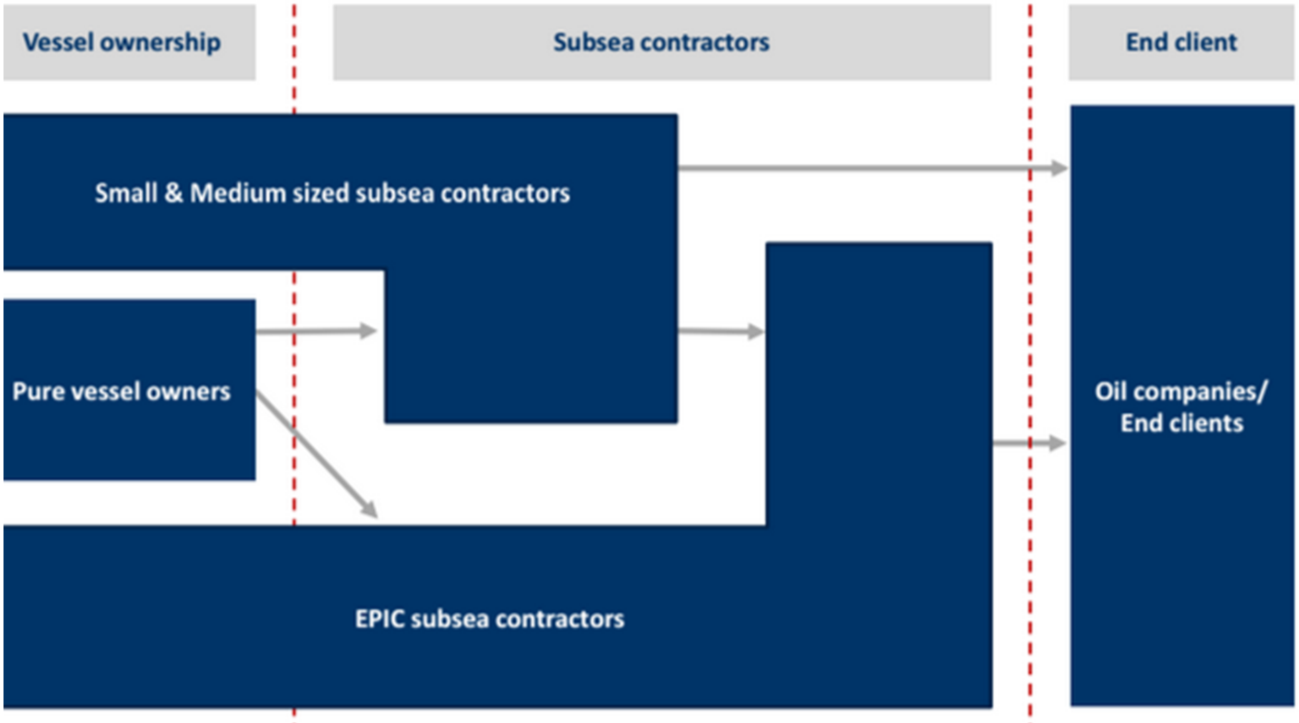


Figure 4.1: Players in the offshore construction market (RS Platou, 2014).

4.2.1 Inspection, Maintenance and Repair

Inspection, maintenance and repair (IMR) is a group of operations that mostly take place during the production phase of the field life. For all IMR operations, ROV (remotely operated vehicle) capabilities are essential as this enables inspections to take place. Work ROVs can perform a lot of maintenance and repair tasks. In the operational breakdown we therefore separate observation ROVs from work ROVs.

Module Handling

Module handling operations refer to the launch and recovery of smaller subsea modules, for the purpose of replacing defective modules. This lifting operation can be done by a crane. In order to increase the operational window and perform this operation in harsh weather conditions, a module handling tower is often used to lift the modules. The module handling tower will be installed above a moonpool at the centerline of the vessel. The following equipment is required as a minimum to be able to perform module handling operations.

- Crane (50 to 150 tonnes) or module handling tower
- Moonpool, if we have a module handling tower
- At least one work ROV

Well Stimulation

Well stimulation aims to "dissolve and remove unwanted scale inside the production tubing" (Ulstein International, 2015). Sometimes a distinction is made between well stimulation and scale squeeze. The differences are summarized in Table 4.4.

Table 4.4: Defining well stimulation and scale squeeze operations.

Well stimulation	**Scale squeeze**
Chemical dissolution	Inhibition
Injection of chemicals to remove scale	Prevent further scale

Well stimulation operations require a cargo manifold for pumping of chemicals and other fluids to the field. Further required equipment include:

- Chemical tanks
- Work ROVs

Commissioning

Commissioning is needed whenever a subsea production system is being shut down for pipeline cleaning, pigging or preparation for repairs. The purpose is to ensure that specific fluids are present in the area where the work shall be executed. Commissioning requires the following systems:

- One or two work ROVs
- Cargo manifold
- Chemical tanks

Work ROV Operations

Work ROV operations refer to maintenance and repair operations performed by a work ROV. As there may be a need for specific ROV tools to perform such work, a crane is required for deployment of ROV tools. This crane does not need to be very large.

Inspection

Inspection is the most basic form of operation. As it only involves inspection of structures and pipelines subsea, the minimum requirement for performing inspection tasks is to have one observation ROV on board.

4.2.2 Subsea Installation, Umbilicals, Risers and Flowlines

SURF is a group of operations involving actual installation of components needed subsea. The term SURF actually covers a wider scope of tasks than the tasks that can be performed by OCVs. Installation of the heaviest subsea installations require vessels with larger cranes. Installation of pipe is very often done by highly specialized pipe-lay vessels or barges, due to the need of very mission specific equipment (Ritchie, 2008), but flexible pipe can be installed by smaller OCVs.

Subsea Installation

For installing subsea structures, the most important vessel equipment is to have a crane of sufficient capacity. The subsea structures need to be lifted and deployed to the field. It is also important to have a lot of free deck area. This is for storage of the subsea modules during transportation to the field.

Installation of Umbilicals, Risers and Flowlines

We here limit the discussion to laying of umbilicals, risers and flowlines by the J-lay method. Laying flexible pipe by the J-lay method requires a J-lay tower installed above the moonpool. The pipe will be lead from a carousel or reel along the J-lay tower and through the moonpool. The systems and the equipment needed to perform installation of umbilicals and flowlines by the J-lay method are (Ulstein International, 2015):

- Crane (up to 250 tonnes)
- J-lay tower
- Carousel/Reel
- Moonpool
- Work ROVs

4.2.3 Light Well Intervention

Well interventions are done to increase the recovery rate of oil wells. This has traditionally been done by drilling rigs. However, riserless light well intervention done by OCVs is emerging as a cost-efficient alternative with a much lower day rate and faster deployment to new fields. To perform the well intervention operations, the vessel needs to be fitted with the following systems:

- Crane (100 tonnes to 250 tonnes)
- Well intervention tower
- Moonpool
- ROVs

4.2.4 Diving Support

Diving support operations were common in the early days of the offshore industry. Many operations formerly performed by divers, are now done using ROVs, as this is cheaper and a lot safer. However, for some precision work in shallow waters, human presence is still preferred. Divers perform operations in several phases of the offshore field life, often related to subsea construction and inspection, maintenance and repair (Ritchie, 2008).

To perform these tasks, diving support vessels need to be equipped with a saturated diving system. This system allows divers to live in a pressurized environment while the operation is taking place. A saturated diving system lets the pressurization take place in a controlled manner. Deployment of divers to the underwater workplace is done by using a diving bell. The following systems are needed for diving operations:

- Saturated diving system, including diving bell
- Moonpool
- Work ROV
- DP3

4.3 Functional Breakdown for Offshore Construction Vessels

Based on the description of systems required to perform specific operations, we can outline a functional breakdown for OCVs. The categorization is based on the system-based design of offshore vessels presented in Erikstad and Levander (2012). The functional breakdown itself can be thought to represent the structural and behavioral aspects of complexity (Gaspar, 2013). The subsystems presented can be thought of as modular structures that each fulfill one function behaving in a certain way.

4.3.1 Ship-Related Functions

Ship-related functions contribute to the seaworthiness of the vessel, and thus "include the systems needed to carry the payload safely from port to port" (Erikstad and Levander, 2012). The ship related functions have a small impact on the level of functional flexibility in OCVs as the topside equipment to a large extent dictates which operations are possible.

Ship Structure

Within the ship structure, the hull is naturally the main element. The hull provides the buoyancy of the vessel, and its size, strength and geometry determines the amount and location of systems that can be fitted in and on the vessel. To increase the flexibility inherent in a design additional strength can be added, for example so that larger offshore cranes can be fitted at later stage. The additional hull strength can be seen as a robust system element, contributing to increasing the overall flexibility of the vessel. The ship structure also set other constraints for later retrofits, for example through stability criteria.

The superstructure of the vessel can include several task related functions, or mainly serve as the location for hotel functions and the bridge. Alternatively, task related systems such as module handling towers are sometimes integrated with the superstructure to increase the operational window further, in environments where the weather may be harsh, or where icing is an issue.

Accommodation

The accommodation can be thought of in terms of the accommodation facilities needed for the crew, plus additional accommodation needs for the operation specific work force. Several task-related systems require teams that are dedicated for the operations of specific systems, thus increasing the need for accommodation space.

Machinery

Even though we will not consider machinery further in this work, the installation of sufficient power so that the vessel becomes capable of swift redeployment to other offshore regions. It should be mentioned that sufficient auxiliary powering should be included, so that the task-related systems can function properly. Dynamic positioning requirements are highly dependent on the nature of operations, and must be carefully thought through, as the demands to system redundancy are high when considering classing for dynamic positioning systems.

4.3.2 Task-Related Functions

The-task related functions are broken down to a third level. The systems described in the third level may be thought of as the modules contributing to the specific missions described in the section on OCV operations.

Cargo Spaces

Cargo spaces needed in OCVs include both dry cargo spaces and wet cargo spaces. Dry cargo spaces include space for storage of subsea modules, carousels and skidding systems. Subsea modules are often stored on deck, creating a potentially large need for free deck area. Carousels used for storage of flexible pipe and reels for cables can both be stored on deck and below deck.

Skidding systems provide storage and easy movement of pallets with equipment. When it comes to wet cargo, assorted chemicals are needed for both IMR operations and well intervention. The functional hierarchy of cargo spaces in OCVs is presented in Figure 4.2.

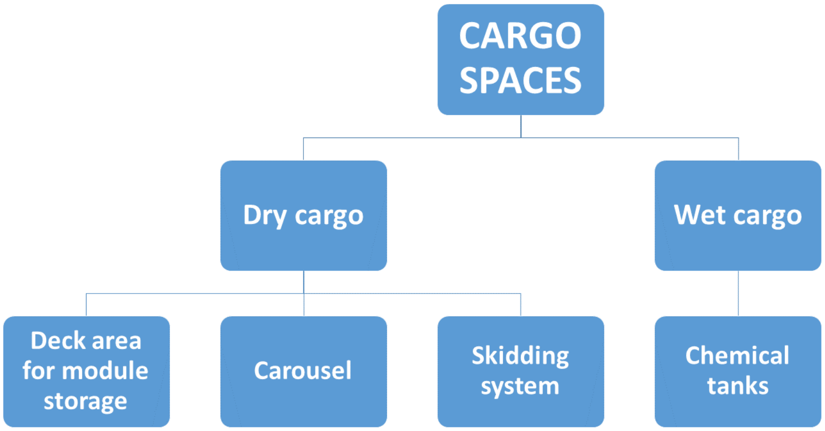


Figure 4.2: Functional breakdown of cargo spaces in offshore construction vessels.

Offshore Construction

Offshore construction functions can be divided into lifting and construction functions, diving functions and pumping functions. Offshore construction equipment is a very diverse group of systems. While some systems, such as reasonably sized offshore cranes, are installed on nearly all vessels, other systems, such as module handling towers, are more operation specific. A functional breakdown of the lifting and construction functions is shown in Figure 4.3. The breakdown of systems for performing diving functions is shown in Figure 4.4.

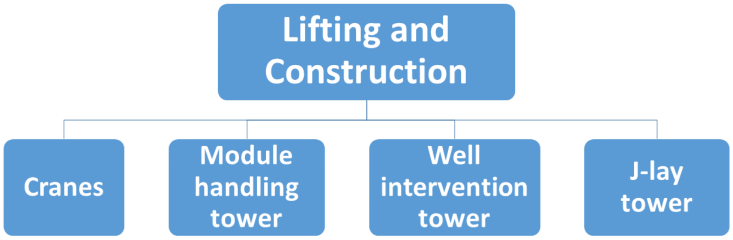


Figure 4.3: Functional breakdown of systems for lifting and construction tasks in offshore construction vessels.

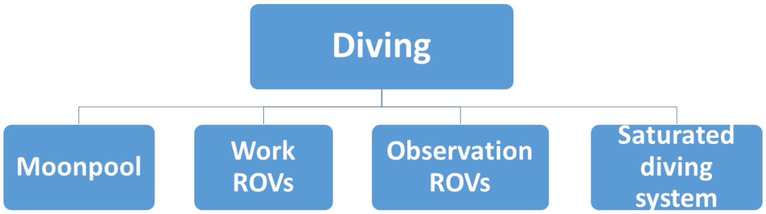


Figure 4.4: Functional breakdown of systems for diving tasks in offshore construction vessels.

4.4 Uncertainties Faced by Offshore Construction Vessels

In the maritime domain future uncertainty in the operating context appear in several different dimensions. A taxonomy of uncertainty provided in Erikstad and Rehn (2015) is shown in Table 4.5.

Table 4.5: Examples of maritime uncertainties, based on Erikstad and Rehn (2015).

Dimension	**Examples**
Economic	Oil price, freight rates, gross domestic product (GDP)
Technical	New fuel types, mission requirements, new equipment
Regulatory	Emission control areas (ECAs), ballast water treatment
Physical	Sea states, sea ice, water depth, port restrictions

Gaspar (2013) propose to divide the uncertainty faced by OCVs more specifically into another four categories. Table 4.6 gives some examples.

Table 4.6: Uncertainties faced by offshore construction vessels, based on Gaspar (2013).

Dimension	**Examples**
Field development	Opening new markets, new requirements
Technology development	New machinery, fuel types, equipment
Policy and regulations	New ECAs, DP requirements
Market trends	Fuel prices, freight rates, demand condition

Naturally, the phenomena shown in Table 4.5 and Table 4.6 require different modeling. Some are easily quantified by probability distributions, based on some expectation of future development or on historical data, while other developments may act as binary or discrete events, or little knowledge exist. Many of the economic factors mentioned in the tables above are more thoroughly explained by the shipping market model of Stopford (2009), even if the context of that model is based on shipping for transportation purposes.

Of the factors mentioned in Table 4.5 some stand out as especially important for OCVs. The oil price is massively influential in determining the activity level in offshore markets. When the price is high, one can assume that there will be a lot of activity, driving chartering rates to higher levels while more contracts become available. One can also expect fuel prices to follow the oil price closely. Further, oil price development is influenced by a number of technical, economic, political and physical parameters, even though it in itself can be thought of as an economic parameter. Some of the background drivers for supply and demand of oil are shown in Figure 4.5.

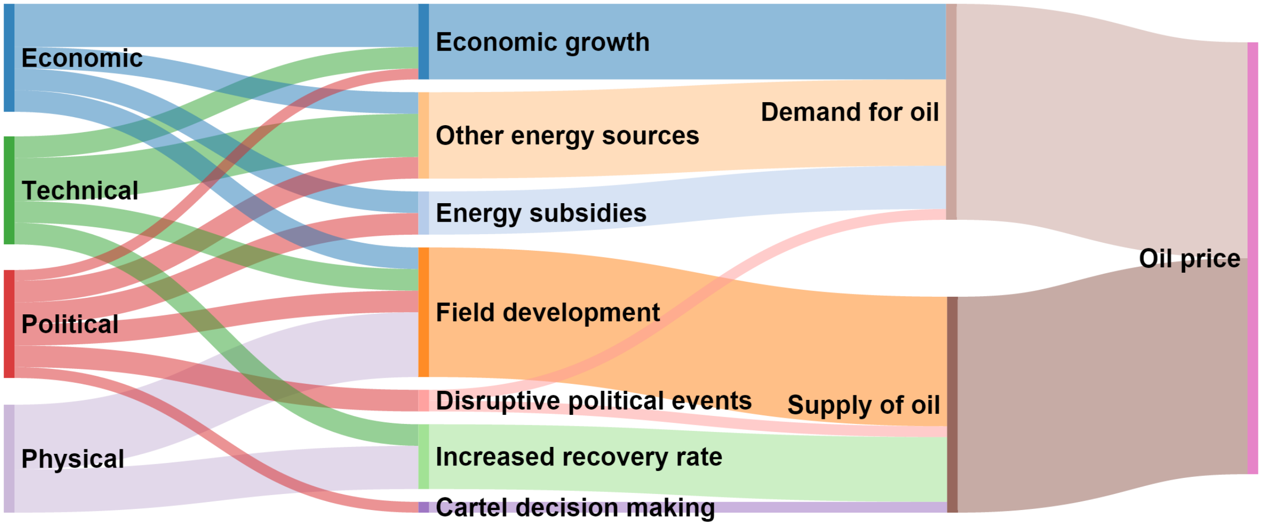


Figure 4.5: Sankey diagram mapping the influence of some economic, technical, political and physical uncertainties on the supply and demand of oil.

Figure 4.5 shows that the oil price is dependent on supply and demand, which in turn depend on a variety of economic, technical, political and physical exogenous factors. For example, new energy sources can emerge, causing a negative shift in the demand for oil. Disruptive political situations such as revolutions or coups in oil producing countries can temporarily interrupt production, causing shocks in the supply. The decision making of actors such as OPEC (Organization of Petroleum Exporting Countries) is often mentioned as an explanatory factor for oil price movements. The 1973 oil embargo effectively crashed tanker markets (Stopford, 2009), and shows that politics can have a large impact on shipping. Another good example is the impact of physical uncertainties such as the amount of oil in new fields being developed. The development of such fields is contingent on political decision making, the economic viability of the field development and on technical solutions. Further discussions of the drivers of the oil price will not be considered, as this represents a divergence from the main topics of this thesis. This example is brought up as it illustrates the complexity of one of the main drivers for the value of OCVs.

Another important example of uncertainty, even though it will not be considered further in this thesis, is the regulations regarding emissions from ships. ECAs have been established, putting strict limits on the emissions of either sulfur or nitrogen oxide, or both (Gaspar, 2013). Other regulations may be initiated as responses to accidents, as seen in the aftermath of events such as the disasters of the *Titanic*, the *Herald of Free Enterprise* and the *Exxon Valdez* (Stopford, 2009). The uncertainty related to stricter regulations as a response to a large accident, may impact OCV designs and could therefore be considered.

4.5 Identifying Sources of Flexibility in Offshore Construction Vessels

4.5.1 The Role of Modularization

Modularization can be applied as a means to increase the level of flexibility inherent in a design, as it allows capabilities to be added or removed through simple connections (de Neufville and Scholtes, 2011). Along with real options, modularity is mentioned as a means of mitigation and exploitation of uncertainty in McManus and Hastings (2006). Modularization is increasingly used in shipbuilding, and is present in the system-based ship design methodology of Levander (2012). System-based ship design applies functional breakdowns representing product architectures as a basis for a modular design approach (Erikstad and Levander, 2012). Each system performs a function, and can be isolated as a module. Numerous alternative vessel configurations can potentially be generated by combining modules.

Modularization in the system-based ship design framework represents the structural and behavioral aspects of complexity (Gaspar, 2013), but it also relates to functional flexibility as a means to handle the temporal aspect and uncertain operating conditions, which is our focus here. A modular shipbuilding approach may reduce the cost of modifying existing designs, and it enables us to look at a vessel as a portfolio of systems, rather than one "integrated" system. The benefit of this is the diversification of the associated risk (Baldwin and Clark, 2002). Viewing the ship as a portfolio of system modules which interact according to some well-defined relationships, we can identify real options in the vessel more easily.

4.5.2 Real Options and Offshore Construction Vessels

Real options in the maritime sector exist both on the form of real options *on* shipping projects, and as real options *in* ship designs, following the discussions of Wang and de Neufville (2005).

Some examples of typical real options *on* shipping projects are found in Alizadeh and Nomikos (2009). As these are not very interesting in the context of this work, we will instead concentrate on real options *in* ship designs as the main source of flexibility. Some examples of real options *in* ship design, include elongation of existing vessels and adding capabilities in multi-functional OCVs. The latter example we will consider further here.

In the case of OCVs, functional flexibility can be used to overcome the differences between vessels customized for specific missions. Below, we consider some examples of how flexibility can mitigate the risks and exploit the opportunities facing an OCV design:

- *Flexibility to facilitate market switching.*
  By identifying the equipment that can easily be replaced in a cost-effective and timely manner, it may be possible to switch markets. For example, it may become possible to use the same vessel for IMR operations before switching to SURF operations. While some market switching can take place at sea, other market switching may require a larger retrofit of the vessel.

- *Flexibility to respond to changes in contractual requirements of the current market.*
  Even though the vessel seeks work in the same market as before, requirements may change according to the preferences of customers, or as determined by the relevant authorities. For example, if there is a need for an increase in operability during module handling operations, it may become a requirement that a dedicated module handling tower is used, rather than a crane.

Looking at the vessel from an operational standpoint, we can identify specific systems as potentially valuable sources of flexibility. The following systems should be further considered as real options in an analysis quantifying the flexibility of the OCV:

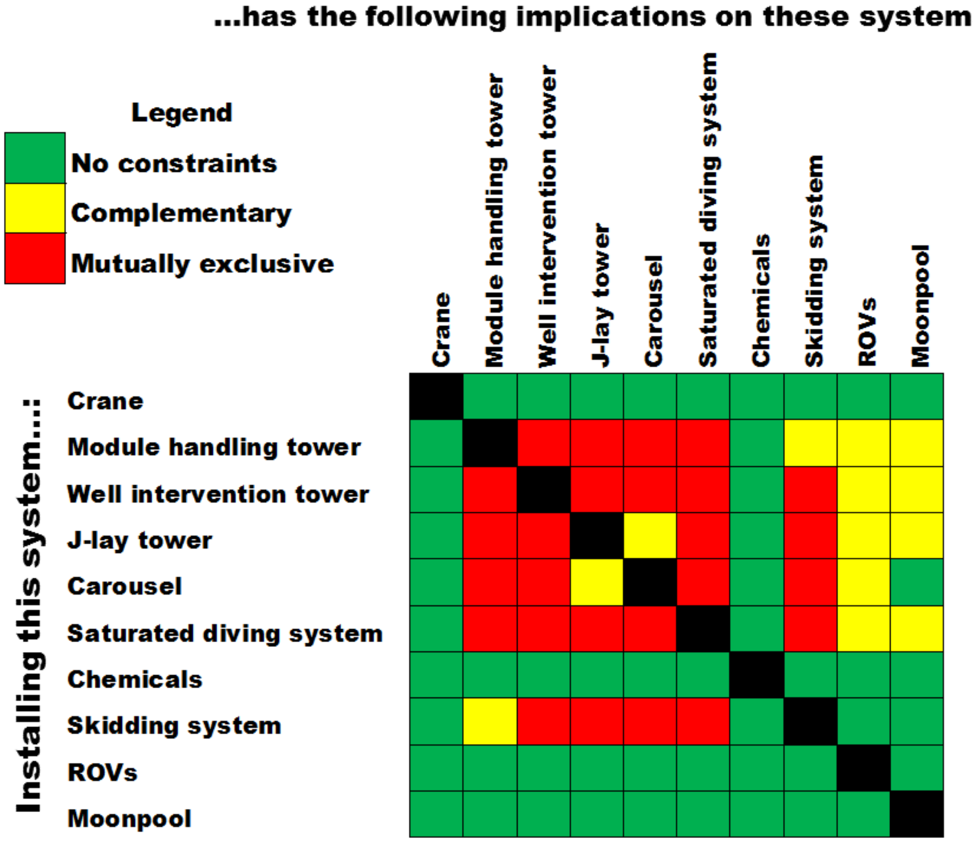
- **Accommodation**
  There are some differences in the need for accommodation based on the nature of the operation. If more space should be needed at later stages, it could be possible to prepare the vessel, at the design stage, for the addition of accommodation space. This would require an initial overdimensioning of the hotel facilities in the vessel.

- **Cranes**
  While nearly all vessels have cranes, the requirements with regards to crane capacity differ. A strategy reducing initial capital expenditures, can be to install a small crane initially, while buying the option to replace it with a larger crane, should this be needed. This may require extra strength added in the hull. The cost of adding additional strength, represents the option price for upgrading the crane capacity.

- **Module handling tower, Well intervention tower and J-lay tower**
  All these systems are placed directly above the moonpool, which means that they are mutually exclusive. However, it should be possible to replace one of these systems with one of the other. It should be mentioned that the module handling tower often is installed along with a skidding system, while J-lay towers require carousels to function.

- **Saturated diving system**
  The diving systems can either be an integral part of the superstructure, or it can be installed as a modular system. If installed in the modular fashion, the system may more easily be replaced or installed at later stages of the vessel lifetime. The saturated diving system is considered as mutually exclusive with module handling towers, well intervention towers and J-lay towers.

Considering the flexibility provided by the opportunity to exchange these systems, it is necessary to have an overview of the logical constraints given by the presence of the different systems. Some mention of these relationships were given above, and are summarized in Figure 4.6.



...has the following implications on these systems:

Legend

🟩 No constraints
🟨 Complementary
🟥 Mutually exclusive

Installing this system...:

	Crane	Module handling tower	Well intervention tower	J-lay tower	Carousel	Saturated diving system	Chemicals	Skidding system	ROVs	Moonpool
Crane	⬛	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Module handling tower	🟩	⬛	🟥	🟥	🟥	🟥	🟩	🟨	🟨	🟨
Well intervention tower	🟩	🟥	⬛	🟥	🟥	🟥	🟩	🟥	🟨	🟨
J-lay tower	🟩	🟥	🟥	⬛	🟨	🟥	🟩	🟥	🟨	🟨
Carousel	🟩	🟥	🟥	🟨	⬛	🟥	🟩	🟥	🟨	🟩
Saturated diving system	🟩	🟥	🟥	🟥	🟥	⬛	🟩	🟥	🟨	🟨
Chemicals	🟩	🟩	🟩	🟩	🟩	🟩	⬛	🟩	🟩	🟩
Skidding system	🟩	🟨	🟥	🟥	🟥	🟥	🟩	⬛	🟩	🟩
ROVs	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬛	🟩
Moonpool	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	⬛

Figure 4.6: Matrix explaining the physical relationships between important topside systems in an offshore construction vessel. Read from the rows to the columns.

Chapter 5

Case Study: Designing a Flexible Offshore Construction Vessel

In this chapter, we present a case study in which an offshore construction vessel (OCV) is to be designed for an uncertain future operating context. Methodologies for the analysis are selected, and a quantitative model for the problem at hand, is presented.

5.1 Case Description

A ship owner has been awarded a five year inspection, maintenance and repair (IMR) contract. Thereafter, there will be uncertainty surrounding market factors, technical requirements and contract availability. The ship owner therefore wishes to order a flexible vessel that can potentially be used in several different markets. The vessel is to be operated for a full lifetime of 25 years. The markets are defined according to their missions:

- Inspection, Maintenance and Repair (IMR)
- Subsea installation, Umbilicals, Risers and Flowlines (SURF)
- Light Well Intervention (LWI)
- Diving Support (DSV)

We only consider one area of operations, with an assumption of shallow water and easy operating conditions. Thus, we put more emphasis on the topside functionalities and define the design solely on this basis. Following the segmentation of main market actors in the previous chapter (see Figure 4.1), the case will concern transactions between a traditional ship owner and customers that are defined as small or medium subsea contractors. Thus, we consider smaller, multi-functional OCV designs in this case.

5.1.1 The Future Expectations of the Ship Owner

The prospective ship owner has some expectations and preferences regarding the future prospects of the vessel lifetime. The expectations of this customer includes both economical and technical sources of uncertainty. Note that the expectations below should be considered a part of the case description, and are based on the future outlook of a hypothetical ship owner. Thus, they should be taken as assumptions, and do not represent the results of any real forecasts or proper analysis. The alternative future outlooks of the ship owner will be further outlined in the era construction.

- **Oil price**
  The oil price is expected to be relatively low for some time, due to the influx of increased US shale oil production. However, in the long term there is reason to expect price increases. The oil price is believed to have an impact on the number of contracts that are available in the markets.

- **Day rates**
  The day rates will fluctuate throughout the lifetime of the vessel. However, the parameters of such a fluctuation is hard to know exactly, due to the lack of historical data related to the markets considered. Still, the ship owner has some expectations regarding this:
  IMR contracts will have low rates, but exhibit small fluctuations, due to the necessity of IMR services both in good times and bad times.
  SURF contracts will have high, but very volatile rates, as the number of new subsea development is dependent on the oil price, but also on the current supply and demand of vessels in the market.
  LWI contracts are very high, but also very volatile. The fluctuations are expected to be substantial as this is an emerging market with little historical data.
  Diving support contracts will have high rates, but more limited fluctuations as diving support is often required for maintenance and repair tasks.

- **Technical developments**
  On one hand, the ship owner expects that offshore development begins in nearby areas with deeper waters, which possibly facilitates an increase in the tie-in distances from new subsea fields to the existing developments. Alternatively, it is possible that the vessel will need to be able to deploy larger subsea modules. Such a development could be coupled with an increase in water depths. New innovative crane wire technologies, such as usage of fibreropes rather than steel wires for cranes is also a factor the ship owner accounts for. Technical factors influence the requirements of the contracts, and the number of contracts available.

5.2 Selecting a Design Methodology for Flexibility

In this case study, the main design methodology is the Responsive Systems Comparison (RSC) method, which was outlined in Chapter 3. This allows us to understand what constitutes a good design, and lets us employ Epoch-Era Analysis to model uncertainty. As part of the final step of the RSC method, we employ a Monte Carlo Simulation (MCS) approach to Real Options Analysis (ROA) and the valuation of flexibility. The approach is summarized below:

1. **Responsive Systems Comparison (Steps 1 - 6)**
   We go through the six first steps of the Responsive Systems Comparison (RSC) method. These were explained in the chapter on methodology. We wish to limit the analysis to the feasible part of the design space, and apply integer and binary constraints on the design space to limit the solution space for the analysis.

2. **Life cycle path analysis with Real Options Analysis (Step 7 of the RSC method)**
   We here assess the economic value of a design in a lifetime perspective. The valuation of flexibility will be included through comparing flexible and inflexible versions of otherwise identical designs. We include flexibility through providing the possibility to transition between point designs on the design space, as defined by several transition rules. A MCS model for the net present value (NPV) is developed to evaluate when and which flexibilities to trigger, as well as quantify the value of flexibility. This thus constitutes a Real Options Analysis.

The model is described in the next section. Each step of the procedures used are first described in generic terms. Thereafter we describe their application on this case. The scripts and functions in Appendix E documents the implementation of the model in MATLAB.

5.3 Modeling With the Responsive Systems Comparison Method

5.3.1 Value-Driving Context Definition for the Offshore Construction Vessel

The ship owner wishes to order a design that can be operated in a profitable way for the full lifetime of 25 years, within the four market segments IMR, SURF, LWI and DSV. In this light, the value of the vessel to the owner is defined as the ability to deliver value in the long term, by allowing adaptation of the vessel corresponding to the needs of different market segments. This goal is signified by the following value attributes:

- **Acquisition affordability**
  The vessel should have low building costs and costs for installation of systems.

- **Operational affordability**
  The vessel should be able to deliver a profit under very volatile market conditions.
- **Mission capability**
  The vessel should be able to perform the operations set by the current contract. Capability increases with the number of available contracts the vessel can match.
- **Mission flexibility**
  The vessel should be able to deliver value under changing operating contexts and stakeholder needs, possibly by adding or removing installed equipment, to match the requirements.

The ship owner wishes that these goals be attained by designing a flexible vessel by specifying vessel topside equipment configurations that can be changed or retrofitted to fulfill the requirements of several of the market segments mentioned. Designing for mission flexibility can increase affordability, by only preparing the vessel for installation of equipment later, instead of including it at the building stage, thus reducing the initial investment cost. Flexibility can increase the mission capability, because the vessel can be retrofitted to fulfill different mission requirements at later stages.

Depending on the outlook of the ship owner other value propositions could be suggested. A more risk-based design approach (in terms of safety) could be to design with reliability, survivability or other safety-related "-ilities" in mind, or towards the "Greener, smarter, safer" approach mentioned in Gaspar et al. (2015). Another aspect that could be further elaborated in a value proposition could be agility, which incorporates the necessity of responding to contextual change in a timely manner. Often, geographical versatility and agility could be an aim, making the vessel able to swiftly redeploy to other offshore regions. This is not accounted for here, as we define that the whole area of operations is within one offshore region.

5.3.2 Value-Driven Design Formulation for the Offshore Construction Vessel

Performance Attributes

Based on the context definition, and the related value proposition given above, some desired performance attributes can be defined for this design. Each performance attribute is connected to a utility function that is used for evaluation of designs. The model assumes that each performance attribute i has a normalized utility value U_i. The utility for each vessel is thus given by:

$$U = \frac{\sum_{i \in I} U_i}{I} \tag{5.1}$$

The mapping from value attributes to performance attributes, and further to design variables and epoch variables is shown in Figure 5.1. It should be noted that only direct relationships are shown. Of course, the epoch variables have an indirect influence on costs, through influencing what constitutes a good design. The quantification of performance attributes applied is shown in Table 5.1.

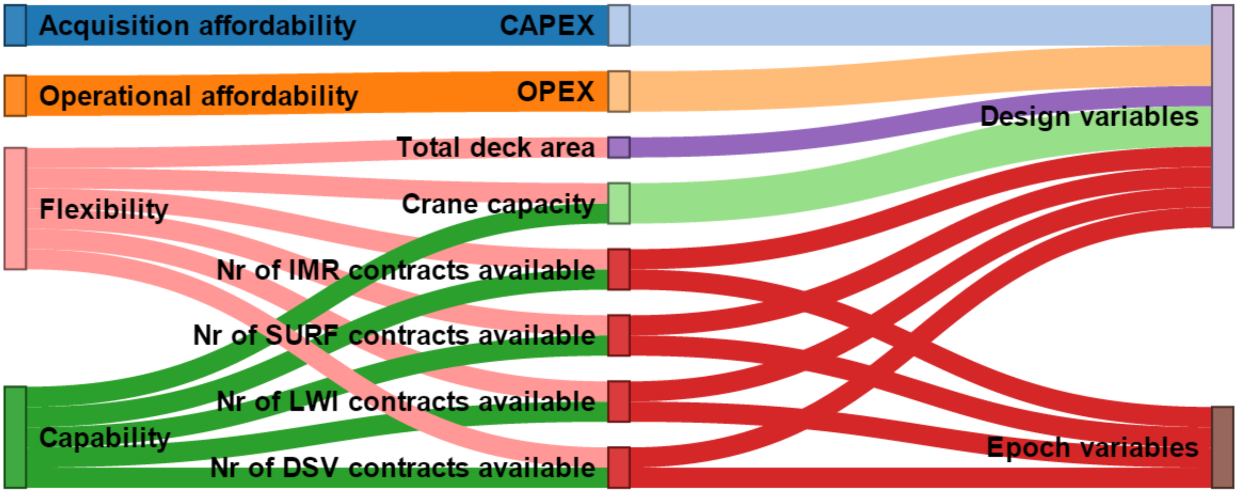


Figure 5.1: Sankey diagram mapping the value attributes explained in the value proposition, to performance attributes, design variables and epoch variables.

Table 5.1: Performance attributes for the offshore construction vessel.

Performance attribute	**Unit**	**Utility = 0 %**	**Utility = 100 %**
CAPEX	[MNOK]	Max cost	Min cost
OPEX	[MNOK/day]	Max cost	Min cost
Crane capacity	[tonnes]	100	300
Total deck area	[m^2]	1000	2000
Nr. of IMR contracts available	[-]	0	10
Nr. of SURF contracts available	[-]	0	10
Nr. of LWI contracts available	[-]	0	10
Nr. of DSV contracts available	[-]	0	10

The performance attributes shown are selected as they contribute towards the goal of having a vessel that is able to handle future uncertainty. Some value is generated in a fully endogenous way, through reduced costs, while other sources of value creation will be more dependent on exogenous epoch variables we define later. Total deck area is used as a performance attribute as it increases the space available for equipment installation topside. The performance attributes relating to contracts available assume that the contractual requirements must be met. Therefore any vessel that is unable to comply with the requirements for any market, will be assigned a utility of 0.

The notion of value is individual, and stakeholders could have different perceptions as to how the individual performance attributes should be weighted. The relative importance of performance attributes could easily be accounted for by assigning different weights to the performance attributes. Even though all performance attributes contribute towards the value proposition, we see from Figure 5.1 that the links between a specific performance attribute and the value attributes differ. For example, in order to consider acquisition affordability as relatively more important, the performance attribute CAPEX should be assigned with a higher weight. The reason is that a larger number of performance attributes are mapped to other value attributes, which reduces the relative importance of affordability, compared to flexibility and capability. Still, we have chosen to weight performance attributes equally as it will likely produce a broader scope of designs at the Pareto front, especially with regards to costs. This puts a larger weight on the influence of uncertainty, as the epoch variables will relate mostly to capability and flexibility,and is less important with regards to affordability.

Design Variables

Evaluation of alternative concepts require us to generate a set of designs in accordance with the set-based ship design of Singer et al. (2009). A generic method for generating the design space is to enumerate all designs, generating all combinations of design variables. The process of generating the design space is grounded in the structural and behavioral aspects of complexity. To avoid solutions that are impossible or do not fulfill some condition, we apply linear, integer and binary constraints. The restrictions on the design space can be grouped as follows:

- System dependencies
- Capacity constraints
- Contract requirements
- Integer and binary constraints

The system dependencies can be complementary or systems can be mutually exclusive. Complementary systems require some other system to function. A generic expression of complementarity between two systems x_A and x_B is shown in Equation 5.2. We assume that x_A, x_B and x_i are binary variables in all the expressions below.

$$x_A - x_B = 0 \tag{5.2}$$

Mutually exclusive systems can for example be located in the same location on board, and thus only one can be selected. Equation 5.3 shows the generic expression for such a constraint for systems x_A and x_B.

$$x_A + x_B \leq 1 \tag{5.3}$$

Capacity constraints relate to the limited space on board the vessel. Capacity constraints can related to the volume, weight or deck area available. In generic terms, the sum of capacities k for systems x_i should not exceed the maximum capacity K of the vessel, as shown in Equation 5.4.

$$\sum_{i \in I} k_i x_i \leq K \tag{5.4}$$

We do not need to generate the designs that do not fulfill the contract requirements. The required capability level in a contract j is Q_j, and the capability of the installed system i is Q_i. A generic contractual requirement constraint is shown in Equation 5.5.

$$Q_i x_i \leq Q_j \tag{5.5}$$

Finally, the integer and binary constraints on the design space is included by parameterizing the design variables as discrete numbers. Discrete design variables are used to limit the total number of solutions that need to be analyzed.

In this case, we describe the possible designs through a set of topside systems shown in Table 5.2. Herein, LARS stands for "launch and recovery system". Each design variable represents a module that fulfills a certain function. These design variables creates a potentially possible design space of 15360 different designs. Due to constraints on the form described above and outlined for this specific case below, the number of designs is reduced to 125.

In accordance with the system dependencies described in Figure 4.6, there are logical relationships between the design variables. Equation 5.6 shows that the module handling tower, the well intervention tower, the J-lay tower and the saturated diving system are mutually exclusive.

$$z_1 + z_2 + z_3 + z_5 \leq 1 \tag{5.6}$$

Table 5.2: Design variables for the offshore construction vessel.

Design variable	Notation	Unit	Range (Min-Max)	Step length	Nr. of levels
Crane	x_1	[tonnes]	100 - 300	50	5
Free deck area	x_2	[m^2]	0 - 1500	250	6
LARS for ROV	x_3	Integer	1 - 2	1	2
Accommodation	y_1	[people]	50 - 150	100	2
Module handling tower	z_1	Binary	0 - 1	1	2
Well intervention tower	z_2	Binary	0 - 1	1	2
J-lay tower	z_3	Binary	0 - 1	1	2
Carousel	z_4	Binary	0 - 1	1	2
Saturated diving system	z_5	Binary	0 - 1	1	2
Chemicals	z_6	Binary	0 - 1	1	2
Skidding system	z_7	Binary	0 - 1	1	2

Equation 5.7 defines that a module handling tower requires a skidding system to be installed, and vice versa. Similarly, the relationship concerning J-lay towers and carousels is given in Equation 5.8.

$$z_1 - z_7 = 0 \tag{5.7}$$

$$z_3 - z_4 = 0 \tag{5.8}$$

When a well intervention tower is installed, we wish to require that chemical capabilities are present. This is defined in Equation 5.9. Note that chemical capabilities can be included without the well intervention tower.

$$z_2 - z_6 \leq 0 \tag{5.9}$$

At last, module handling towers (Equation 5.10), well intervention towers (Equation 5.11) and saturated diving systems (Equation 5.12) are considered to require two LARS for WROVs:

$$z_1 - x_3 \leq -1 \tag{5.10}$$

$$z_2 - x_3 \leq -1 \tag{5.11}$$

$$z_4 - x_3 \leq -1 \tag{5.12}$$

There are two capacity constraints in this case. For each design variable, there is a connected accommodation need and a deck area required. The free deck area is a special case, as the addition to the deck area determined by this variable. This is shown in Table 5.3.

Table 5.3: Accommodation and deck area needed for the installation of specific systems.

Design variable	**Requirements**	
	Accommodation [people]	**Deck area** [m^2]
Crane (regardless of capacity)	4	20
Free deck area	0	x_2
LARS for ROV (for each ROV)	6	25
Accommodation	-	0
Module handling tower	8	50
Well intervention tower	16	100
J-lay tower	16	150
Carousel	0	300
Saturated diving system	24	250
Chemicals	4	0
Skidding system	0	500

We set the following constraint (Equation 5.13) to define that the systems represented by integer variables x_i, just need to be installed to trigger a need for accommodation and deck area. Here, M_i represents the maximum capacity of system i. The binary variable δ_i is equal to 1, if system i is installed, and 0 otherwise.

$$M_i\delta_i - x_i \geq 0 \tag{5.13}$$

The accommodation is thus set according to the constraint in Equation 5.14. The accommodation A, needed for systems represented by integer (i) and binary (j) variables, is connected to the accommodation variable y. A_b indicates the basic crew needed to run ship-related systems.

$$A_b + \sum_{i \in I} A_i\delta_i + \sum_{j \in J} A_j z_j \leq y_1 \tag{5.14}$$

The deck area for each system is given by D_i for systems given by integer variables, and D_j for systems given by binary variables. The deck area D^{TOT} is determined by Equation 5.15.

$$\sum_{i \in I} D_i\delta_i + \sum_{j \in J} D_j z_j = D^{TOT} \tag{5.15}$$

The total deck area can not exceed a maximum D^{MAX} of 2000 m^2 or fall below a minimum D^{MIN} of 1000 m^2. The limits are set to keep the vessel size within the range for small to medium sized OCVs. The lower bound is set, so that no unrealistically small vessels could pass as OCVs. The total deck area is rounded to reasonable increments by applying a step size of 500 m^2. Equation 5.16 and Equation 5.17 provide the restrictions on deck area.

$$D^{TOT} \leq D^{MAX} \tag{5.16}$$

$$D^{TOT} \geq D^{MIN} \tag{5.17}$$

The total deck area is mentioned as a performance attribute, as it defines bounds on the amount of equipment that can be installed at a later stage. When it comes to flexibility, the total deck area is used as a criteria to decide whether a transition between designs is possible, as a transition requires that the total deck area remains the same. We do not consider transitions that include alteration in size of the vessel itself, only its system capabilities.

At last, we choose only to generate those designs that fulfill the requirements for the initial IMR contract, for which the vessel is to be deployed. This is accordance with the generic constraint given by Equation 5.5. The initial minimum requirements for all markets are given in Table 5.4.

Table 5.4: Minimum requirements for the initial operating context.

	Mission Based Markets			
Design Variables	**IMR**	**SURF**	**LWI**	**DSV**
Crane [tonnes]	100	200	100	0
Free deck area [m^2]	500	1000	500	0
Accommodation [people]	50	150	150	150
Module handling tower	0	0	0	0
Well intervention tower	0	0	1	0
J-lay rig	0	0	0	0
Carousel	0	0	0	0
Saturated diving system	0	0	0	1
Chemicals	1	0	1	0
Skidding system	0	0	0	0
LARS for WROV	1	1	1	2

By imposing the constraints outlined above on the design, we reduce the design space drastically. Instead of evaluating many thousand alternative designs, we now only need to consider 125 designs in the tradespace evaluation. We should mention the assumption that every design alternative is equipped with a moonpool, one LARS for an observation ROV, and one LARS for a work ROV, as well as all ship-related systems that are needed in an OCV. For this reason, moonpool and observation ROVs are not considered in the design analysis at all, while one LARS for a work ROV (WROV) is set as the minimum in Table 5.2.

In reality, the design task is much more complex than considered here, and there are numerous highly non-linear relationships to consider. For example, instead of using total deck area for vessel size measurement, the length, beam and draft could be used to set the vessel geometry. The relationship between length, beam, draft and system related variables, would force us to consider ship stability and resistance. With regards to ship stability, the beam would dictate crane capacity, as transverse stability becomes an issue with large loads. By including stability, we would need to consider the exact location of the systems installed, and not just consider whether they are installed or not. This would complicate the design problem tremendously. These examples point to some potential weaknesses of the approach taken with regards to design variables. Still, the goal here is to identify functional flexibility and capture its value, not to understand the interactions between all aspects of the design.

Cost Model

The costs of this vessel were mentioned as performance attributes. The capital expenditures (CAPEX) is seen as a function of the following:

- **Total deck area**
  Total deck area defines the size of the vessel. We therefore use it to define the building costs of the vessel, before any topside systems are added.
- **Design variables**
  We consider the fact that there are additional costs for buying and installing the topside systems that are represented by the design variables. In addition to the price of buying these systems, a 20 percent extra fee is required for installation.

Equation 5.18 gives the function for CAPEX, C^C.

$$C^C = C^B_{MIN} + \Delta C^B \cdot \frac{(D^{TOT} - D^{MIN})}{\Delta D} + g \cdot \sum_{i \in I} C^E_i \tag{5.18}$$

Here, C^B are the building costs based on the total deck area D^{TOT}, while C^E_i is the cost for investing in equipment i. ΔC^B refers to the stepwise increase in the building costs. D^{MIN} is the minimum possible total deck area. The factor accounting for the additional installation fee in percentage of system cost, is g. 70 percent of the initial investment costs are paid by a loan, with a 20 percent discount rate. The numbers used for the systems and total deck area in the cost model are based on indicative values for generic systems supplied by Ulstein International. The exact values are provided in Appendix B.

The operational expenditures (OPEX) are a function of the CAPEX. Table 5.5 explains how some factors are accounted for, as given in Stopford (2009). In addition to the factors presented in Table 5.5, manning is included, but based on the cost of hiring the crew members for the vessel only. Note that only the crew handling ship-related tasks are paid for by the ship owner, and that tasks related to the actual operation of the vessel is assumed to be the responsibility of the contractor or oil company chartering the vessel. We assume that there are no stochastic elements in the cost model. This is assumed both for the initial CAPEX and for the cost of adding equipment later, as well as for OPEX.

Table 5.5: Components of the operational expenditures.

Cost factor	**[%] of CAPEX**
Stores and lubricants	1.2
Management	1
Repair and maintenance	1
Insurance	0.6
Depreciation	3

In reality, the CAPEX initially may be subjected to uncertainty during the shipbuilding process. Shipping is highly cyclical (Stopford, 2009), and the demand for new vessels in good times may drive the newbuilding costs up. For offshore vessels, it could be relevant to connect the prices for newbuildings to the oil price, which is a main driver in the offshore market. Increases in shipbuilding activity can contribute to delays, which can result from a variety of other sources. For example, if the hull is build in a low-cost country, and the plan is to move the unfinished vessel to a high-cost country for outfitting, the project completion will depend on transportation risks as well. Other uncertainties that could relate to our cost model, is the possible fluctuations in prices for equipment over the next 25 years. The volatility of such prices may be substantial, as innovative new systems may emerge as alternatives. Such risks have not been included, as our focus is the value of the vessel in a lifetime perspective, and not on the shipbuilding process.

5.3.3 Epoch Characterization for the Offshore Construction Vessel

Epoch variables capture the future expectations of the ship owner. The sources of uncertainty that have been focused on, were given in the case description. The epoch variables are shown in Table 5.6.

The total enumerated epoch space resulting from these epoch variables, consists of 144 potential future contexts for the vessel. The selected epoch variables are only a very small set of potential uncertainties that can have a large impact on offshore construction vessels. The current selection can be justified through looking at the structure of the epochs here. We have set them to the length of a contract, so it makes sense to tie the epoch variables up to the specific missions that are performed. The chosen epoch variables set the stage for looking into how topside functionalities respond to changes in the operating context that are in accordance with

Table 5.6: Epoch variables selected for the analysis.

Epoch variable	Range (min-max)	Step length	Nr. of levels
Oil price	10 - 100	30	4
Module size	200 - 300	50	3
Water depth	1000 - 3000	1000	3
Tie ins	0 - 1	1	2
Fibre rope technology	0 - 1	1	2

stakeholder expectations. If the system is defined through other design variables, such as dynamic positioning capabilities, machinery configurations or ice classing, another set of epoch variables should definitely be used. In such a case, one could quantify uncertainties related to weather conditions, distance to shore or the need to operate in the Arctic.

The level of resolution that is set for the epoch variables is another issue that could emerge. What if there are great changes in the value generating properties of one epoch variable, that is not captured by the current level of resolution? On the other hand, too high resolutions can lead to an excessive number of epochs to evaluate, and cause a focus on differences in some epoch variables that are too small to matter for the system as a whole. This would increase the numbers of tradespaces that must be generated, and can thus create a substantial increase in the computational effort needed for a large problem. One should be able to justify the step length finally applied for the epoch variables. In this case, the reasoning about contractual requirements and contractual availability next, justifies the level of resolution applied.

The epoch variables presented in Table 5.6 have a direct influence on contractual requirements and contract availability. These factors mainly influence the feasibility of a vessel to perform in a specific mission-based market, and the probability of winning a contract. Both in relation to the tradespace exploration in the next section, the subsequent multi-epoch analysis, and in relation to the life cycle analysis later, these are highly important factors.

Contractual Requirements

The vessel need to fulfill the contractual requirements set in each market, in order to be able to compete for a contract. Here, the influence of the individual epoch variables on the contractual requirements, are defined.

- **Oil price**
  The oil price has no direct influence on the requirements.

- **Module size**
  The module size influences the crane capacity and the required free deck area for SURF operations. The crane capacity required is set equal to the module size. The required free deck area increases with 250 m^2 for each 50 tonnes increase in module size. All increases in module size trigger a module handling tower requirement for IMR operations.

- **Water depth**
  Water depths beyond 1000 meters, trigger a need for module handling towers to perform IMR operations, a requirement of 2 WROVs both for IMR and SURF operations, as well as increasing all crane capacity requirements with 50 tonnes per 1000 meters, due to the increased weight of the steel wire deployed.

- **Tie-in to existing field**
  Increasing demand for tie-in services trigger a requirement concerning the J-lay rig and carousel aboard vessels engaging in SURF operations. In addition, 2 WROVs will be required for SURF operations.

- **Fibrerope technology**
  The development of fibrerope technology to be used as a substitute for steel wires for cranes, will eliminate the need to increase the requirement for crane capacity as water depths increase. The reason is that fibreropes have an approximately neutral buoyancy.

Contractual Availability

Contractual availability is one of the performance attributes that were defined. The influence of the epoch variables on the contractual availability are described below. In addition, it is necessary that the contractual requirements in a market is met, if there are to be any contracts available.

- **Oil price**
  The number of contracts available rises with the oil price. This holds for all markets.

- **Module size**
  The module size does not affect the contractual availability of any market.

- **Water depth**
  The water depth affects the number of LWI contracts positively, due to an increase in the need for cost-efficient well intervention services at deep water. The number of diving contracts is affected negatively, as deep waters make diving impossible.

- **Tie in to existing fields**
  The number of available contracts in the SURF market increase if tie-ins are used in new fields being developed. The same is true for the DSV market.

- **Fibrerope technology**
  This has no influence on the number of contracts available.

The Probability of Winning a Contract

The probability of winning a contract is based on the contractual requirements and the contractual availability. The influences are summarized through the Sankey diagram in Figure 5.2. As we see the design variables need to comply with the contractual requirements, and there are differences in the impact of the epoch variables on the requirements and the contractual availability.

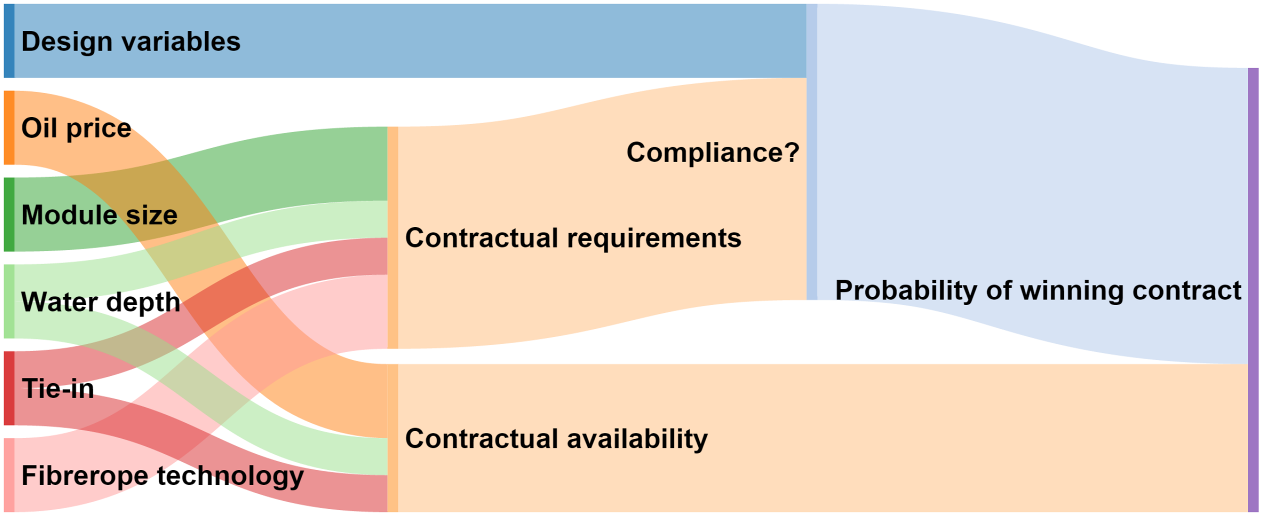


Figure 5.2: The influence of epoch variables and design variables on the requirements, availability and the probability of winning contracts.

The probability P_{mve} that vessel v will win a contract in a given market m in epoch e is found through the following relationship:

$$P_{emv} = \frac{X_{emv}}{\max\limits_{e \in E}(X_{emv})} \tag{5.19}$$

X_{emv} is the number of available contracts for vessel v in market m in epoch e. If vessel v does not fulfill the requirements of market m in epoch e, X_{emv} is set to 0. The probability of winning a contract needs to be accounted for, as the access to new missions is necessary for the later contracts. This probability plays a role in the life cycle analysis. The estimation used for the probability of winning a contract is presented here, as it strongly relates to the epoch variables.

The probability of winning a contract in reality depends on a lot of uncertainties that we have not at all considered in this case. To make a realistic assessment of this we would have to know a lot about the potential customers of the ship owner as well. The perceptions of both the contractors and the oil companies would have to be assessed, as well as the vessel capabilities and experience with the operations. In addition, the overall reputation of the ship owner would have to be questioned, with regards to parameters concerning environmental performance and other things that this analysis does not touch upon at all. Figuring out the magnitude of these potential influences falls outside the scope of this work. The estimation applied in this case can be justified by the obvious reduction of complexity.

5.3.4 Tradespace Evaluation for the Offshore Construction Vessel

Through the tradespace evaluation we calculate the utility and costs of each point design, according to the principles outlined in the description of performance attributes and the cost model. The utility of the vessel will be contingent on both the design and epoch variables, as shown in Figure 5.1, while costs do not change with the epochs, being deterministic. In addition, the utility is set to 0 for any design that is incapable of meeting any contractual requirements for the current epoch.

A typical tradespace for Epoch 1, is shown in Figure 5.3. In the figure, each ring represents a different design alternative. Table 5.7 provide the color legend for all tradespaces. This legend will be applied for the other tradespaces presented in this analysis as well. Assessing design alternatives in a tradespace allows us to consider further the designs along the Pareto front. The designs along the Pareto front, are highlighted by the red line in Figure 5.3.

Table 5.7: Tradespace coloring legend, based on total deck area. This legend applies to all tradespaces.

Total Deck Area $[m^2]$	**Color**
1000	Blue
1250	Cyan
1500	Green
1750	Red
2000	Black

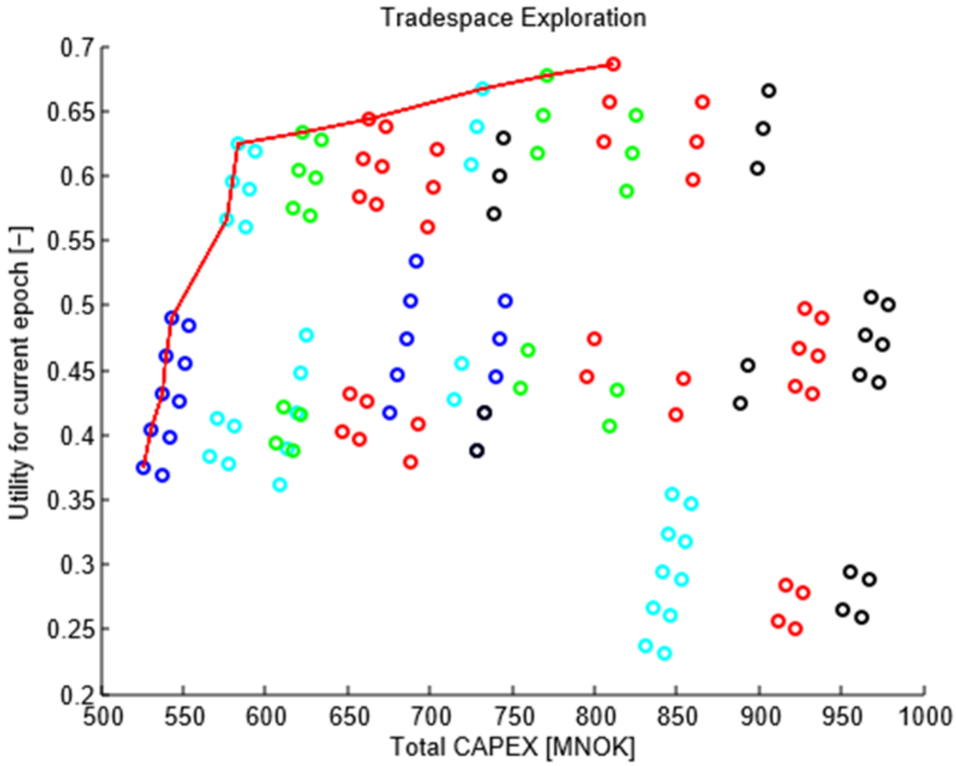


Figure 5.3: Tradespace exploration for a single epoch. The Pareto front is highlighted in red, while the color coding is presented in Table 5.7.

While zooming into the Pareto set in each epoch allows us to find valuable solutions in static contexts, a single tradespace evaluation alone does not account for uncertainty. Value robustness, both active and passive, is assessed in the three last steps of the RSC method.

5.3.5 Multi-Epoch Analysis for the Offshore Construction Vessel

In this analysis we will apply the Pareto trace measure to evaluate passive value robustness. This step thus quantifies the performance of designs throughout many epochs, without letting the design change. When finding the Pareto trace we could weight the importance of the epochs according to its probability, to account for the stakeholder belief of what epochs are most likely.

The stakeholder expectations regarding the actual progression of epochs, could be further accounted for by conducting a multi-era analysis (Curry and Ross, 2015). In such an analysis we could backtrack from the era construction procedure and define the Pareto trace based on the epochs that are included in an era.

An alternative procedure is to measure the passive value robustness by using an average utility estimate across all epochs. This would produce an additional tradespace to be explored, and we get an average Pareto set.

5.3.6 Era Construction for the Offshore Construction Vessel

We construct eras according to the narrative storytelling approach applied by Gaspar et al. (2012). The reason for using storytelling is that we capture the stakeholder expectations. The eras as such is therefore only based on the expectations of a hypothetical customer. By creating eras according to a narrative, we allow the stakeholders to include likely causal relationships between the epochs as the era progresses. For example, it is more likely that fibrerope technology is developed when difficulties with operating conditions relating to deep waters and large modules is experienced. Further, technology levels should not decrease, meaning that eras with fibrerope technology developed in one epoch, and then disappearing in the next epoch, should not be considered. Handpicking epochs that suit our needs allow us to incorporate the relation between several uncertainties, and focus on plausible phenomena. Note that for each era in this case, the first epoch will be Epoch 3. The reason is that this epoch describes the initial conditions, where we assume an IMR contract is secured. The eras are specified below. The exact values each epoch variable takes in each era, is given in Appendix C.

- **Era 1**
  After the initial IMR contract, the *oil price drops* to 10 [$/bbl] for the next five years. The *oil price* quickly responds to increasing demand by jumping to 100 [$/bbl], while *deep water* capabilities (3000 meters) become a requirement. The *oil price decreases* to 70 [$/bbl], while new field developments occur on medium depths (2000 meters) as *tie-ins* to existing fields. Finally, the *oil price* hits 100 [$/bbl].

- **Era 2**
  After the initial IMR contract, the *oil price falls* to 40 [$/bbl], while the typical *subsea modules increase* to 250 tonnes. The next period sees an *oil price* at 10 [$/bbl], while *module sizes* stay the same size. *Oil prices* thereafter start rising each period, hitting 70 [$/bbl], while *module sizes increase* further to 300 tonnes.

- **Era 3**
  After the initial IMR contract, the *oil prices keep stable* for the rest of the life cycle, expect for a slight fall to 40 [$/bbl] after ten years. *Module sizes increase* rapidly to 300 tonnes from the second period and on, while the *water depth increases* after ten years, and further to 3000 meters for the final contract period. After some time at deep water, *fibrerope technology* is finally developed in the final period.

- **Era 4**
  After the initial IMR contract, the *oil price* rise to 100 [\$/bbl], while *module size* rapidly increase to 300 tonnes as larger systems are built. *Tie ins* to existing fields become more common, and at the same time *water depths* increase to 3000 meters in the third period. At the same time, *oil prices drop*, first to 40 [\$/bbl], before increasing to 70 [\$/bbl] for the fourth period. *Fibrerope technology* is finally developed as a response to large modules and deep waters in the fourth period.

- **Era 5**
  After the initial IMR contract, the *oil price* quickly increases to 100 [\$/bbl], while *module sizes increase* to 300 tonnes, and *water depth increase* to 3000 meters. A large amount of fields are built as *tie-ins*, as they are too marginal to be independently developed. Next, *oil prices collapse*, but increases slightly to stabilize at 40 [\$/bbl]. *Subsea modules* revert back to smaller sizes, due to the high focus of using proven technology when meeting bad times. No initiative to develop *fibrerope technology* make it to the market.

5.3.7 Life Cycle Path Analysis for the Flexible Offshore Construction Vessel

The life cycle analysis constitutes the last step of the Responsive Systems Comparison method. Here, we evaluate the economic performance of the vessel through its lifetime by using Monte Carlo Simulation. The objective in this case is to assess the value of flexibility. This will be done by comparing the economic performance of an inflexible design with the performance of a flexible version of the same design. This life cycle path analysis thus represents an example of a Real Options Analysis. Flexibility will be introduced through enabling transition paths between points in the design space. This fulfills the purpose of a real options screening model and allows us to bypass the problems faced by real options *in* systems, as it was called in Wang and de Neufville (2004).

The analysis in this section represents a break from the six first steps presented in this chapter, as the methodology applied stems partially from finance, in addition to the systems engineering paradigm. This causes a diversion from value quantified through performance attributes. Instead we now use net present value (NPV) as the main estimate of value. The life cycle path analysis applies MCS, which while it is based upon simple principles outlined in Chapter 3, becomes computationally costly when many designs are tested. We therefore choose to focus this analysis on single point designs that were found to be good solutions in the earlier parts of the analysis.

For the MCS model, we use a mean-reverting process as a base for the fluctuations of the time charter rates. There is thus an underlying normal distribution connected to the time charter rates. The mathematical expression for the mean-reverting process is given in Equation 3.2. Mean-reverting processes capture the important microeconomic concepts of supply and demand. As rates rise, more supply in the form of vessels will enter the market causing a reduction in prices. This is seen as a sound basis for fluctuations of prices in a market. However, as the contracts are all agreed for 5 years, the time charter rate as simulated for the initial year of a contract will be taken as the rate for the whole of the five year contractual period. In this simulation model we have not accounted for any direct effect of the oil price on the rates. However, oil prices indirectly affect the expected time charter rate, as it influences the probability of winning a specific contract. This relationship was modeled in Step 3 of the RSC method, and it is shown in Figure 5.2.

The simulation of time charter rates is based on indicative day rate data values supplied by Ulstein International. The standard deviations and the mean-reversion rates of the mean-reverting process are first set to comply with the expectations of the ship owner mentioned in Section 5.1.1. Subsequently they are tuned to get a realistic distribution of the output. The mean time charter rate for each market is based on the initial time charter rate. Appendix B shows the exact rates and stochastic parameters applied.

In the calculation of NPV, a discount rate of 20 percent is applied. This assumption can greatly influence the NPV estimates, as higher discount rates makes the future profits less important. Portfolios of other assets could potentially be used to replicate the payoff of the system, thus helping us estimate more realistic discount rates (de Neufville and Scholtes, 2011).

Inflexible Design

We first simulate the NPV for an inflexible design i, letting it select the feasible contract with the maximum NPV for each epoch e, as shown in Equation 5.20.

$$NPV_i, e = \sum_{t=e_{start}}^{e_{end}} \frac{D_O \cdot \max_{m \in M^*_{ie}} (TC_{me}) - 365 \cdot (C_{it}^{O,daily} - C_{it}^{C,daily})}{(1+r)^{t-1}} \tag{5.20}$$

Here, we calculate the NPV for a vessel i in epoch e, which for each epoch selects the contract in market m with a maximum day rate TC, from a set of feasible markets M^*_{ie} in epoch e. D_O refers to the number of days per year the vessel is operative. e_{start} and e_{end} refer to the start year and end year of epoch e. $C_{it}^{O,daily}$ refers to the daily OPEX of vessel i in year t. Similarly, $C_{it}^{C,daily}$ refers to the daily CAPEX. r is the discount rate.

Flexible Design

To enable the valuation of a flexible design, we assume that transitions between alternative designs are allowed. By a transition we mean that a vessel initially presented as a Design A, is retrofitted to be presented as a Design B. The transition thus represent the removal of some systems, and the installation of some other systems on board the vessel. Through the process of transitioning between two designs, sets of real options are exercised. We can view the removal of equipment as an exercise of a put option, while the installation of new systems can be seen as an exercise of a call option. The flexibility gained by allowing transition, shall enable the vessel to switch markets if the current vessel configuration is unable to meet contract requirements, or if other contracts provide more value. Transitions between all designs are not allowed. As this work is focused on functional flexibility, we assume that altering the vessel geometry, for example by elongation, is not an available real option. Thus, it is necessary that the next stage Design B has an equal total deck area as the initial Design A. Further, the cost of a transition C^T between design i and j, should it be a feasible transition, is given by Equation 5.21.

$$C^T_{ij} = h \cdot \sum_{k=1}^{K} C^E_{ik} + g \cdot \sum_{l=1}^{L} C^E_{jl} \tag{5.21}$$

K is the set of equipment being removed from design i, while L is the set of equipment being installed to transition into design j. C^E denotes the investment cost in equipment. h expresses the factor for the cost of removing a system as a part of the equipment cost, while g expresses the factor for the cost of installing new equipment. Here we assume that the costs for a transition is the total cost associated with flexibility, which means that we neglect that the maritime platform will likely be more costly if flexibility is allowed. Another important simplification made in quantifying the costs of each transition, is the assumption that the costs of equipment is static.

To avoid the above assumptions, we could argue that a more conservative transitioning rule should be applied. For example, the systems it is possible to install at later stages of the lifetime, will depend on whether the vessel has been prepared for exactly this added functionality. If the hull has been strengthened with an upgrade from a 100 tonnes crane to a 200 tonnes crane in mind, a transition to a design with a 300 tonnes crane would not be possible. Similarly, the cost of installing a specific subsystem as a modular system is likely more expensive than integrating it into the design. However, the integrated subsystem will make it more difficult to implement changes at a later stage. To simplify, we only make the distinction between allowing flexibility, and not allowing flexibility. Thus we do not have to quantify the costs of preparing the hull for each individual real option. This reduces the complexity of the problem immensely, as well as the complexity associated with the coupling of such preparation costs.

Next, the conditions for triggering a transition must be defined. Real options should only be exercised if the corresponding transition leads to added value. Formulation of triggering conditions enables simulation of a flexible design under otherwise equal conditions as the inflexible design. In this case, we trigger real options through a specific transition if this will maximize the ENPV of the current epoch. A summary of transition and triggering rules for this case study are given in Table 5.8.

Table 5.8: Conditions for making a transition between two designs.

Transition rule	Transitions for a vessel are permitted if the design being transitioned to, has an equal total deck area as the design being transitioned from.
Triggering rule	A transition is triggered (ie. a set of real options is exercised) if this transition maximizes the current epoch NPV.

When allowing transitions according to the triggering rules, we need to make alterations to the expression for the NPV. The transition cost need to be taken account for. The modified NPV expression for evaluating the economics of a strategy in which design i is being transitioned into design j, is shown in Equation 5.22. The OPEX will be altered to the OPEX of the new design, while the CAPEX paid will always be the CAPEX for the initial design. The reason is that OPEX depends on the current systems on board, while CAPEX consists of the initial investment costs. Below, we use the index d in the CAPEX term $C^{C,daily}$ to specify that we mean the initial design d. It is assumed that the entire costs of a retrofit from design i to j is all accounted for in the year the transition is made. Here, we maximize TC across the set of feasible contracts M^*_{je}, that can be achieved for the design j being transitioned into. The number of operative days per year, D_O^{FLEX} will be less than D_O to account for the time spent retrofitting the vessel.

$$NPV_{ije}^{FLEX} = \sum_{t=e_{start}}^{e_{end}} \frac{D_O^{FLEX} \cdot \max\limits_{m \in M^*_{je}} (TC_{me}) - 365 \cdot (C_{jt}^{O,daily} - C_{dt}^{C,daily}) - C_{ij}^{T}}{(1+r)^{t-1}} \tag{5.22}$$

Making the decision of whether or not to exercise the flexibility thus becomes a question of maximizing the NPV for the current epoch, by comparing the transition paths from design i to all alternative designs j in the set of feasible transitions J^*_i, with the alternative of not exercising flexibility at all. The triggering rule for flexibility boils down to Equation 5.23, for each epoch e.

$$NPV_e = \max(\max_{j \in J^*_i}(NPV_{ije}^{FLEX}), NPV_i) \tag{5.23}$$

For the next transition, allowing design j to be altered, we apply the same logic presented above. This is repeated until the last epoch in the era. Finally, the NPV of all epochs included in the era selected for this simulation run are summed, yielding a total NPV for the lifetime of the vessel.

This MCS model enables the identification of transition paths providing potential strategies for how the design can evolve, adapting to new contexts by exercising flexibility. Note that this approach does not optimize the result. The simulation provides the overview of many possible NPV outcomes both for a flexible and an inflexible design, making it possible to derive an estimate of the value of flexibility, as shown in Equation 3.4. In a practical sense, this becomes the upper bound for the price we should pay to prepare the vessel for flexibility. The output target curves will serve as an illustration to whether flexibility increases the upside, reduces the downside, or both.

5.4 Model Assumptions

Throughout this chapter, a large amount of assumptions are been made. While many of the simplifications may seem simple to circumvent and it may be relatively easy to implement into the model, they all add to the complexity of the problem. Still, being aware of these drawbacks increases our understanding of the capabilities of the model and the results. Thus, we state all assumptions outright in the list below:

1. **Value proposition**
   The value proposition of the stakeholder is defined through value attributes mapped onto performance attributes.

2. **Performance attributes**
   All performance attributes are weighted equally in the utility function.

3. **Design variables**
   We assume that all possible designs are defined through a set of design variables and constrained by system dependencies, capacity constraints and contract requirements.

4. **Vessel size**
   The size of the vessel is represented through the total deck area, which is between 1000 m^2 and 2000 m^2.

5. **Cost function**
   The costs (CAPEX) are determined as a linear function of total deck area and design variables. OPEX is calculated as a function of CAPEX. Both OPEX and CAPEX are deterministic.

6. **Epoch variables**
   A set of epoch variables capture uncertainty regarding the oil price and technology. The consequence for the utility function is found through a mapping of contractual requirements and contractual availability. If a vessel matches no current contractual requirements, its utility for the current epoch is set to 0. Epochs last five years.

7. **Probability of winning a contract**
   The probability of winning a contract is derived from the current availability of contracts, given that the design matches the requirements of the contract.

8. **Era construction**
   Eras are constructed according to stakeholder preferences and future expectations. They last 25 years, or five consecutive epochs.

9. **Time charter rates in simulation**
   The time charter rates move according to a mean-reverting process sampled every five years (epoch length). Volatility and rate of mean-reversion are tuned, and in accordance with the expectation put forth in Section 5.1.1. The mean time charter rate is set equal to the initial time charter rate.

10. **Discount rate**
    The discount rate for future earnings is 20 percent.

11. **Era selection for simulation runs**
    For each simulation run one era is used as a basis. The era is selected at random, with equal probabilities assigned for each era.

12. **Design transition**
    Transitions between two point designs is allowed if the total deck area symbolizing vessel size, is equal.

13. **Flexibility exercise cost**
    The cost of the feasible transitions are based on the cost of the equipment being removed, and the equipment being installed.

14. **Flexibility exercise time**
    The time it takes to exercise flexibility is set equally for any transition path.

15. **Triggering rule**
    A specific transition between two point designs is done if the transition is feasible, and the transition maximizes the current epoch NPV.

Chapter 6

Results and Discussion

In this chapter, we present the results from the case study analyzed in Chapter 5. Results from tradespace exploration for individual epochs will be contrasted with the results of the multi-epoch analysis and the multi-era analysis. Finally, life cycle path analyses are performed for some of the most interesting design alternatives, in which flexibility is evaluated. Underway we show good design concepts found from the results. Finally, we discuss the results in light of the findings of the model. We also discuss the industrial implications of the model and its findings.

6.1 Tradespace Exploration

We generate tradespaces for each epoch, and plot each design according to their performance and their costs. As Epoch 3 describes the initial five year period regardless of how the future may materialize, we show the tradespace for Epoch 3 in Figure 6.1.

Designs along the Pareto front for this epoch will generate a lot of value initially. If we for a moment neglect all future uncertainty, one of the designs on this Pareto front would be very good choices. They adhere to the overall value proposition of the ship owner, and are capable of performing operations required by the initial inspection, maintenance and repair (IMR) contract.

An interesting observation made from Figure 6.1 is that the Pareto front does not cover the most expensive alternatives. One could easily be lead to think that the most specialized, most expensive vessels would have the advantage of economies of scale. Rather than being successfully multi-functional, it seems the term "multi-useless" fits these vessels better. The reason it is hard to exploit economies of scale may be related to the fact that the more expensive vessels have more specialized equipment that is perhaps not utilized for all operations. Still such equipment would have to be paid for even when it is not used. Ultimately the dominance of the less costly vessels goes back to the affordability criterion that was introduced as part of the value proposi-

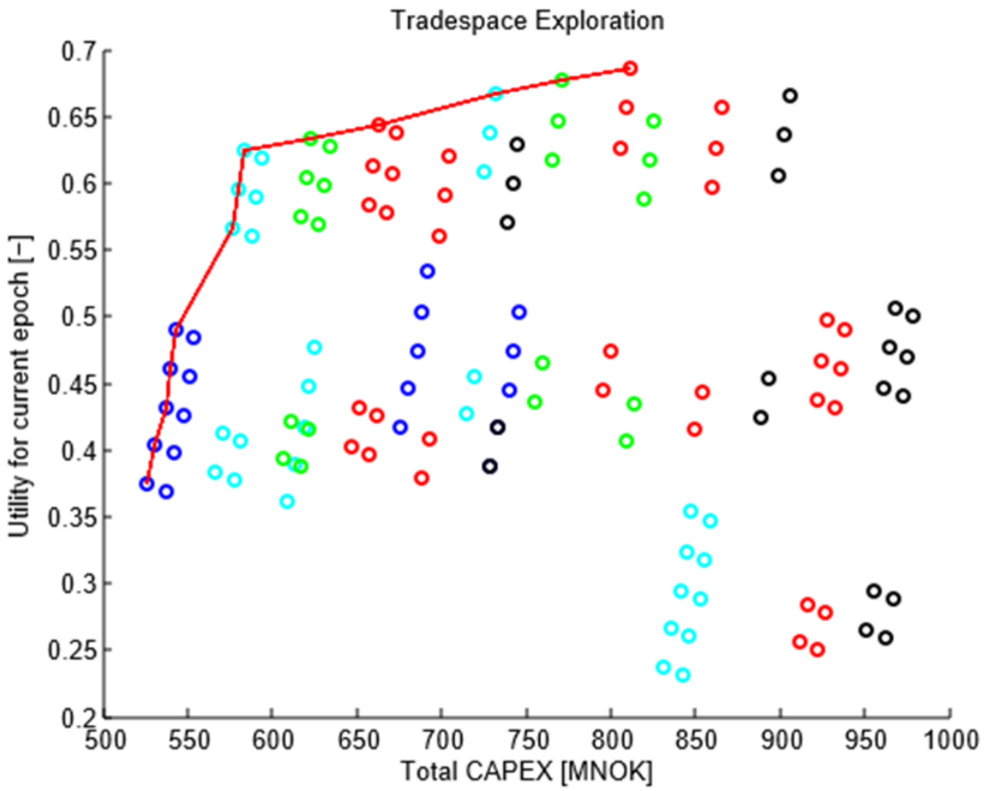


Figure 6.1: Tradespace for Epoch 3. The Pareto front is shown in red. The colors adhere to the legend in Table 5.7.

tion. Table 6.1 provides key utility and cost data for some of the designs that are found along the Pareto front in Epoch 3, namely Design 51 and Design 106.

Table 6.1: Comparing key tradespace data for Design 51 and Design 106 in Epoch 3.

Design	Utility	Total CAPEX [MNOK]
Design 51	0.6860	811.76
Design 106	0.6433	662.96

Table 6.1 shows that there is a limited amount of payoff associated with the additional costs of Design 51 compared to Design 106. One could speculate whether or not such an increase in the utility will be worth about 150 MNOK more when considering the vessel performance in Epoch 3. This question illustrates perfectly the point of using tradespaces. Tradespace exploration facilitates a wide discussion about the tradeoffs the decision maker face when selecting a design.

Figure 6.2 shows the configuration of equipment onboard Design 51, while Figure 6.3 shows the configuration of Design 106. Table 6.2 shows the match of these vessels with the alternative contracts in Epoch 3.

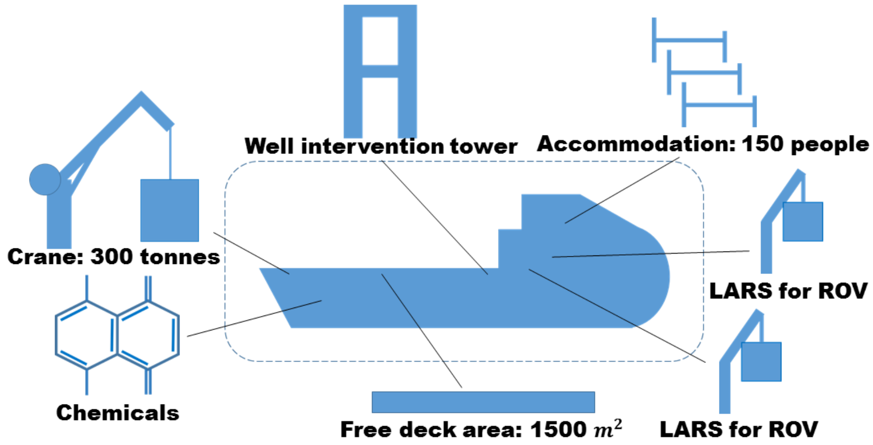


Figure 6.2: Vessel Configuration for Design 51.

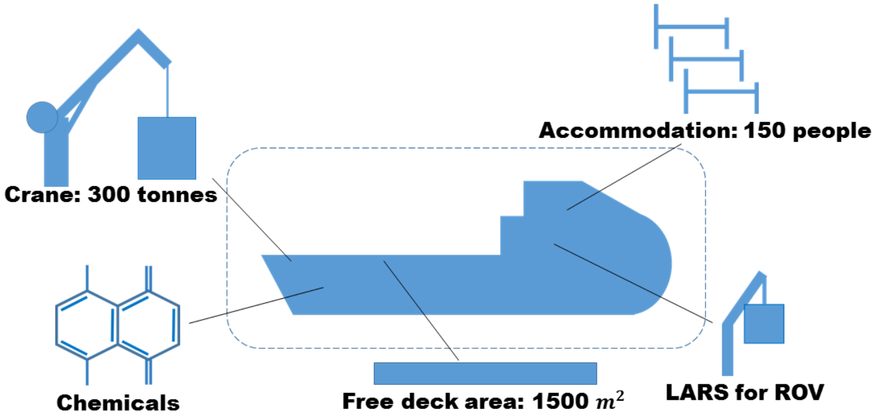


Figure 6.3: Vessel Configuration for Design 106.

Table 6.2: Vessel - contract match in Epoch 3.

Contract	Design 51	Design 106
IMR	Yes	Yes
SURF	Yes	Yes
LWI	Yes	No
DSV	No	No

The consequence of Table 6.2, is that a retrofit transitioning Design 106 to Design 51, would enable the vessel to take light well intervention (LWI) contracts. A transition between Design 51 and Design 106 is allowed as they have the same total deck area. Other transition paths could enable the vessel to take diving support (DSV) contracts, while IMR and subsea installation, umbilicals, risers and flowlines (SURF) contracts are readily available for both Design 51 and Design 106 in Epoch 3. We get back to discussions of such flexibility in the section on the life cycle path analysis.

6.2 Multi-Epoch Analysis

Through the multi-epoch analysis we gain an understanding of which designs that excel in handling contextual and perceptual changes without being altered. Even though the purpose in this work is the investigation of flexibility, these results are important as they allow the identification of passive value robustness. We can compare these passively value robust designs with vessels thriving in individual epochs that need to be flexible to achieve value robustness. As mentioned in Chapter 5, the multi-epoch analysis can either include all epochs, or use a selection of epochs contained in the constructed eras. Then we call it a multi-era analysis.

For the multi-epoch analysis we produce a Pareto trace, which shows the frequency with which the individual designs occur on the Pareto front. In our case, only 37 individual designs ever make it on to any Pareto front. Figure 6.4 illustrates the Pareto trace for each design in the design space, with the frequency of occurrence on a Pareto front (the Pareto trace) on the x-axis, and the design number on the y-axis. We clearly see that most designs should not be considered at all if we reason on the basis of Pareto trace, as they totally drop out of the discussion on passively value robust designs. An obvious drawback is that good designs close to the Pareto front are left out.

As a complement to the use of Pareto trace, we can evaluate the designs in a tradespace in which we calculate the average utility of each design across all epochs. This approach produces the tradespace shown in Figure 6.5.

Some designs that score well both in terms of Pareto trace, and in terms of average utility across epochs are shown below. Dependent on the stakeholder perceptions, it may be smart to move upwards along the Pareto front to evaluate designs with higher utility. Design 1 maximizes the average utility against a total CAPEX of 744.96 MNOK. Design 1 is shown in Figure 6.6. Design 11 and Design 13 can also be found on this Pareto front. Design 11 is shown in Figure 6.7. Design 13 is shown in Figure 6.8.

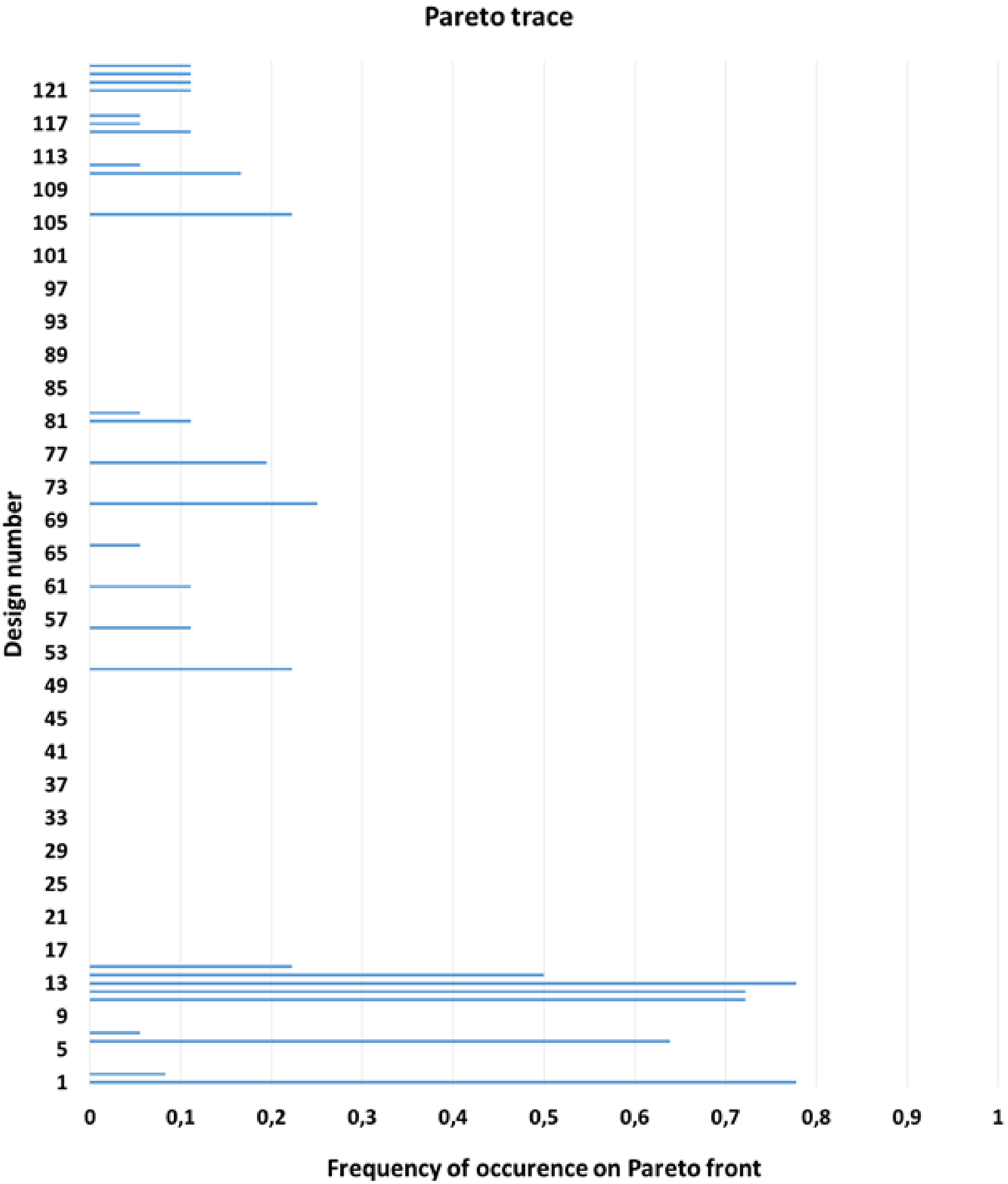


Figure 6.4: Pareto trace for the whole enumerated design space. Frequency refers to the share of epochs in which the design is Pareto optimal.

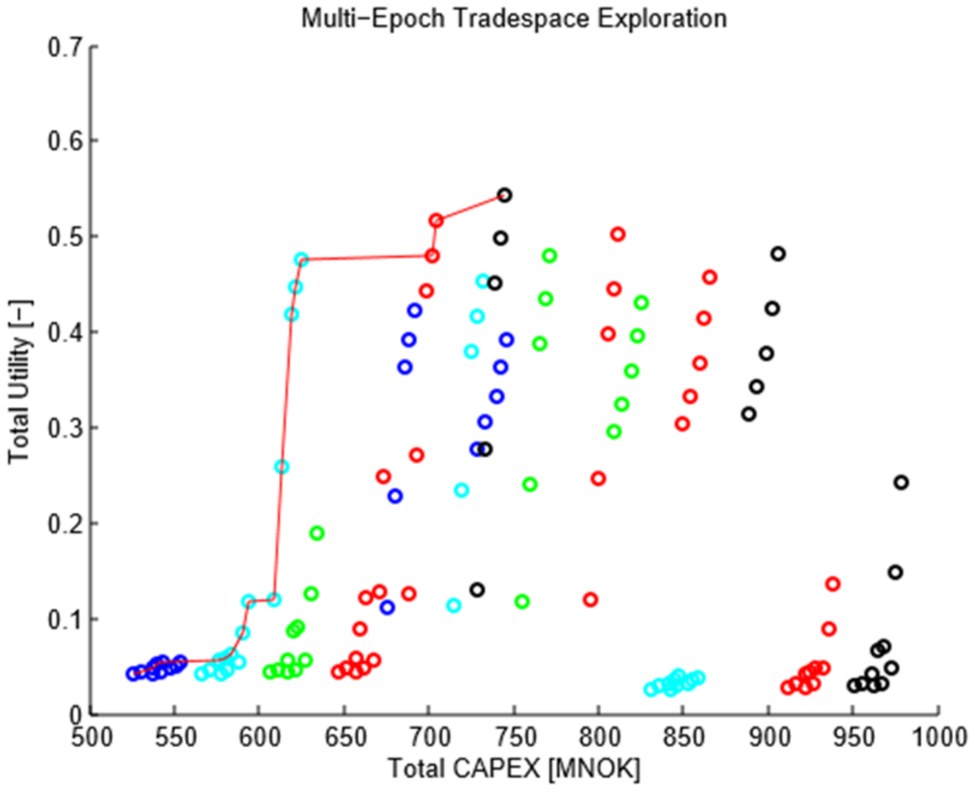


Figure 6.5: Multi-epoch tradespace exploration. Pareto front shown in red. Colors according to Table 5.7.

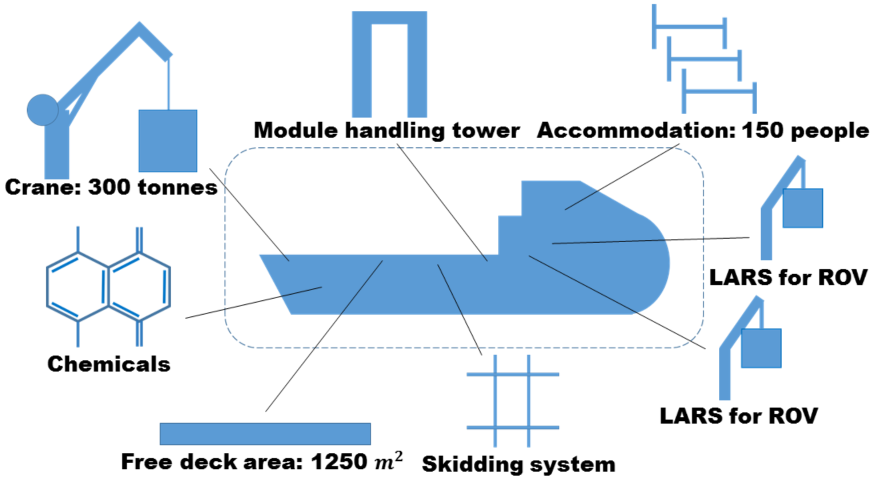


Figure 6.6: Vessel Configuration for Design 1.

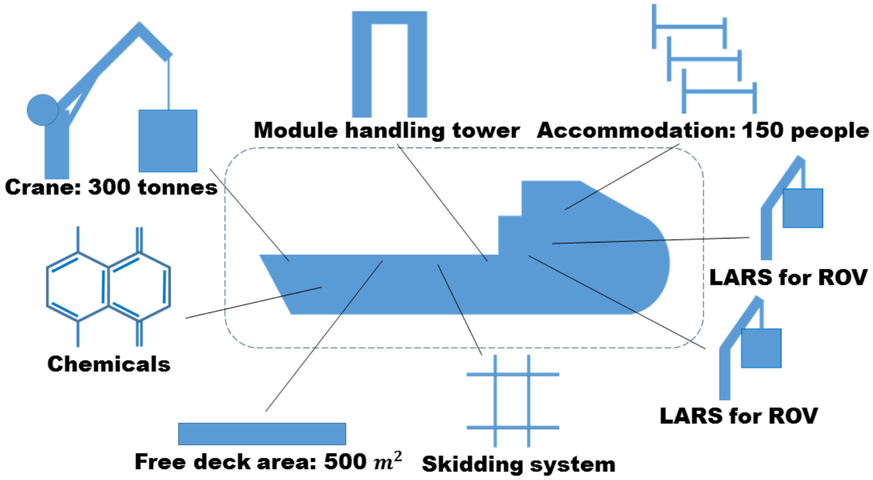


Figure 6.7: Vessel Configuration for Design 11.

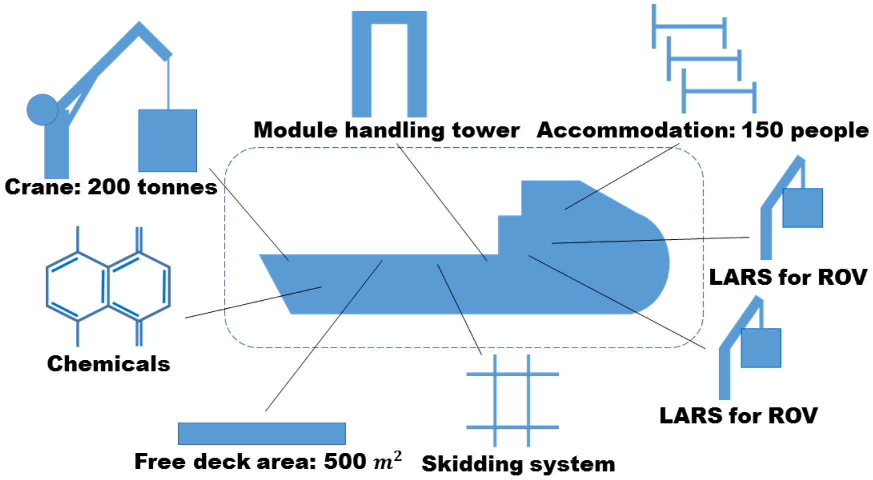


Figure 6.8: Vessel Configuration for Design 13.

In the case of Design 11, an interesting observation is made. Design 13 has a higher Pareto trace, but a lower average utility across all epochs. Design 11 is not Pareto optimal in as many epochs. The only difference between Design 11 and Design 13, is the crane capacity. This means that costly excessive capability is penalized by the Pareto trace. In other words, there is added value in matching the requirements of a contract exactly, instead of exceeding the requirements in the hope that the extra capability will be needed later. Exceedance of requirements can decrease the overall value of the vessel. This point resonates with the earlier discussion of "multi-useless" vessels as an opposite to multi-functional vessels. This argument constitutes a case for flexibility as it rewards the exact fit of vessel and contract, that can be obtained through retrofitting the vessel.

As a final point of discussion in the multi-epoch analysis, we compare the results with a multi-era analysis. We apply the eras constructed in Step 6 of the RSC method. Table 6.3 shows the average utility for the multi-era analysis and the multi-epoch analysis, as well the CAPEX for the designs discussed in Section 6.1 and Section 6.2. The designs maximizing utility are shown in bold. Designs appearing on the Pareto front are shown in italics. The utility for each era takes the average utility across all epochs included in that era.

Table 6.3: Average utility for each era, compared to the average utility from the multi-epoch and multi-era analysis.

	Average utility					**Average utility**		**Total CAPEX [MNOK]**
Designs	Era 1	Era 2	Era 3	Era 4	Era 5	**Multi-era analysis**	**Multi-epoch analysis**	
1	***0.5792***	***0.6042***	*0.5292*	*0.5292*	***0.5292***	***0.5542***	***0.5424***	744.96
11	0.4768	0.4768	*0.4768*	*0.4768*	*0.4768*	*0.4768*	*0.4768*	624.96
13	0.4176	0.4176	0.4176	0.4176	0.4176	*0.4176*	*0.4176*	618.96
51	0.5610	0.5860	***0.5360***	***0.5360***	0.4860	0.5410	0.5020	811.76
106	0.2573	*0.5433*	0.2323	0.2323	0.1287	0.2788	0.1221	662.96

While there are not huge differences between multi-epoch and multi-era results in terms of average utility, one could expect other results if the eras were different. The era construction is strongly dependent on the expectations of the ship owner, and the results will thus likely vary for stakeholders with other perceptions. Decisions made on the basis of multi-era analyses will be more contingent on stakeholder expectations of the future than the results of a multi-epoch analysis.

What has not been accounted for in the multi-epoch and multi-era analysis is the revenue. When we base decisions on performance attributes rather than revenue, we risk losing out on profits. We now turn to redefine our notion of value, to provide a further basis for decision making throughout the vessel lifetime. The focus turns from identification of passive value robustness towards active value robustness and flexibility.

6.3 Life Cycle Path Analysis with Flexibility

In this step, we perform the Real Options Analysis (ROA) within the context of a life cycle path analysis. The lifetime of the vessel is simulated using Monte Carlo Simulation (MCS) to account for uncertainty. In the light of uncertainty, we compare the performance of flexible and inflexible designs.

The analysis so far has not given any weight to the earnings. The revenue side is not accounted for in the value proposition, and not reflected in performance attributes. In this section, we alter our definition of value to an economic measure, namely net present value. Table 6.4 compares how we have treated value robustness so far, with the treatment it is given through the life cycle path analysis with ROA. Further, we show results for the analysis that was presented in Section 5.3.7. The resulting distributions of net present value are all based on 10000 simulation runs.

Table 6.4: Reviewing the contribution to value robustness.

The RSC method (Step 1 - 6)	Evaluating designs according to passive value robustness. Using utility functions based on performance attributes to measure value.
ROA model (Step 7 of the RSC method)	Evaluating designs according to active value robustness, or flexibility. Using NPV to measure value

6.3.1 Life Cycle Path Analysis for Design 1

We first run the simulation model for Design 1. A life cycle path analysis for Design 1 yields the cumulative net present value (NPV) distribution shown in Figure 6.9. In Figure 6.10 we illustrate the NPV distribution of the inflexible Design 1 in a histogram. Similarly, the flexible Design 1 is shown in Figure 6.11.

From Figure 6.9, it becomes evident that flexibility has a value for this vessel. The NPV estimates for the flexible version of Design 1 is almost consistently higher than the NPV estimates of the inflexible Design 1. The risk of losing money in the lifetime perspective (NPV below zero), is reduced from about 45 percent to about five percent. The upside is also increased. As we see from Figure 6.10, the vast amount of outcomes are centered around some peaks in the NPV distribution for the inflexible Design 1. The reason for this is that the events regarding the contracts assigned every five years, are discrete events defined through the epoch variables. It is apparent that the epoch variables accounting for the more disruptive changes in oil price, module size, water depth, tie-in demand and fibrerope technology development has a large say, when it comes to the inflexible design. Forcing the vessel to take a contract it complies with, makes the distribution peak at specific NPV bundles.

In comparison, the flexible Design 1 in Figure 6.11 has a somewhat more smooth distribution showing some resemblance to the normally distributed mean-reverting process of the time charter rates, even though there are peaks here as well. The differences show that flexibility

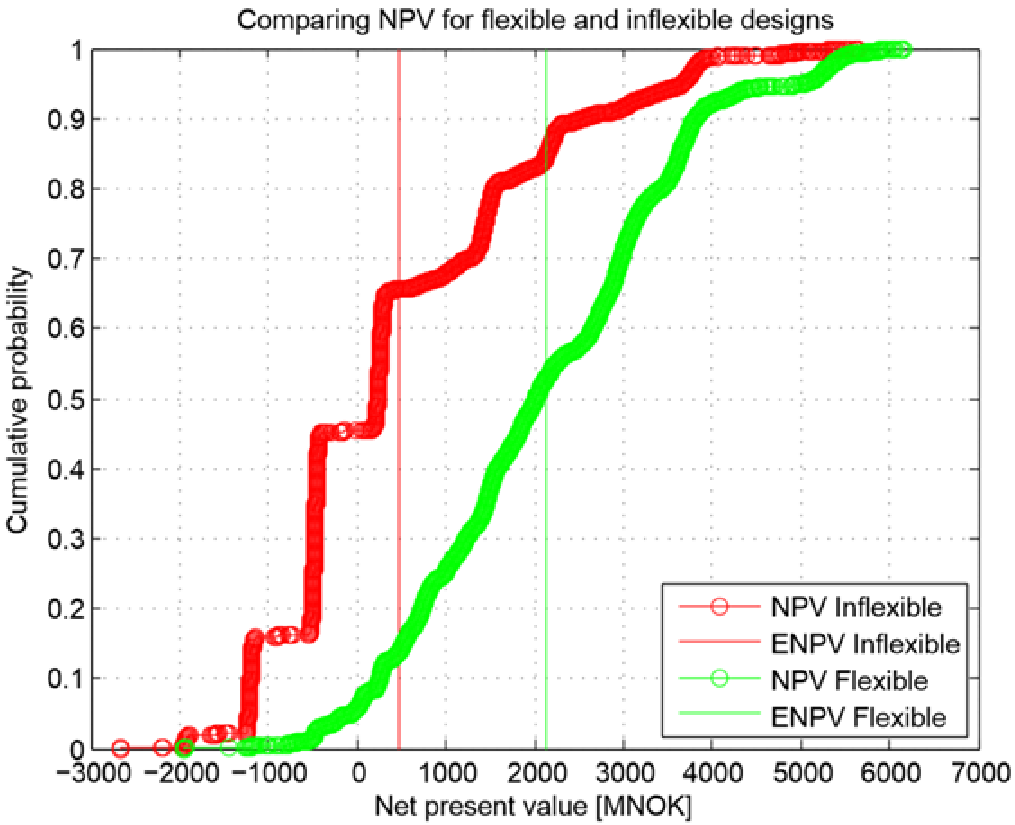


Figure 6.9: Cumulative NPV distribution for Design 1. Red curves show inflexible design NPV, while green show flexible design NPV. Vertical lines illustrate expected NPV.

makes compliance with future requirements much less of an issue, as it becomes possible to adapt the vessel to new requirements. The uncertainty regarding future contractual requirements is effectively mitigated through flexibility. In addition, the comparison of Figure 6.10 and Figure 6.11 illustrates that there is a shift to much higher NPVs, when flexibility is considered. Some key data gathered from the NPV distribution are given in Table 6.5.

Table 6.5: NPV data for Design 1.

	Net present value [MNOK]		
	Minimum	**Maximum**	**Expected**
Inflexible	-2663	5682	452
Flexible	-1953	6210	2105

According to Equation 3.4, Table 6.5 will indicate that flexibility is worth more than 1600 MNOK, which justifies huge investments in making the vessel flexible. A flexible strategy for this vessel, gathered from one run of the MCS model in which Era 1 occurs, is presented in Table 6.6.

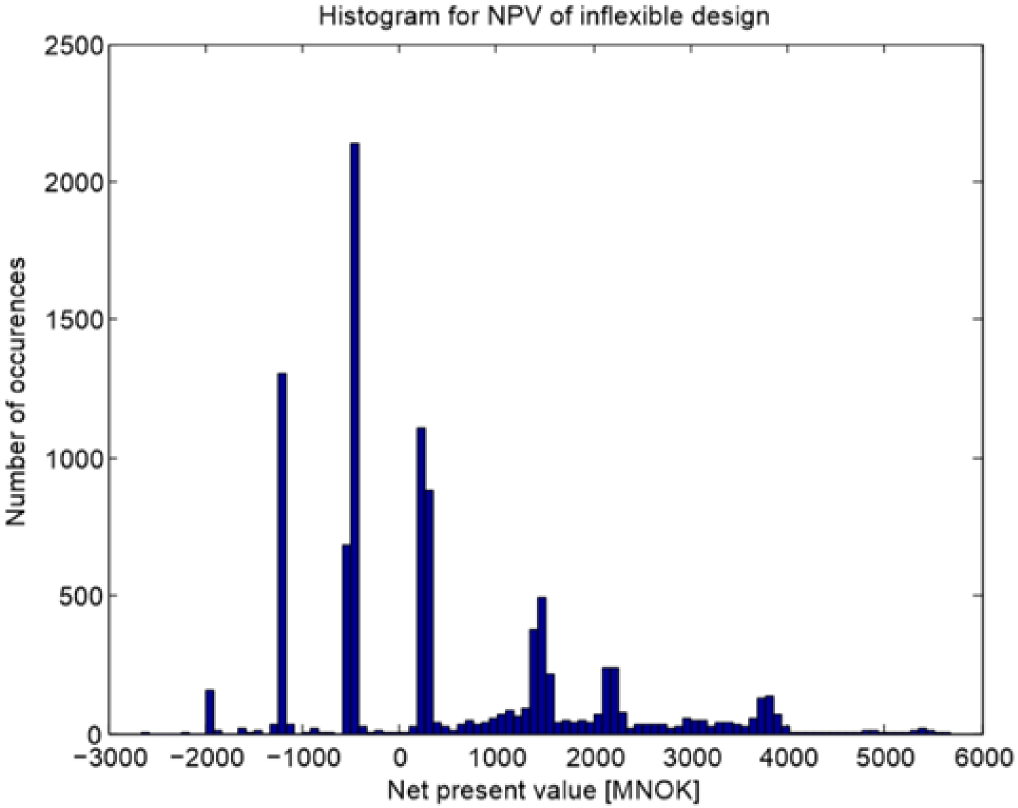


Figure 6.10: NPV distribution for inflexible Design 1.

Table 6.6: Possible flexible design strategy for an initial Design 1 in Era 1.

Epochs	**Contracts**		**Design transition**
	Inflexible	**Flexible**	
3	IMR	IMR	1
1	SURF	SURF	None
28	SURF	SURF	None
51	IMR	SURF	36
52	IMR	SURF	None

We observe that the inflexible vessel is assigned to either IMR or SURF contracts. In the third epoch, Epoch 51, the requirements for SURF contracts are altered to include a J-lay tower, rendering the inflexible design incapable of taking SURF contracts. When flexibility is allowed, the vessel transitions from Design 1 to Design 36 at this time. This enables the vessel to meet the contractual requirements of SURF contracts for the remainder of the lifetime. This retrofit is equivalent to exercising the set of real options presented in Table 6.7.

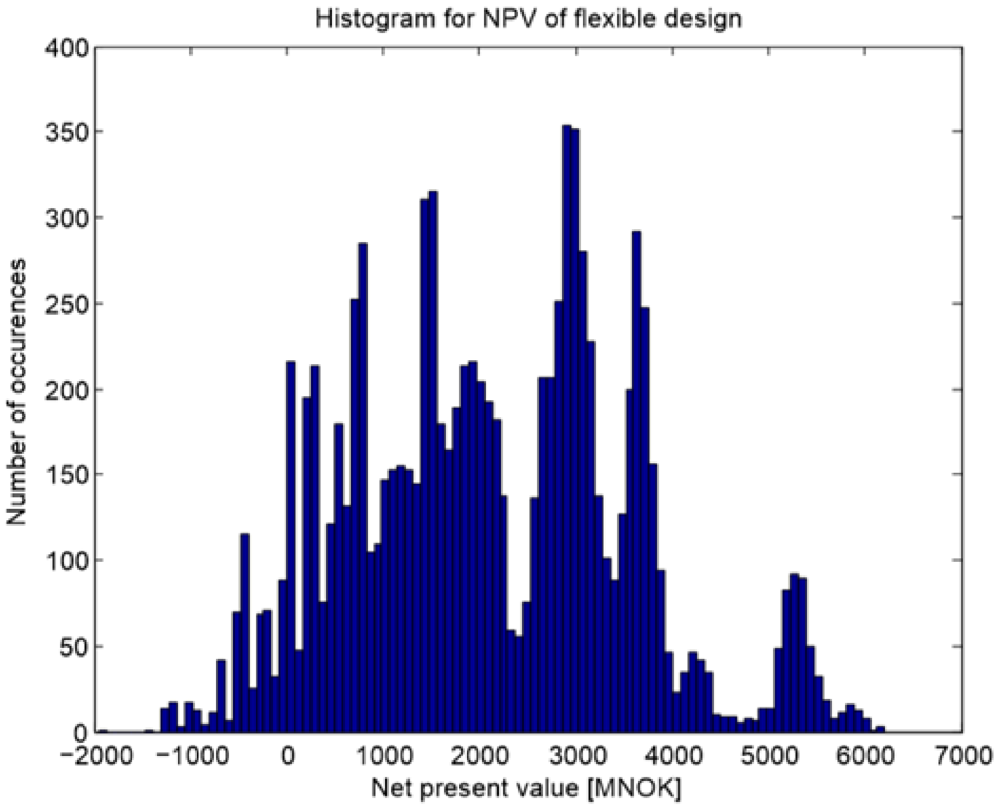


Figure 6.11: NPV distribution for flexible Design 1

Table 6.7: Set of real options for transition between Design 1 and Design 36.

Put option	Removing from vessel: Module handling tower, skidding system
Call option	Adding to vessel: J-lay tower, carousel

One of several alternative trajectories that is observed for an initial Design 1, is to transition into Design 16. This implies an exercise of the same set of put options as the example simulation run described in Table 6.6, but exercise of a call option on a saturated diving system. Configurations for Design 16 and Design 36 are shown in Appendix D.

6.3.2 Life Cycle Path Analysis for Design 11

Design 11 has a high Pareto trace, scoring quite well in terms of passive value robustness according to the multi-epoch analysis. We therefore test its economic performance in a life cycle perspective. Figure 6.12 show the cumulative NPV distribution for Design 11. Figure 6.13 and Figure 6.14 show the NPV histograms for the inflexible and flexible versions of Design 11 respectively.

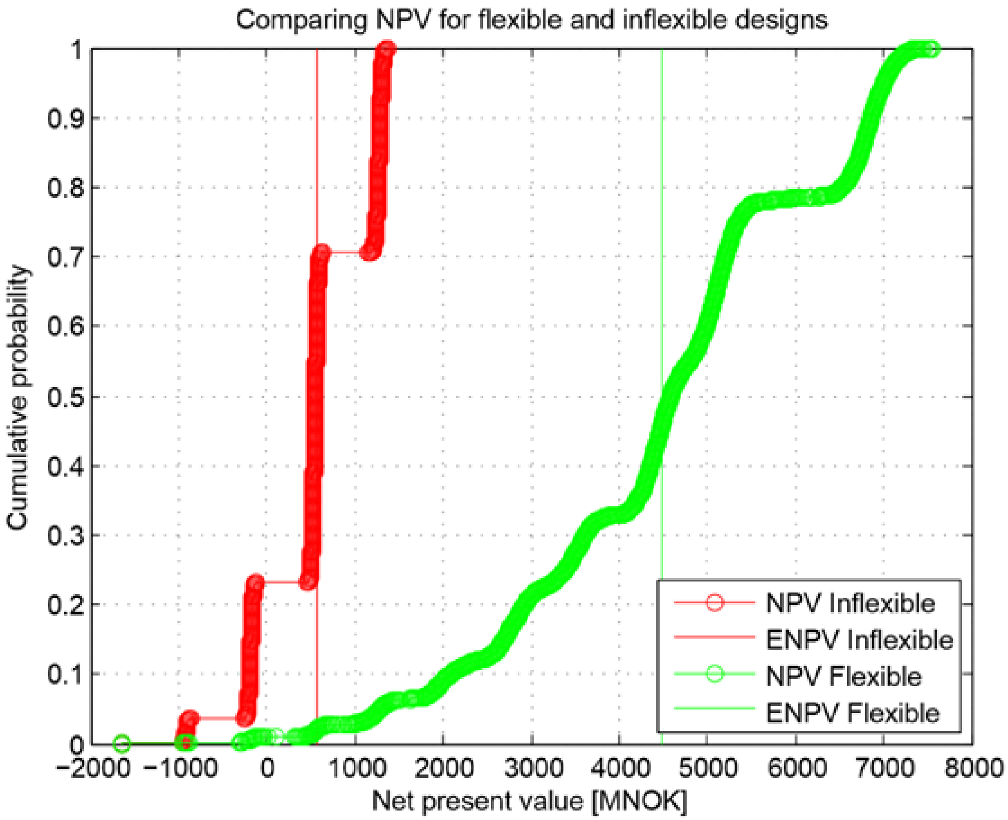


Figure 6.12: Cumulative NPV distribution for Design 11. Red curves show inflexible design NPV, while green show flexible design NPV. Vertical lines illustrate expected NPV.

We observe from Figure 6.12 that flexibility massively increases the upside. It reduces the risk of losing money to a near zero, from more than 20 percent. In Figure 6.13 we observe that the impact of the current epochs is massive on the NPV of the inflexible design. The output distribution is highly discontinuous as the feasibility of the inflexible Design 11 for several contracts is affected severely by the underlying era structure. For the flexible Design 11 in Figure 6.14 the peaks are evened out somewhat, even though the effect of the discrete changes between epochs is still visible. The shift towards higher NPVs is substantial when the design is flexible. Some key data for the NPV of Design 11 is shown in Table 6.8.

Table 6.8: NPV data for Design 11.

	Net present value [MNOK]		
	Minimum	**Maximum**	**Expected**
Inflexible	-1642	1372	557
Flexible	-1642	7526	4514

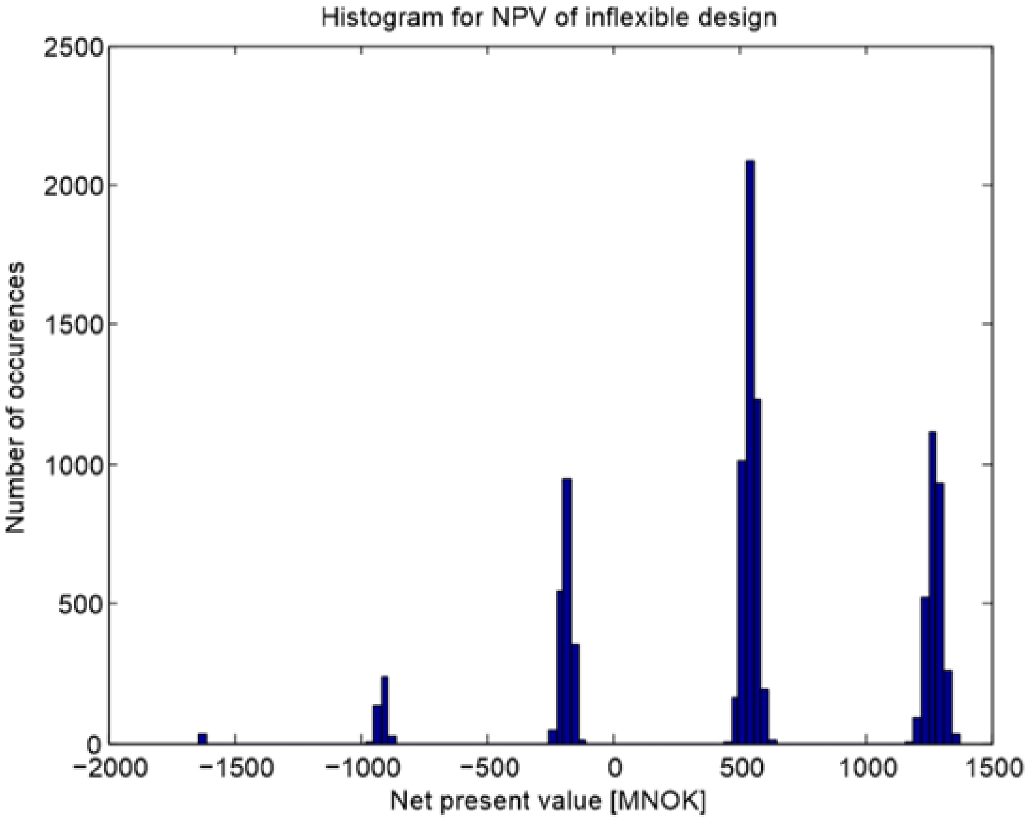


Figure 6.13: NPV distribution for inflexible Design 11.

Several results from this analysis are striking. First, the flexibility seems to be tremendously valuable. The value of flexibility seems to exceed 3900 MNOK! The reason flexibility is so valuable in this case, is that it enables the small vessel with low costs to take a profitable LWI contract, rather than the IMR contract. We see that flexibility makes this vessel perform better than Design 1, in terms of NPV. Comparing the inflexible versions, the opposite is true. The inflexible Design 11 will have trouble meeting the requirements of SURF contracts due to insufficient free deck area, while the inflexible Design 1 can enter this market, unless a J-lay rig becomes a requirement. A flexible strategy associated with one simulation run for this initial design is shown in Table 6.9.

The flexibility enables the vessel to take LWI contracts that pay much better than IMR contracts normally. The set of real options that are associated with the transition between Design 11 and Design 61, is shown in Table 6.10. The configuration of Design 61 is shown in Appendix D.

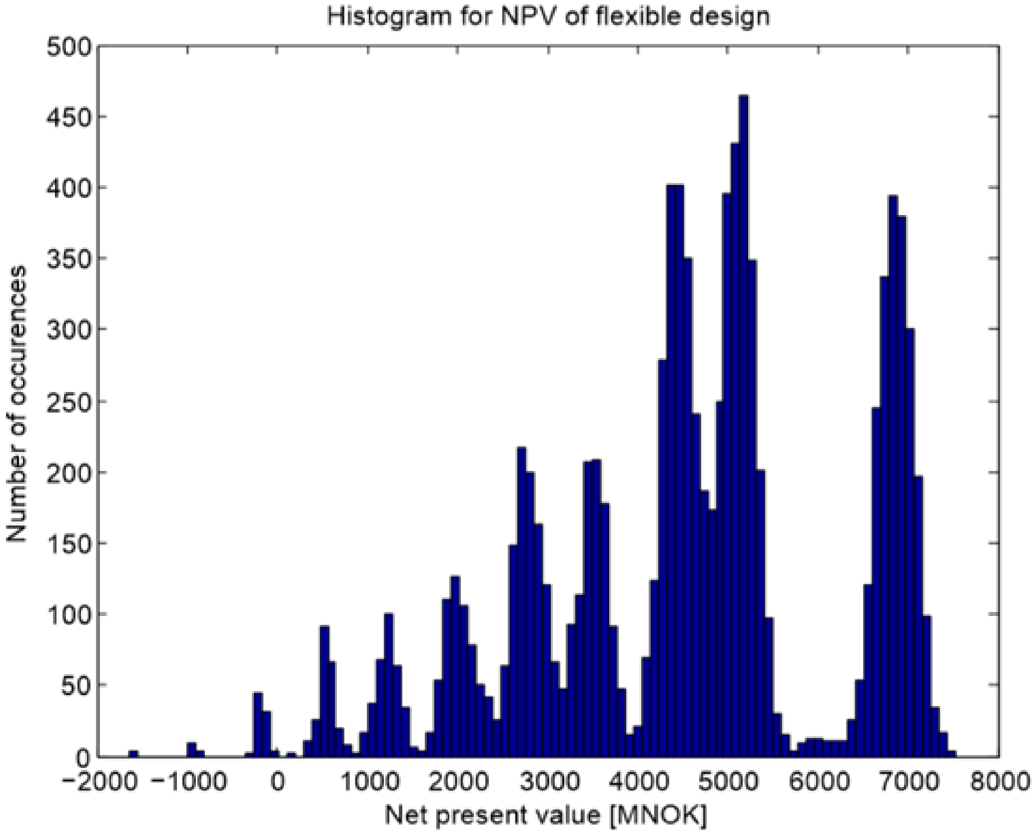


Figure 6.14: NPV distribution for flexible Design 11.

Table 6.9: Possible flexible design strategy for an initial Design 11 in Era 1.

Epochs	**Contracts**		**Design**
	Inflexible	**Flexible**	**transition**
3	IMR	IMR	11
1	IMR	LWI	61
28	IMR	LWI	None
51	IMR	LWI	None
52	IMR	LWI	None

Table 6.10: Set of real options for transition between Design 11 and Design 61.

Put option	Removing from vessel: Module handling tower, skidding system
Call option	Adding to vessel: Well intervention tower

Performing this analysis, we observe divergence in the results. Design 11 was supposed to be passively value robust according to the multi-epoch analysis. However, this life cycle path analysis shows that its performance as a rigid, unchangeable vessel that only takes IMR contracts is quite bad. This indicates that the Pareto front alone does not necessarily provide us with a robust background for decision making. When the Real Options Analysis is applied however, the flexible Design 11 emerges as a very profitable alternative, indicating that Design 11 should be seen as an actively value robust vessel. While one reason may be that profitability was neglected as a value attribute in Step 1 of the RSC method, this alone does not explain the differences between the results. The differences in results observed, help us see the value of applying multiple methodologies, as information that may be obscured in some results are revealed through another approach.

6.3.3 Life Cycle Path Analysis for Design 51

Design 51 was found to drop out of the Pareto front on many occasions in the multi-epoch analysis and had a low Pareto trace. However, as we see from the discourse on Design 11, this does not necessarily mean that Design 51 is a bad design. It does quite well in the only context we consider known, Epoch 3, which is the epoch representing the initial IMR contract. The NPV distribution for Design 51 is shown in Figure 6.15. Figure 6.16 and Figure 6.17 illustrate the NPV distribution of an inflexible and a flexible Design 51 respectively, as histograms.

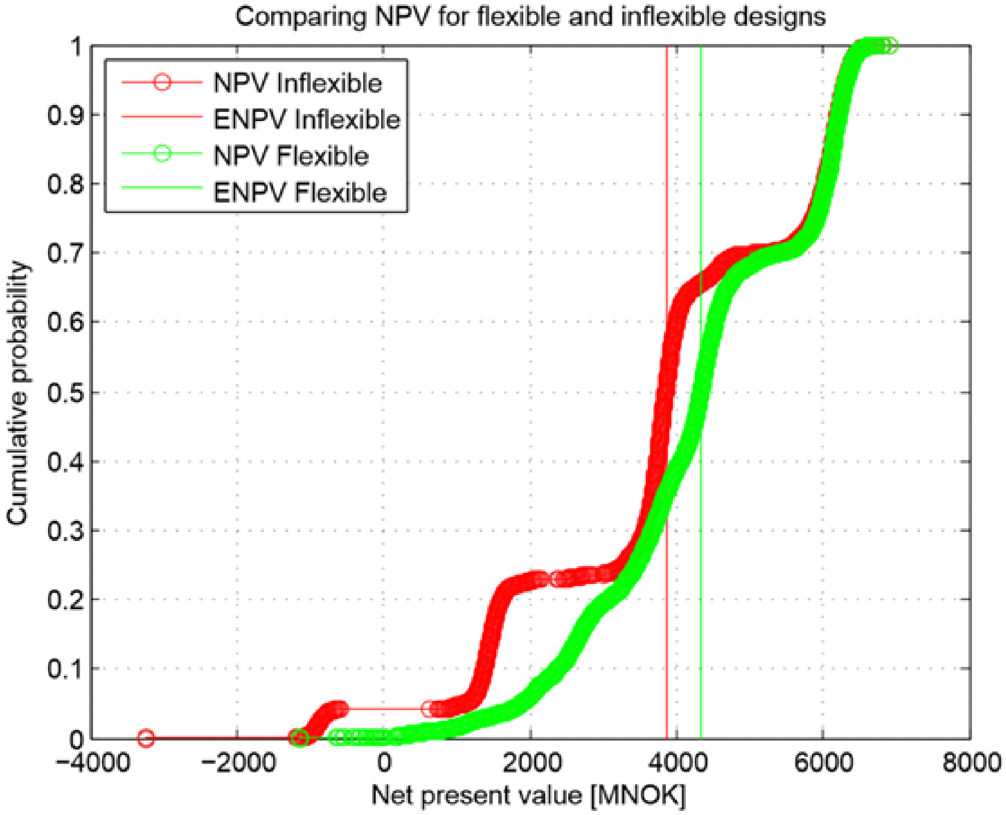


Figure 6.15: Cumulative NPV distribution for Design 51. Red curves show inflexible design NPV, while green show flexible design NPV. Vertical lines illustrate expected NPV.

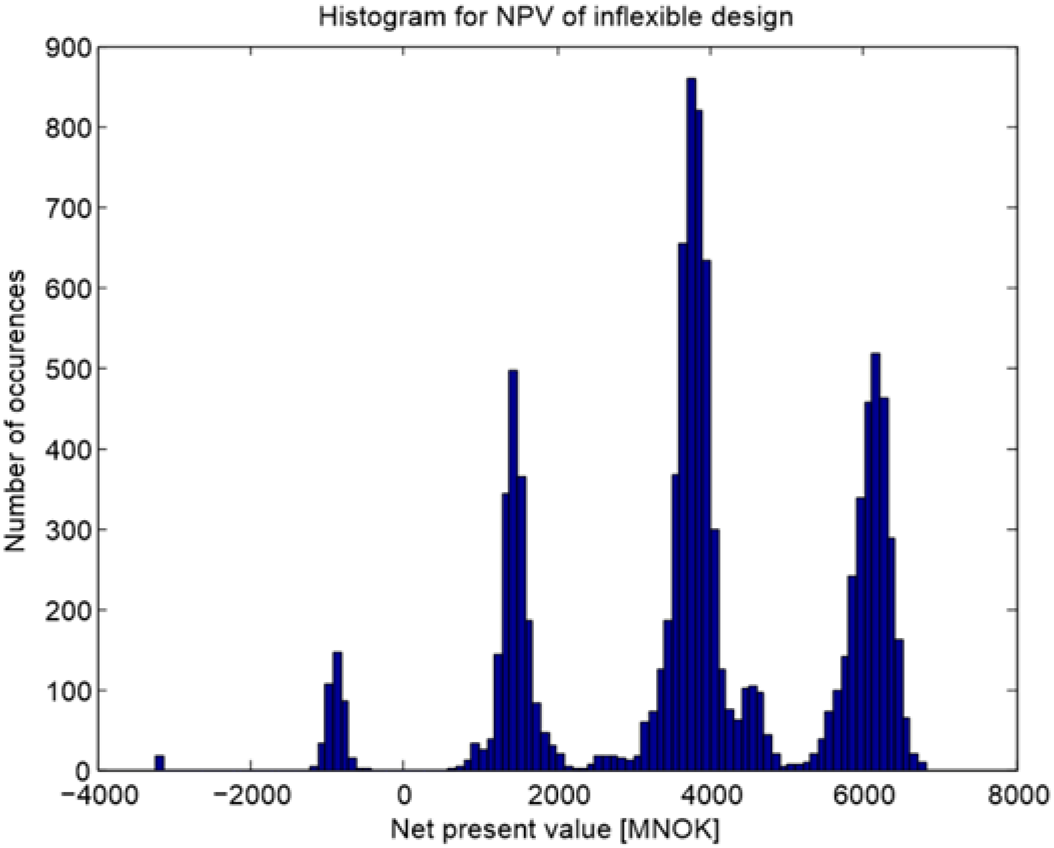


Figure 6.16: NPV distribution for inflexible Design 51.

The expected NPV (ENPV) shown both for flexible and inflexible designs show that Design 51 in fact is a good design alternative. This was questioned through the multi-epoch analysis and the multi-era analysis, that only considered value as stated in the value proposition. When accounting for the revenue earned through time charter rates, we see that the design is actually a lot more valuable in an economic sense. It even performs quite well in its inflexible version. Along a large part of the curve it seems that the inflexible design performs equally well as the flexible version.

A look at the NPV histograms for Design 51 shows that in the best-case scenarios, the inflexible vessel may earn as much as the flexible vessel. This is observed at the peak in the distribution at NPVs around 6000 MNOK, which is quite similar for both the inflexible and the flexible case. We still observe the tendency to lower peaks in the flexible histogram, meaning that the events associated with the eras matter a lot more for the inflexible design, than for the flexible Design 51. Some key numbers from this NPV distribution are given in Table 6.11.

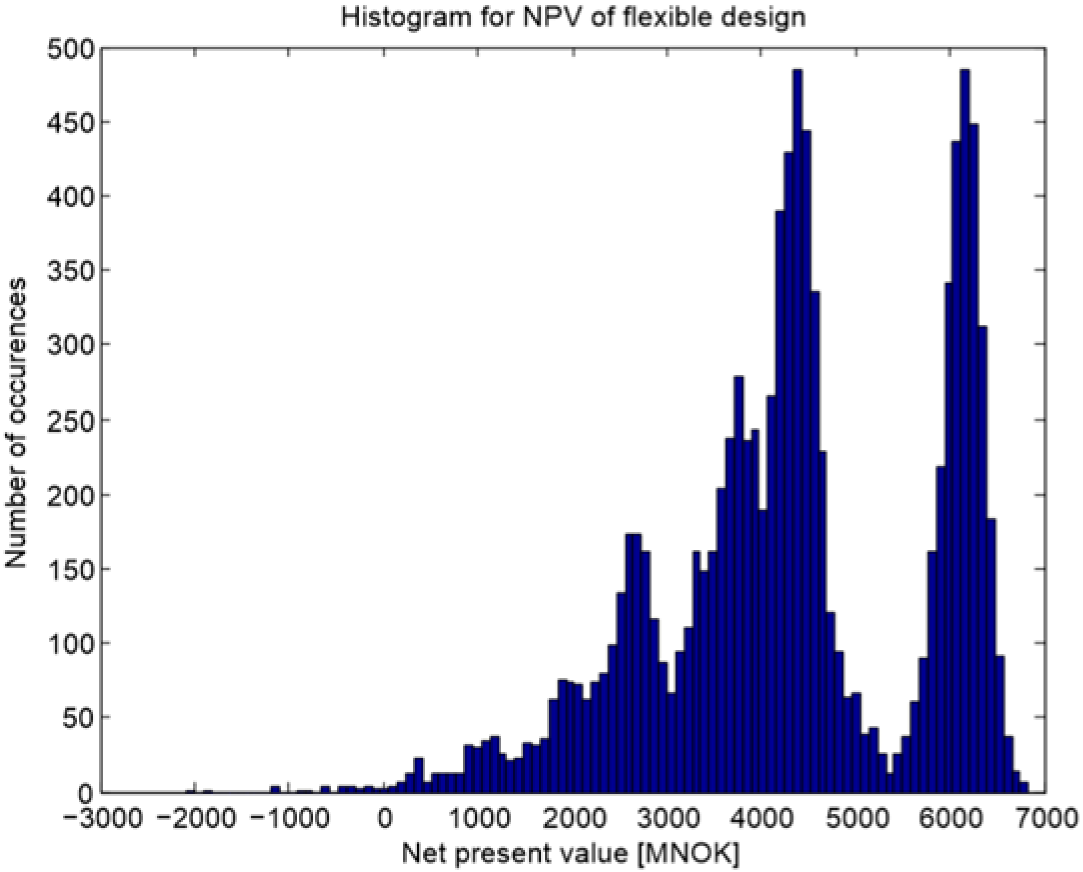


Figure 6.17: NPV distribution for flexible Design 51.

Table 6.11: NPV data for Design 51.

	Net present value [MNOK]		
	Minimum	**Maximum**	**Expected**
Inflexible	-3232	6817	3863
Flexible	-2080	5833	4336

From Table 6.11 we see that the value of flexibility is around 470 MNOK. However, Design 51 has the highest ENPV of any of the inflexible designs tested. This indicates that Design 51 can be seen as more of a passively than actively value robust design. This contrasts with the results of the multi-epoch analysis. An example of a flexible strategy for Design 51 is shown in Table 6.12, for Era 1, which was also used to produce the example strategies for Design 1 and Design 11.

The strategy in Figure 6.12 actually shows us that in this run of the simulation, no flexibility was exercised. It is possible for Design 51 to be equally valuable without being changed. This confirms our belief that the Pareto trace undercommunicates the passive value robustness of Design 51. Still, it is not the only possible strategy for this design. Sometimes, real options are

Table 6.12: Possible flexible design strategy for an initial Design 51 in Era 1.

Epochs	**Contracts**		**Design transition**
	Inflexible	**Flexible**	
3	IMR	IMR	51
1	LWI	LWI	None
28	LWI	LWI	None
51	LWI	LWI	None
52	LWI	LWI	None

exercised, transitioning Design 51 into Design 21. The configuration for Design 21 is shown in Appendix D. The set of real options exercised to obtain the transition between Design 51 and Design 21, is presented in Table 6.13.

Table 6.13: Set of real options for transition between Design 51 and Design 21.

Put option	Removing from vessel: Module handling tower, skidding system
Call option	Adding to vessel: Saturated diving system

A comment to the estimates of NPV found from all three life cycle path analyses, is that the economic value of the vessels seem very high. The discount rate can be a possible reason for this. Especially with regards to other assumptions made, higher discount rates could be applied to account for the effects of other risks that are not included in the model.

6.4 Discussion

In the initial chapter we proposed two research questions. In light of the analysis and our results, there is a need to ask whether these questions have been answered. First, have we been successful in identifying and valuing flexibility in OCVs? Next, is the combination of the Responsive Systems Comparison method and a Real Options Analysis in the form of a life cycle path analysis a viable approach to handle uncertainty in ship design? Can this improve decisions?

The review of literature on the existing theory and methodology reveals a gap in the ability of financially based real options methodologies to identify where and which options exist in complex engineering systems. ROA approaches the valuation of flexibility in an objective way, excluding any thorough discussion of stakeholder needs, and with a limited handle on the uncertainty represented by non-economic issues. Due to these shortcomings, the RSC method is applied analyzing the whole design space in light of value robustness. Only after this, we perform a ROA using Monte Carlo Simulation. Once some designs are found to have properties aligning with the stakeholders perception of value, the life cycle path analysis is used to assess the economic value of flexible designs.

The results from our case study show that flexibility under the assumptions we have made, is valuable. It seems flexibility can enhance the economic value of vessels throughout their lifetime. By maximizing the net present value of the current epochs, we succeed in identifying what contracts should be taken. We see which changes that need to be made to some specific vessels in order to take the most valuable contract in the next epoch. In this respect, the model suggests specific retrofits, effectively making a ship the "right vessel for the right mission" (Gaspar et al., 2015). Over the vessel lifetime this constitutes a flexible strategy that suggests whether changes should be made each time a new contract is needed, or if the ship owner will be better off sticking to the current equipment configuration. The NPV estimates found are somewhat optimistic. This may be due to the applied discount rate that perhaps should be set higher. If the discount rate was higher, the value of flexibility would be lower, as future profits would be seen as less important.

In the Monte Carlo Simulation model, some stochastic parameters are obtained by tuning rather that using historical data. As Rader et al. (2010) points out, MCS is most useful when we have "known systematic uncertainties". Historical data is often used to fit the input distribution to the existing knowledge of the past. However, trend breakers may disrupt the accuracy of these distributions (de Neufville and Scholtes, 2011), potentially making the use of forecasts based on historical data deceitful. Especially when considering immature markets in the offshore construction industry, this can be true. Often data only goes a few years back, such as in the case of light well intervention, which itself represents a disruption from traditional well intervention services done by rigs. The distribution of existing time charter rate data for well intervention rigs can not necessarily be expected to fit the future rates of LWI vessels.

Contrary to the example of the time charter rates of LWI contracts, a lot of data exists for the oil price. This makes the oil price development a potential candidate for modeling by fitting it to a stochastic process, for example with a Geometric Brownian Motion or with a mean-reverting process (Lin et al., 2013). When we include oil price as an epoch variable and define it discretely, it is because we use it to define the availability of new contracts in epochs. Another reason it is included as an epoch variable, is that it plays a central part of the storytelling procedure applied in the era construction.

Another problem related to economic uncertainty, exists on the cost side. The cost model is completely deterministic, while the costs of equipment in reality can change a lot during the lifetime of the vessel. Cheaper alternatives to equipment may become available, or more technologically advanced equipment may be selected. Thus, some probability distribution could be fitted to the equipment costs if data is available. However, fitting distributions based on historical data for the equipment costs would face many of the same problems as for the time charter rates, mentioned above. Usage of epoch variables is an alternative way to consider the uncertainty in the cost elements.

Many examples of uncertainties that could have impacted the performance of an OCV, without them being included in this analysis. The epoch variables are set in accordance with phenomena that relate to the contractual requirements for topside functionalities in OCVs and the availability of contracts. The epoch variables selected for analysis, and the mapping of epoch variables towards their consequences for the utility of each design, is worthy of discussion. In this case we used fibrerope technology as an example of an emerging technology that could reduce the requirements for crane size. Similarly, innovations concerning other design variables in our case could have been introduced as epoch variables. Second, the mapping from epoch variables and design variables to utility functions can be done in a variety of ways. An alternative to our modeling, could be to use a subset of the design variables as epoch variables. These epoch variables could thus directly constitute the technical requirements for a contract.

Era construction should also be discussed. Epochs are manually handpicked to constitute eras, and then assigned equal probability in the simulation. A benefit of this, is that the stakeholder expectations are accounted for to a large extent, in itself contributing to value robustness. Even though the stakeholder assumptions about the future may be incorrect, it allows a more subjective approach to the design accounting for expectations, compared to a situation in which purely objective measures of uncertainty based on historical data are used. However, there is a risk that too strong an emphasis on stakeholder expectations may influence the decision makers to make choices based on wishful thinking. In this respect the approach we take here, with stakeholder generated eras combined with time charter rates moving according to a mean reverting process balances the effects of subjective and objective modeling of the future.

The problem of real options *in* systems (Wang and de Neufville, 2004) has been circumvented by defining transition rules, and enumerating the entire design space before performing the ROA. We thus find good flexible strategies to employ when the vessel becomes infeasible for its current contract, or if other contracts pay so well that a retrofit could make it more profitable. Still, we should question how likely it is that following a flexible strategy recommended by the output of the life cycle path analysis will be the best decision. The exercise of real options means that a retrofit has to be done in a yard. As with any project, a retrofit introduces several additional risks. Ross et al. (2008a) mentions that chasing the needs of the current context of a system can lead to cost slips and delays potentially destroying the theoretical benefit of flexibility. Considering the cyclical nature of shipbuilding markets, it may be difficult to exercise flexibility in good times, as yards tend to have a lot of newbuilding projects. This may make it hard to find a yard that can do a retrofit. In Sødal et al. (2008) it is pointed out that flexibility through triangulation (taking one cargo one way, and another cargo on the return trip) was difficult to successfully apply in combination carriers, and flexibility should rather be used to switch between markets in a less agile manner, more as a part of a long term strategy. Due to the problems pointed out here, it could be reasoned that flexibility involving retrofits should be used as a part of long term strategies. A possible alteration to the model in this respect, could be to set a higher threshold for transitions, requiring a more substantial increase in NPV before exercising flexibility. More strict transitioning rules could also be considered. In the analysis here, we only used the condition that the total deck area should remain the same. However, if we want to quantify the real option value of upgrading from a 100 ton crane to a 300 ton crane, a more strict transition rule could be imposed. In such an example, the transition rule could be that all systems except the crane should remain the exact same before and after transition.

The second research question is answered through a comparison between the results of the life cycle path analysis, and the tradespace evaluation and multi-epoch analysis. Design 51 exemplifies perfectly that the measure of passive value robustness in the multi-epoch analysis does not match what seems to be more valuable in an economic sense, as it has a low Pareto trace. The diverging results could perhaps be fixed through redefining Step 1 and Step 2 of the RSC method. First, profitability could be added as a value attribute in the value proposition in Step 1 of the RSC method. Second, the potential to earn a specific time charter rate could be included as a performance attribute connected to the profitability. The question of how to account for this attribute in the utility function thus becomes interesting. Further, accounting for an additional uncertainty such as time charter rates may require us to redefine the set of epoch variables. Perhaps we should not consider the divergence of the results as a serious drawback. As Rader et al. (2010) points out, Epoch-Era Analysis and Monte Carlo Simulation are different, and thus different answers are justified. Their differences may even be an advantage, as it provides a deeper insight into further aspects of the design process, and arranges for a more thorough discussion of the design properties. In this sense, the RSC method and ROA are complementary methodologies for investigation of design performance under uncertainty.

Chapter 7

Conclusions

This thesis set out to investigate the current approaches into identification and valuation of functional flexibility in the design of offshore construction vessels, and to compare how different methodologies for decision making under uncertainty could answer this. The research questions were answered by applying the Responsive Systems Comparison method for Epoch-Era Analysis with a Monte Carlo Simulation approach to Real Options Analysis.

We have been able to identify system elements that can be seen as real options *in* the OCV, by allowing transitions between many different alternative designs in a design space. Utilizing Monte Carlo Simulation as the approach to Real Options Analysis, we get many possible flexible strategies as output. These flexible strategies enable designers and stakeholders to see which changes can be made to the design in order to mitigate risks and exploit opportunities, as a response to future uncertainty. We thus regard the thesis as successful in identifying flexibility, and in finding actively value robust OCV designs that can gain value by being retrofitted later.

We manage to value flexibility in OCV designs as well. However, this conclusion should not be drawn from looking at the single number estimates. Rather, we have found the value of flexibility on the form of NPV distributions. For the case studied, with the assumptions that have been made regarding future uncertainty, the output NPV distributions are valid.

A final remark regarding the secondary research question, is that the notion of value makes it difficult to reach identical recommendations for the design selection. This is true for the passively value robust design. Application of purely monetary measures of value in Real Options Analysis, will not give the same result as an Epoch-Era Analysis, which puts a value on the attributes of a design directly. This divergence in recommendations may not necessarily be bad, as it facilitates a broader discussion on what design to finally select, incorporating both subjective and objective notions of value. To give a final answer to the secondary research question, using several methodologies to assess the value and performance of a design may cast additional light on the decision making process, and should therefore be seen as something positive.

7.1 Further Work

The discussion and conclusion show that there is a need for additional work on both uncertainty and flexibility in marine systems design.

Investigation into the merger of Real Options Analysis and the Responsive Systems Comparison method should be continued. With regards to this, the era construction procedures could be automated using Monte Carlo Simulation. Formulation of continuous epoch variables would be an advantage in reconciling these methodologies. There may be value in extending the scope of the case study developed. Considerations of further sources of uncertainty to increase the realism could be relevant in this respect, with additional use of parameters set by statistical analysis. Alternative real options screening procedures could also be tested on an OCV case, especially if a more detailed design formulation was to be considered. More elaborate formulation of transition paths and triggering rules could be helpful in increasing the applicability of the Real Options Analysis within the context of the RSC method. In a more complex design formulation constraints regarding stability or hydrodynamics could also be accounted for. An extension of the model proposed in this thesis could be combined with an optimization approach, such as the Ship Design and Deployment Problem of Erikstad et al. (2011). Dealing with flexibility in a fleet design perspective also represents an opportunity for further work.

It may be valuable to further consider flexibility and its relation to the five aspects of complexity in ship design, as it was outlined in Gaspar (2013). Investigating the relationship between flexibility and modularization in a more structured, system-based ship design approach akin to Levander (2012) and Erikstad and Levander (2012), could provide additional insight in how the structural and behavioral aspects of complexity can mitigate uncertainty. As the use of Epoch-Era Analysis is also gaining interest from businesses in the maritime sector, such as the Ulstein Group (Gaspar et al., 2015), the industrial aspects of the OCV case study could be further developed. A possible goal in the longer term could be the inclusion of Epoch-Era Analysis as a tool in ship design consulting processes.

Bibliography

Alizadeh, A. and Nomikos, N. (2009). *Shipping Derivatives and Risk Management*. Palgrave MacMillan, London, UK.

Baldwin, C. Y. and Clark, K. B. (2002). The option value of modularity in design. An example from Design Rules, Volume 1: The power of modularity. *Harvard NOM Research Paper*, 3(11).

Black, F. and Scholes, M. (1973). The pricing of options and corporate liabilities. *The Journal of Political Economy*, 81(3):637 – 654.

Cox, J. C., Ross, S. A., and Rubinstein, M. (1979). Option pricing: A simplified approach. *Journal of Financial Economics*, 7(3):229–263.

Curry, M. and Ross, A. M. (2015). Considerations for an extended framework for interactive epoch-era analysis. *Procedia Computer Science*, 44:454–465.

de Neufville, R. (2003). Real options: Dealing with uncertainty in systems planning and design. *Integrated Assessment*, 4(1):26–34.

de Neufville, R., Hodota, K., Sussman, J., and Scholtes, S. (2007). Using real options to increase the value of intelligent transportation systems. *Transportation Research Record*, 2086:40–47.

de Neufville, R. and Scholtes, S. (2011). *Flexibility in Engineering Design*. Engineering Systems. The MIT Press, Cambridge, MA.

Diez, M. and Peri, D. (2010). Two-stage stochastic programming formulation for ship design optimisation under uncertainty. *Ship Technology Research*, 57(3):172–181.

Erikstad, S. O., Fagerholt, K., and Solem, S. (2011). A ship design and deployment model for non-transport vessels. *Ship Technology Research*, 58(3):132–142.

Erikstad, S. O. and Levander, K. (2012). System based design of offshore support vessels. In *11th International Marine Design Conference*, volume 1.

Erikstad, S. O. and Rehn, C. F. (2015). Handling uncertainty in marine systems design – state-of-the-art and need for research. In *12th International Marine Design Conference*.

Evans, J. H. (1959). Basic design concepts. *American Society of Naval Engineers Journal*, 71(4):672–678.

Gaspar, H. M. (2013). *Handling Aspects of Complexity in Conceptual Ship Design*. PhD thesis, Norwegian University of Science and Technology.

Gaspar, H. M., Brett, P. O., Erikstad, S. O., and Ross, A. M. (2015). Quantifying value robustness of OSV designs taking into consideration medium to long term stakeholders' expectations. In *12th International Marine Design Conference*.

Gaspar, H. M., Rhodes, D. H., Ross, A. M., and Erikstad, S. O. (2012). Addressing complexity aspects in conceptual ship design: A systems engineering approach. *Journal of Ship Production and Design*, 28(4):145–159.

Hassan, R., de Neufville, R., and McKinnon, D. (2005). Value-at-risk analysis for real options in complex engineered systems. In *2005 IEEE International Conference on Systems, Man and Cybernetics*, volume 4, pages 3697–3704. IEEE.

Higle, J. L. (2005). Stochastic programming: Optimization when uncertainty matters. *Tutorials in operations research*, pages 30 – 53.

King, A. J. and Wallace, S. W. (2012). *Modeling With Stochastic Programming*. Springer Series in Operations Research and Financial Engineering. Springer, New York, NY.

Levander, K. (2012). *System Based Ship Design*. Norwegian University of Science and Technology, Trondheim, Norway.

Lin, J., de Weck, O., de Neufville, R., and Yue, H. K. (2013). Enhancing the value of offshore developments with flexible subsea tiebacks. *Journal of Petroleum Science and Engineering*, 102(0):73–83.

McManus, H. and Hastings, D. (2006). A framework for understanding uncertainty and its mitigation and exploitation in complex systems. *IEEE Engineering Management Review*, 34(3):81–94.

Merton, R. C. (1973). Theory of rational options pricing. *The Bell Journal of Economics and Management Science*, 4(1):141–183.

Metropolis, N. and Ulam, S. (1949). The Monte Carlo method. *Journal of the American Statistical Association*, 44(247):335–341.

Rader, A. A., Ross, A. M., and Rhodes, D. H. (2010). A methodological comparison of Monte Carlo simulation and epoch-era analysis for tradespace exploration in an uncertain environment. In *4th Annual IEEE Systems Conference*.

Rhodes, D. H. and Ross, A. M. (2010). Five aspects of engineering complex systems emerging constructs and methods. In *4th Annual IEEE Systems Conference*, pages 190–195. IEEE.

Ritchie, G. (2008). *Offshore Support Vessels: A Practical Guide*. The Nautical Institute, London, UK.

Ross, A. M., McManus, H. L., Long, A., Richards, M. G., Rhodes, D. H., and Hastings, D. E. (2008a). Responsive systems comparison method: Case study in assessing future designs in the presence of change. In *AIAA Space 2008*.

Ross, A. M., McManus, H. L., Rhodes, D. H., Hastings, D. E., and Long, A. (2009). Responsive systems comparison method : Dynamic insights into designing a satellite radar system. In *AIAA Space 2009*.

Ross, A. M. and Rhodes, D. H. (2008). Architecting systems for value robustness: Research motivations and progress. In *2nd Annual IEEE Systems Conference*.

Ross, A. M., Rhodes, D. H., and Hastings, D. E. (2008b). Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value. *Systems Engineering*, 11(3):246–262.

RS Platou (2014). Subsea construction market.

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

Sødal, S., Koekebakker, S., and Aadland, R. (2008). Market switching in shipping - a real option model applied to the valuation of combination carriers. *Review of Financial Economics*, 17(3):183 – 203.

Singer, D. J., Doerry, N., and Buckley, M. (2009). What is set-based design? *Naval Engineers Journal*, 121(4):31–43.

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

Ulstein, T. and Brett, P. O. (2012). Critical systems thinking in ship design approaches. In *11th International Marine Design Conference*, volume 1.

Ulstein, T. and Brett, P. O. (2015). What is a better ship? - it all depends... In *12th International Marine Design Conference*, volume 1.

Ulstein International (2015). Subsea operations and subsea vessels.

Wang, T. and de Neufville, R. (2004). Building real options into physical systems with stochastic mixed-integer programming. In *8th Annual International Conference On Real Options*.

Wang, T. and de Neufville, R. (2005). Identification of real options “in” projects. In *9th Annual International Conference On Real Options*.

Wijst, N. v. d. (2013). *Finance: A Quantitative Introduction*. Cambridge University Press, New York, NY.

Appendix A

Acronyms

CAPEX Capital Expenditures

DSV Diving Support Vessel

EEA Epoch-Era Analysis

ENPV Expected Net Present Value

EPCI Engineering, Procurement, Commissioning and Installation

GBM Geometric Brownian Motion

IMR Intervention, Maintenance and Repair

LARS Launch And Recovery System

LWI Light Well Intervention

MCS Monte Carlo Simulation

MIT Massachusetts Institute of Technology

NPV Net Present Value

OCV Offshore Construction Vessel

OPEC Organization of Petroleum Exporting Countries

OPEX Operational Expenditures

RSC Responsive Systems Comparison

ROA Real Options Analysis

ROV Remotely Operated Vehicle

SDDP Ship Design and Deployment Problem

SEARI Systems Engineering Advancement Research Initiative

SURF Subsea installation, Umbilicals, Risers and Flowlines

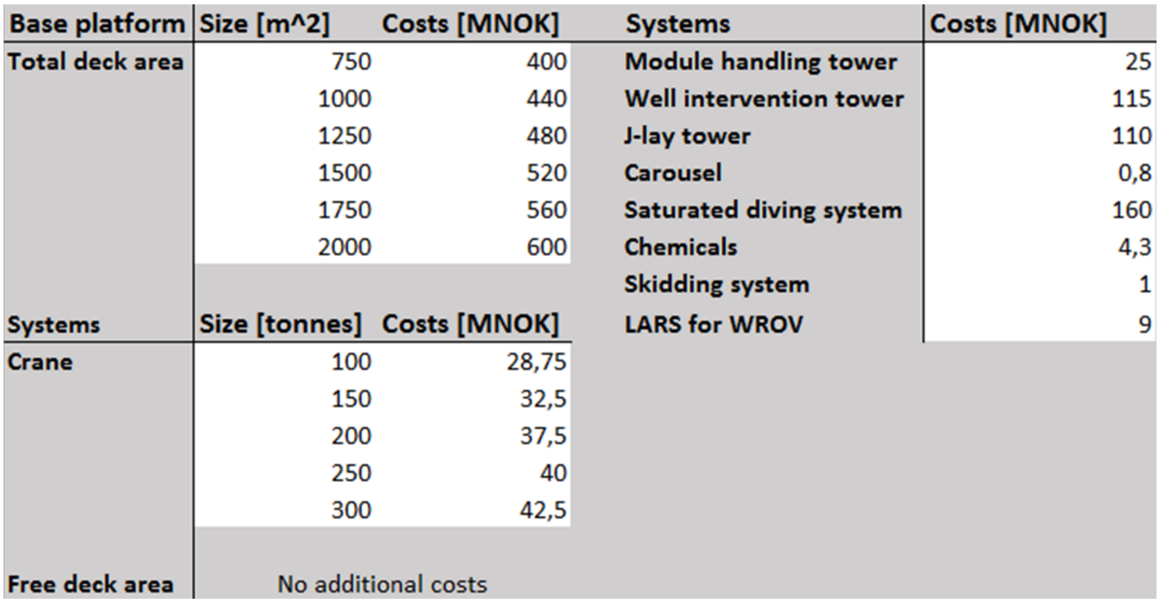
WROV Work ROV

Appendix B

Economic Data for the Case Study

This appendix shows some key economic input data that have been used in the case study.

The cost data for the vessel, and all systems included in the design formulation as design variables, are given in Figure B.1.



Base platform	Size [m^2]	Costs [MNOK]	Systems	Costs [MNOK]
Total deck area	750	400	Module handling tower	25
	1000	440	Well intervention tower	115
	1250	480	J-lay tower	110
	1500	520	Carousel	0,8
	1750	560	Saturated diving system	160
	2000	600	Chemicals	4,3
			Skidding system	1
Systems	**Size [tonnes]**	**Costs [MNOK]**	LARS for WROV	9
Crane	100	28,75		
	150	32,5		
	200	37,5		
	250	40		
	300	42,5		
Free deck area	No additional costs			

Figure B.1: Costs for investment in systems

Table B.1 shows the day rates and parameters of the mean reverting process. The mean day rate is set equal to the initial day rate.

Table B.1: Initial day rates and stochastic process parameters for contracts

Contract	**Day rate [MNOK]**	**Mean-reversion rate**	**Standard deviation**
IMR	0.5	0.8	0.1
SURF	1.6	0.5	0.2
LWI	1.6	0.5	0.25
DSV	1	0.8	0.12

Appendix C

Era Construction for the Case Study

Here we present each era as the sequence of epochs, and give the exact values for each epoch variable, in Table C.1 through to Table C.5.

Table C.1: Epoch progression of Era 1

	Epochs in Era 1				
Epoch Variables	Epoch 3	Epoch 1	Epoch 28	Epoch 51	Epoch 52
Oil price [$]	70	10	100	70	100
Module size [tonnes]	200	200	200	200	200
Water depth [m]	1000	1000	3000	2000	2000
Tie in need	0	0	0	1	1
Fibrerope technology	0	0	0	0	0

Table C.2: Epoch progression of Era 2

	Epochs in Era 2				
Epoch Variables	Epoch 3	Epoch 6	Epoch 5	Epoch 6	Epoch 11
Oil price [$]	70	40	10	40	70
Module size [tonnes]	200	250	250	250	300
Water depth [m]	1000	1000	1000	1000	1000
Tie in need	0	0	0	0	0
Fibrerope technology	0	0	0	0	0

Table C.3: Epoch progression of Era 3

	Epochs in Era 3				
Epoch Variables	Epoch 3	Epoch 11	Epoch 22	Epoch 35	Epoch 107
Oil price [$]	70	70	40	70	70
Module size [tonnes]	200	300	300	300	300
Water depth [m]	1000	1000	2000	3000	3000
Tie in need	0	0	0	0	0
Fibrerope technology	0	0	0	0	1

Table C.4: Epoch progression of Era 4

	Epochs in Era 4				
Epoch Variables	Epoch 3	Epoch 12	Epoch 70	Epoch 143	Epoch 106
Oil price [$]	70	100	40	70	40
Module size [tonnes]	200	200	300	300	300
Water depth [m]	1000	3000	3000	3000	3000
Tie in need	0	0	1	1	0
Fibrerope technology	0	0	0	1	1

Table C.5: Epoch progression of Era 5

	Epochs in Era 5				
Epoch Variables	Epoch 3	Epoch 72	Epoch 65	Epoch 54	Epoch 50
Oil price [$]	70	100	10	40	40
Module size [tonnes]	200	300	250	250	200
Water depth [m]	1000	3000	3000	2000	2000
Tie in need	0	1	1	1	1
Fibrerope technology	0	0	0	0	0

Appendix D

Offshore Construction Vessel Configurations

In this appendix the vessel configurations discussed as possible results of some flexible strategies for the vessels, are shown.

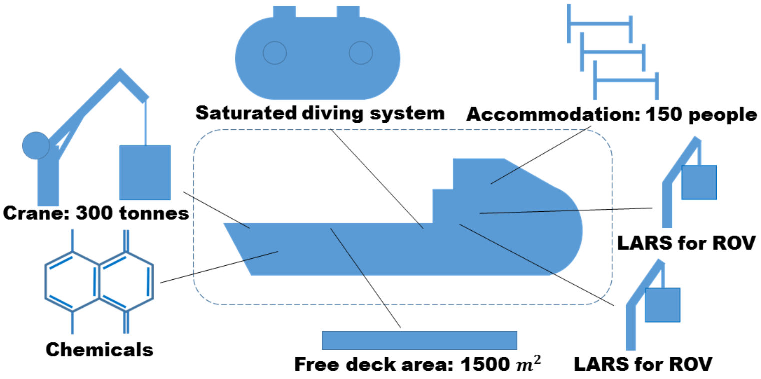


Figure D.1: Vessel Configuration for Design 16

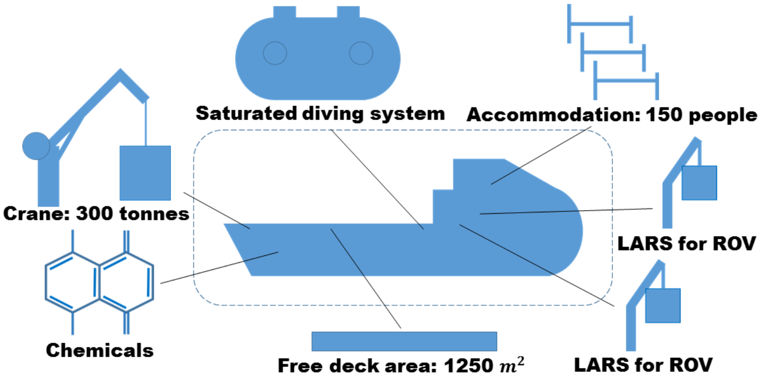


Figure D.2: Vessel Configuration for Design 21

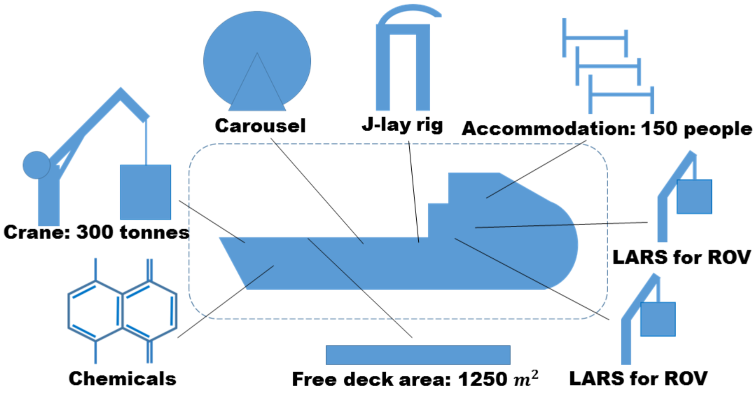


Figure D.3: Vessel Configuration for Design 36

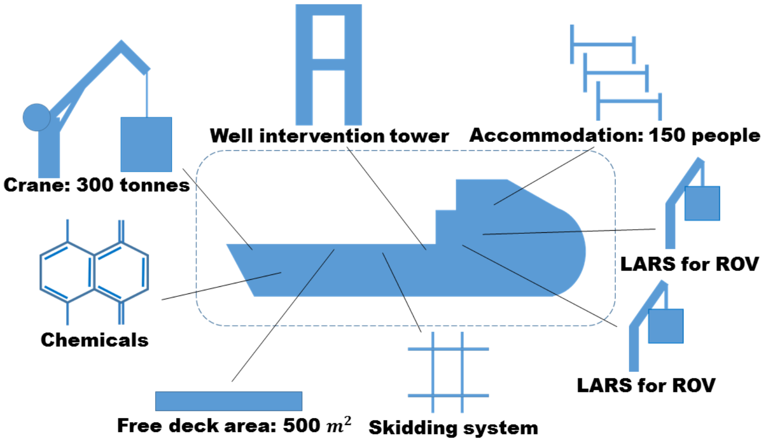


Figure D.4: Vessel Configuration for Design 61

Appendix E

MATLAB Code

This appendix includes the MATLAB code for the analysis in Chapter 5.

E.1 MATLAB Files for the Responsive Systems Comparison Method

This section provides the MATLAB code for the scripts and functions relating to Step 2 - 6 in the Responsive Systems Comparison method.

ResponsiveSystemsComparisonModel.m

```
%This script runs through Step 2 - 6 of the Responsive Systems Comparison
%method.

%% Step 2 and 3 of RSC: Design, attributes and epoch enumeration.
%Design space enumeration, generation of feasible designs:
[Design_Space,Design_Space_infeasible,Total_Deck_Area] = ...
    Designs(Design_Variables,levels_desvar,Deck_Area,...
    Accommodation_Required,Min_Req);
%Cost model calculating CAPEX and OPEX:
[CAPEX_Total,CAPEX_Daily,OPEX_Daily] = ...
    Costs(Design_Variables,Design_Space,Total_Deck_Area,...
    T_life,T_payback,CAPEX_DV,r_discount);
%Epoch space enumeration:
Epoch_Space = Epochs(levels_epochvar,Epoch_Variables);
%Defining contract requirements according to epochs:
Min_Req_Space = Requirements(Epoch_Space,Min_Req);
%Defining contract feasibility of designs in epochs:
[All_Contracts,Contracts_Feasible,IMR_Contract,SURF_Contract,...
    LWI_Contract,DSV_Contract] = Contracts(Min_Req_Space,Design_Space);
```

```
%Defining contractual availability in epochs:
[All_Contracts_Availability,IMR_Availability,SURF_Availability,...
    LWI_Availability,DSV_Availability] = AvailableContracts...
    (Epoch_Space,IMR_Contract,SURF_Contract,LWI_Contract,DSV_Contract);

%% Step 4 of RSC: Tradespace Exploration.
%Calculating utility for each design in each epoch:
[Utility] = Attributes(CAPEX_Daily,OPEX_Daily,Design_Space,...
    Total_Deck_Area,Contracts_Feasible,IMR_Availability,...
    SURF_Availability,LWI_Availability,DSV_Availability);

%% Step 5 of RSC: Multi-Epoch Evaluation.
%Calculating total average utility and ranks designs according to this.
[Total_Utility] = MultiEpoch(Utility,Design_Space);
%See also Pareto.m, MultiEpochEraAnalysis.m.

%% Step 6 of RSC: Era Construction.
%Constructing eras according to stakeholder expectations:
[Era_Description_Expectations,Era_Epoch_Progression] = ...
    EraConstruction(Epoch_Space);

%Performing multi-epoch analysis for the specified eras:
[Utility_Era,Total_Utility_Era] = MultiEpochEraAnalysis...
    (Utility,Era_Epoch_Progression);

%Finding Pareto fronts and Pareto trace:
[Total_Pareto_Set,Total_Pareto_Set_Eras,Pareto_Set_Eras,...
    Pareto_Set,Pareto_Trace] = Pareto...
    (Utility,CAPEX_Total,Total_Utility,Utility_Era,Total_Utility_Era);
```

Designs.m

```
function [Design_Space,Design_Space_infeasible,Total_Deck_Area] = ...
    Designs(Design_Variables,levels_desvar,Deck_Area,...
    Accommodation_Required,Min_Req)
%This function creates all the designs that are feasible, based on the
%design variables defined and constraints on the design space.

%Initializing design variables:
DesVar_Crane = zeros(1,levels_desvar(1));
DesVar_Free_Deck_Area = zeros(1,levels_desvar(2));
DesVar_Accommodation = zeros(1,levels_desvar(3));
DesVar_LARS_ROV = zeros(1,levels_desvar(11));
DesVar_Mod_Hand = zeros(1,levels_desvar(4));
```

```
DesVar_Well_Int = zeros(1,levels_desvar(5));
DesVar_J_Lay = zeros(1,levels_desvar(6));
DesVar_Carousel = zeros(1,levels_desvar(7));
DesVar_Sat_Div = zeros(1,levels_desvar(8));
DesVar_Chemicals = zeros(1,levels_desvar(9));
DesVar_Skidding = zeros(1,levels_desvar(10));

%Defining all design variables:
for i = 1:max(levels_desvar)
    if i <= levels_desvar(1)
        DesVar_Crane(i) = Design_Variables(i,1);
    end
    if i <= levels_desvar(2)
        DesVar_Free_Deck_Area(i) = Design_Variables(i,2);
    end
    if i <= levels_desvar(3)
        DesVar_Accommodation(i) = Design_Variables(i,3);
    end
    if i <= levels_desvar(4)
        DesVar_Mod_Hand(i) = Design_Variables(i,4);
    end
    if i <= levels_desvar(5)
        DesVar_Well_Int(i) = Design_Variables(i,5);
    end
    if i <= levels_desvar(6)
        DesVar_J_Lay(i) = Design_Variables(i,6);
    end
    if i <= levels_desvar(7)
        DesVar_Carousel(i) = Design_Variables(i,7);
    end
    if i <= levels_desvar(8)
        DesVar_Sat_Div(i) = Design_Variables(i,8);
    end
    if i <= levels_desvar(9)
        DesVar_Chemicals(i) = Design_Variables(i,9);
    end
    if i <= levels_desvar(10)
        DesVar_Skidding(i) = Design_Variables(i,10);
    end
    if i <= levels_desvar(11)
        DesVar_LARS_ROV(i) = Design_Variables(i,11);
    end
end

%Generating all potentially possible designs (feasible and infeasible):
```

```
DesVars = {DesVar_Crane, DesVar_Free_Deck_Area, DesVar_Accommodation, ...
           DesVar_Mod_Hand, DesVar_Well_Int, DesVar_J_Lay, ...
           DesVar_Carousel, DesVar_Sat_Div, DesVar_Chemicals, ...
           DesVar_Skidding, DesVar_LARS_ROV};
[a b c d e f g h i j k] = ndgrid(DesVars{:});
Design_Space_infeasible = ...
    [a(:) b(:) c(:) d(:) e(:) f(:) g(:) h(:) i(:) j(:) k(:)];
[num_designs_1,dvs] = size(Design_Space_infeasible);

%Initializing:
Total_Deck_Area_1 = zeros(num_designs_1,dvs);
%Defining the deck area needed for systems installed
for i = 1:num_designs_1
    %Setting total deck area initially equal to free deck area:
    Total_Deck_Area_1(i) = Design_Space_infeasible(i,2);
    %Adding required deck area for systems to the total deck area:
    for j = 1:dvs
        if Design_Space_infeasible(i,j) > 0
            Total_Deck_Area_1(i) = Total_Deck_Area_1(i) + Deck_Area(j);
        end
    end
    %Rounding to closest 250 m^2:
    if Total_Deck_Area_1(i) <= 1000
        Total_Deck_Area_1(i) = 1000;
    elseif (Total_Deck_Area_1(i) > 1000) && (Total_Deck_Area_1(i) <= 1250)
        Total_Deck_Area_1(i) = 1250;
    elseif (Total_Deck_Area_1(i) > 1250) && (Total_Deck_Area_1(i) <= 1500)
        Total_Deck_Area_1(i) = 1500;
    elseif (Total_Deck_Area_1(i) > 1500) && (Total_Deck_Area_1(i) <= 1750)
        Total_Deck_Area_1(i) = 1750;
    elseif (Total_Deck_Area_1(i) > 1750) && (Total_Deck_Area_1(i) <= 2000)
        Total_Deck_Area_1(i) = 2000;
    end
end

%Initializing:
Accommodation_Total = zeros(1,num_designs_1);
%Defining the accommodation needed for systems installed:
for i = 1:num_designs_1
    %Setting initial accommodation to 50:
    Accommodation_Total(i) = 50;
    %Adding accommodation needed for systems:
    for j = 1:dvs
        if Design_Space_infeasible(i,j) > 0
            Accommodation_Total(i) = ...
```

```
                Accommodation_Total(i) + Accommodation_Required(j);
        end
    end
end

%Initializing the designs that are to be allowed for analysis:
Design = ones(num_designs_1,1);
%Pruning the design space, excluding infeasible designs:
for i = 1:num_designs_1
    %Module handling tower, well intervention tower, j-lay rig and
    %saturated diving system can not co-exist in the same design.
    if ((Design_Space_infeasible(i,4) + Design_Space_infeasible(i,5)...
        + Design_Space_infeasible(i,6) + Design_Space_infeasible(i,8)) > 1)
        Design(i) = 0;
    %Module handling tower requires skidding system, and vice versa,
    %so if the sum of these are 1, the design is infeasible.
    elseif ((Design_Space_infeasible(i,4) ...
            + Design_Space_infeasible(i,10)) == 1)
        Design(i) = 0;
    %Module handling tower requires two LARS for WROV:
    elseif ((Design_Space_infeasible(i,4) ...
            - Design_Space_infeasible(i,11)) > -1)
        Design(i) = 0;
    %J-lay rigs require carousels, and vice versa, so if the sum of
    %these are 1, the design is infeasible.
    elseif ((Design_Space_infeasible(i,6) ...
            + Design_Space_infeasible(i,7)) == 1)
       Design(i) = 0;
    %Well intervention tower requires chemicals:
    elseif ((Design_Space_infeasible(i,5) ...
            - Design_Space_infeasible(i,9)) > 0)
        Design(i) = 0;
    %Well intervention tower requires two LARS for WROV:
    elseif ((Design_Space_infeasible(i,5) ...
            - Design_Space_infeasible(i,11)) > -1)
        Design(i) = 0;
    %Saturated diving system requires two LARS for WROV:
    elseif ((Design_Space_infeasible(i,8) ...
            - Design_Space_infeasible(i,11)) > -1)
        Design(i) = 0;
    %At least the required amount of accommodation should be included in
    %the vessel:
    elseif (Design_Space_infeasible(i,3) < Accommodation_Total(i))
        Design(i) = 0;
    %Total deck area is maximum 2000 m^2.
```

```
    elseif Total_Deck_Area_1(i) > 2000
        Design(i) = 0;
    end
end
%Pruning the design space, excluding designs not feasible for initial IMR
%contract:
for i = 1:num_designs_1
    for d = 1:dvs
        if (Design_Space_infeasible(i,d) < Min_Req(1,d))
            Req(i,d) = 0;
        else
            Req(i,d) = 1;
        end
    end
    if sum(Req(i,:)) ~= dvs
        Design(i) = 0;
    end
end

%Initializing output variables:
Design_Space = [];
Total_Deck_Area = [];
%Defining design space and total deck area:
for i = 1:num_designs_1
    if Design(i) == 1;
        Design_Space = [Design_Space_infeasible(i,:); Design_Space];
        Total_Deck_Area = [Total_Deck_Area_1(i); Total_Deck_Area];
    end
end
```

Costs.m

```
function [CAPEX_Total,CAPEX_Daily,OPEX_Daily] = ...
    Costs(Design_Variables,Design_Space,Total_Deck_Area,...
    T_life,T_payback,CAPEX_DV,r_discount)
%This function calculates CAPEX and OPEX.

%Initializing:
[num_designs,dvs] = size(Design_Space);
[levels,dvs] = size(Design_Variables);
CAPEX_Total = zeros(1,num_designs);
loan_remaining = zeros(1,num_designs);
CAPEX_equity = zeros(1,num_designs);
CAPEX_loan = zeros(1,num_designs);
```

```
CAPEX1 = zeros(num_designs,T_life);
CAPEX_Daily = zeros(num_designs,T_life);
OPEX_Daily = zeros(num_designs,1);

%Calculating the CAPEX for all design alternatives:
for d = 1:num_designs
    %Calculating the "platform design" building cost in MNOK,
    %as a function of total deck area:
    CAPEX_Total(d) = 440 + 40*((Total_Deck_Area(d) - 1000)/250);
    %Including the CAPEX for installing the design variables in the design:
    for j = 1:dvs
        for l = 1:levels
            if Design_Space(d,j) == Design_Variables(l,j)
                CAPEX_Total(d) = CAPEX_Total(d) + 1.2*CAPEX_DV(l,j);
            end
        end
    end
    %CAPEX split in equity and loan:
    CAPEX_equity(d) = 0.3*CAPEX_Total(d);
    CAPEX_loan(d) = 0.7*CAPEX_Total(d);
    loan_remaining(d) = CAPEX_loan(d);
    for t = 1:T_life
        %Calculating CAPEX paid per period as long as loan remains.
        if t <= T_payback
            CAPEX1(d,t) = ...
            CAPEX_equity(d)/T_life + CAPEX_loan(d)/T_payback...
            + r_discount*loan_remaining(d);
            loan_remaining(d) = loan_remaining(d)...
            - (1/T_payback)*loan_remaining(d);
        %Calculating CAPEX paid per period when loan is repaid.
        else
            CAPEX1(d,t) = CAPEX_equity(d)/T_life;
        end
        %CAPEX paid per day, each year.
        CAPEX_Daily(d,t) = CAPEX1(d,t)/365;
    end
    %Operational expenditures found as a function of CAPEX:
    OPEX_Daily(d,:) = 46000/(10^6) + (CAPEX_Total(d)*(6.8/100))/365;
end
end
```

Epochs.m

```
function Epoch_Space = Epochs(levels_epochvar,Epoch_Variables)
%This function creates all epochs, based on the epoch variables defined.

%Initializing epoch variables:
EpochVar_Oil_Price = zeros(1,levels_epochvar(1));
EpochVar_Mod_Size = zeros(1,levels_epochvar(2));
EpochVar_Water_Depth = zeros(1,levels_epochvar(3));
EpochVar_Tie_In = zeros(1,levels_epochvar(4));
EpochVar_Fibrerope = zeros(1,levels_epochvar(5));

%Defining all epoch variables:
for i = 1:max(levels_epochvar)
    if i <= levels_epochvar(1)
        EpochVar_Oil_Price(i) = Epoch_Variables(i,1);
    end
    if i <= levels_epochvar(2)
        EpochVar_Mod_Size(i) = Epoch_Variables(i,2);
    end
    if i <= levels_epochvar(3)
        EpochVar_Water_Depth(i) = Epoch_Variables(i,3);
    end
    if i <= levels_epochvar(4)
        EpochVar_Tie_In(i) = Epoch_Variables(i,4);
    end
    if i <= levels_epochvar(5)
        EpochVar_Fibrerope(i) = Epoch_Variables(i,5);
    end
end
%Generating all possible epochs:
EpochVars = {EpochVar_Oil_Price, EpochVar_Mod_Size, ...
             EpochVar_Water_Depth, EpochVar_Tie_In, ...
             EpochVar_Fibrerope};
[a b c d e] = ndgrid(EpochVars{:});
Epoch_Space = [a(:) b(:) c(:) d(:) e(:)];
end
```

Requirements.m

```
function Min_Req_Space = Requirements(Epoch_Space,Min_Req)
%This function defines the contractual requirements over time, as depending
%on the realization of epoch variables. Variables accounted for are:
%Module size, Max water depth, Tie-in, Fibrerope technology

%Initializing:
[num_epochs,epoch_var] = size(Epoch_Space);
[markets,design_vars] = size(Min_Req);
Min_Req_Space_1 = zeros(num_epochs,markets,epoch_var,design_vars);
Min_Req_Space = zeros(num_epochs,markets,design_vars);
for i = 1:num_epochs
    for m = 1:markets
        for v = 1:num_epochs
            for d = 1:design_vars
                Min_Req_Space_1(i,m,v,d)=Min_Req(m,d);
            end
        end
    end
end
for i = 1:num_epochs
    for m = 1:markets
        %Accounting for the impact single epoch variables have on the
        %requirements.
        for v = 2:epoch_var
            %Epoch variable: Oil price:
            %No direct impact on minimum requirements.
            %Epoch variable: Module size:
            if v == 2
                %No change if module size is 200 tonnes.
                %Module size is 250 tonnes.
                if Epoch_Space(i,v) == 250
                    %IMR requirements:
                    if m == 1
                        %Will require module handling tower.
                        Min_Req_Space_1(i,m,v,4) = 1;
                    %SURF requirements:
                    elseif m == 2
                        %Require 250 tonnes crane.
                        Min_Req_Space_1(i,m,v,1) = Epoch_Space(i,v);
                        %Require 1250 m^2 free deck area.
                        Min_Req_Space_1(i,m,v,2) = 1250;
                    end
```

```
            %Module size is 300 tonnes.
            elseif Epoch_Space(i,v) == 300
                %IMR requirements:
                if m == 1
                    %Will require module handling tower.
                    Min_Req_Space_1(i,m,v,4) = 1;
                %SURF requirements:
                elseif m == 2
                    %Require 300 tonnes crane.
                    Min_Req_Space_1(i,m,v,1) = Epoch_Space(i,v);
                    %Require 1500 m^2 free deck area.
                    Min_Req_Space_1(i,m,v,2) = 1500;
                end
            end
        %Epoch variable: Maximum water depth:
        elseif v == 3
            %MAx water depth is 1000 m. No change from minimum.
            %Max water depth is 2000 m:
            if Epoch_Space(i,v) == 2000
                %IMR requirements:
                if m == 1
                    %Will require 150 tonnes crane.
                    Min_Req_Space_1(i,m,v,1) = 150;
                    %Will require module handling tower.
                    Min_Req_Space_1(i,m,v,4) = 1;
                    %Will require 2 ROVs.
                    Min_Req_Space_1(i,m,v,11) = 2;
                %SURF requirements:
                elseif m == 2
                    %Will require 250 tonnes crane.
                    Min_Req_Space_1(i,m,v,1) = 250;
                    %Will require 2 ROVs.
                    Min_Req_Space_1(i,m,v,11) = 2;
                %LWI requirements:
                elseif m == 3
                    %Will require 150 tonnes crane.
                    Min_Req_Space_1(i,m,v,1) = 150;
                end
            %Max water depth is 3000 m:
            elseif Epoch_Space(i,v) == 3000
                %IMR requirements:
                if m == 1
                    %Will require 200 tonnes crane.
                    Min_Req_Space_1(i,m,v,1) = 200;
                    %Will require module handling tower.
```

```
                        Min_Req_Space_1(i,m,v,4) = 1;
                        %Will require 2 ROVs.
                        Min_Req_Space_1(i,m,v,11) = 2;
                    %SURF requirements:
                    elseif m == 2
                        %Will require 300 tonnes crane.
                        Min_Req_Space_1(i,m,v,1) = 300;
                        %Will require 2 ROVs.
                        Min_Req_Space_1(i,m,v,11) = 2;
                    %LWI requirements:
                    elseif m == 3
                        %Will require 200 tonnes crane.
                        Min_Req_Space_1(i,m,v,1) = 200;
                    end
                end
            %Epoch variables: Tie-in need:
            elseif v == 4
                if Epoch_Space(i,v) == 1
                    %SURF requirements.
                    if m == 2
                        %J-lay rig and carousel required.
                        Min_Req_Space_1(i,m,v,6) = 1;
                        Min_Req_Space_1(i,m,v,7) = 1;
                        %Two ROVs required.
                        Min_Req_Space_1(i,m,v,11) = 2;
                    end
                end
            end
        end
        %Accounting for epoch variable interactions on the requirements.
        %Crane:
        if (Epoch_Space(i,3) == 2000)
            %No fibrerope:
            if (Epoch_Space(i,5) == 0)
                %Impact on SURF crane capacity:
                Min_Req_Space_1(i,2,v,1) = Epoch_Space(i,2) + 50;
            %Fibrerope:
            elseif (Epoch_Space(i,5) == 1)
                Min_Req_Space_1(i,2,v,1) = Epoch_Space(i,2);
            end
        elseif (Epoch_Space(i,3) == 3000)
            %No fibrerope:
            if (Epoch_Space(i,5) == 0)
                Min_Req_Space_1(i,2,v,1) = Epoch_Space(i,2) + 100;
            %Fibrerope:
```

```
            elseif (Epoch_Space(i,5) == 1)
                Min_Req_Space_1(i,2,v,1) = Epoch_Space(i,2);
            end
        end
    end
end
%Setting the minimum requirements in each epoch for each market:
for i = 1:num_epochs
    for m = 1:markets
        for d = 1:design_vars
            Min_Req_Space(i,m,d) = max(Min_Req_Space_1(i,m,:,d));
        end
    end
end
end
```

Contracts.m

```
function [All_Contracts,Contracts_Feasible,IMR_Contract,SURF_Contract,...
    LWI_Contract,DSV_Contract] = Contracts(Min_Req_Space,Design_Space)
%This function checks contract feasibility for designs in each epoch.

%Initializing:
[num_designs,dvs] = size(Design_Space);
[num_epochs,markets,dvs] = size(Min_Req_Space);
IMR_requirement = zeros(num_epochs,num_designs,dvs);
SURF_requirement = zeros(num_epochs,num_designs,dvs);
LWI_requirement = zeros(num_epochs,num_designs,dvs);
DSV_requirement = zeros(num_epochs,num_designs,dvs);
IMR_Contract = zeros(num_epochs,num_designs);
SURF_Contract = zeros(num_epochs,num_designs);
LWI_Contract = zeros(num_epochs,num_designs);
DSV_Contract = zeros(num_epochs,num_designs);
Contracts_Feasible = zeros(num_epochs,num_designs);
All_Contracts = zeros(num_epochs,num_designs,markets);
%Defines whether or not a design matches the minimum requirements in a
%contract:
for i = 1:num_epochs
    for j = 1:num_designs
        for d = 1:dvs
            %Checking whether the individual requirements on design
            %variable values are fulfilled:
            if Design_Space(j,d) >= Min_Req_Space(i,1,d)
                IMR_requirement(i,j,d) = 1;
```

```
            end
            if Design_Space(j,d) >= Min_Req_Space(i,2,d)
                SURF_requirement(i,j,d) = 1;
            end
            if Design_Space(j,d) >= Min_Req_Space(i,3,d)
                LWI_requirement(i,j,d) = 1;
            end
            if Design_Space(j,d) >= Min_Req_Space(i,4,d)
                DSV_requirement(i,j,d) = 1;
            end
        end
        %Checking if all requirements are fulfilled:
        if sum(IMR_requirement(i,j,:)) == dvs
            IMR_Contract(i,j) = 1;
        end
        if sum(SURF_requirement(i,j,:)) == dvs
            SURF_Contract(i,j) = 1;
        end
        if sum(LWI_requirement(i,j,:)) == dvs
            LWI_Contract(i,j) = 1;
        end
        if sum(DSV_requirement(i,j,:)) == dvs
            DSV_Contract(i,j) = 1;
        end
        %Finds the total number of feasible contracts for each design in
        %each epoch:
        Contracts_Feasible(i,j) = IMR_Contract(i,j) ...
            + SURF_Contract(i,j) + LWI_Contract(i,j) + DSV_Contract(i,j);
    end
end
%Creating a matrix defining feasibility of designs in all epochs for all
%markets, in one single matrix:
All_Contracts(:,:,1) = IMR_Contract(:,:);
All_Contracts(:,:,2) = SURF_Contract(:,:);
All_Contracts(:,:,3) = LWI_Contract(:,:);
All_Contracts(:,:,4) = DSV_Contract(:,:);
end
```

AvailableContracts.m

```
function [All_Contracts_Availability,IMR_Availability,SURF_Availability,...
    LWI_Availability,DSV_Availability] = AvailableContracts...
    (Epoch_Space,IMR_Contract,SURF_Contract,LWI_Contract,DSV_Contract)
%This function generates a number of available contracts based on epoch
```

```
%variables and vessel feasibility.

%Initializing:
markets = 4;
[num_epochs,num_designs] = size(IMR_Contract);
IMR_Availability_ = zeros(num_epochs,1);
SURF_Availability_ = zeros(num_epochs,1);
LWI_Availability_ = zeros(num_epochs,1);
DSV_Availability_ = zeros(num_epochs,1);
IMR_Availability = zeros(num_epochs,num_designs);
SURF_Availability = zeros(num_epochs,num_designs);
LWI_Availability = zeros(num_epochs,num_designs);
DSV_Availability = zeros(num_epochs,num_designs);
All_Contracts_Availability = zeros(num_epochs,num_designs,markets);

for i = 1:num_epochs
    %Defining contracts available based on epoch variables:
    %IMR availability only depends on oil price:
    IMR_Availability_(i) = 4 + ...
        6*((Epoch_Space(i,1) - min(Epoch_Space(:,1)))/...
        (max(Epoch_Space(:,1)) - min(Epoch_Space(:,1))));
    %SURF availability depends on oil price and tie-in:
    SURF_Availability_(i) = 2 + ...
        6*((Epoch_Space(i,1) - min(Epoch_Space(:,1)))/...
        (max(Epoch_Space(:,1)) - min(Epoch_Space(:,1))))...
        + 2*((Epoch_Space(i,4) - min(Epoch_Space(:,4)))/...
        (max(Epoch_Space(:,4)) - min(Epoch_Space(:,4))));
    %LWI availability depends on oil price and water depth:
    LWI_Availability_(i) = 2 + ...
        6*((Epoch_Space(i,1) - min(Epoch_Space(:,1)))/...
        (max(Epoch_Space(:,1)) - min(Epoch_Space(:,1))))...
        + 2*((Epoch_Space(i,3) - min(Epoch_Space(:,3)))/...
        (max(Epoch_Space(:,3)) - min(Epoch_Space(:,3))));
    %DSV availability depends on oil price, water depth and tie-in need:
    DSV_Availability_(i) = 4 + ...
        6*((Epoch_Space(i,1) - min(Epoch_Space(:,1)))/...
        (max(Epoch_Space(:,1)) - min(Epoch_Space(:,1))))...
        - 2*((Epoch_Space(i,3) - min(Epoch_Space(:,3)))/...
        (max(Epoch_Space(:,3)) - min(Epoch_Space(:,3))))...
        + 2*((Epoch_Space(i,4) - min(Epoch_Space(:,4)))/...
        (max(Epoch_Space(:,4)) - min(Epoch_Space(:,4))));
    %Defining only the feasible designs as having contracts available:
    for j = 1:num_designs
        IMR_Availability(i,j) = IMR_Contract(i,j)*IMR_Availability_(i);
        SURF_Availability(i,j) = SURF_Contract(i,j)*SURF_Availability_(i);
```

```
        LWI_Availability(i,j) = LWI_Contract(i,j)*LWI_Availability_(i);
        DSV_Availability(i,j) = DSV_Contract(i,j)*DSV_Availability_(i);
    end
end
%Generating a matrix with the number of contracts available for all
%markets in each epoch.
All_Contracts_Availability(:,1) = IMR_Availability_(:);
All_Contracts_Availability(:,2) = SURF_Availability_(:);
All_Contracts_Availability(:,3) = LWI_Availability_(:);
All_Contracts_Availability(:,4) = DSV_Availability_(:);

end
```

Attributes.m

```
function [Utility] = Attributes(CAPEX_Daily,OPEX_Daily,Design_Space,...
    Total_Deck_Area,Contracts_Feasible,IMR_Availability,...
    SURF_Availability,LWI_Availability,DSV_Availability)
%This function calculates the utility of each design in each epoch based
%on the attributes for the tradespace exploration.

%Initializing:
[num_epochs,num_designs] = size(Contracts_Feasible);
Utility = zeros(num_epochs,num_designs);
Utility_CAPEX = zeros(1,num_designs);
Utility_OPEX = zeros(1,num_designs);
Utility_Crane = zeros(1,num_designs);
Utility_IMR = zeros(num_epochs,num_designs);
Utility_SURF = zeros(num_epochs,num_designs);
Utility_LWI = zeros(num_epochs,num_designs);
Utility_DSV = zeros(num_epochs,num_designs);
Utility_Deck_Area = zeros(1,num_designs);

%Identifying the minimum and maximum values for each attribute:
%CAPEX attribute:
Utility_Min(1) = max(CAPEX_Daily(:,1));
Utility_Max(1) = min(CAPEX_Daily(:,1));
%OPEX attribute:
Utility_Min(2) = max(OPEX_Daily(:,1));
Utility_Max(2) = min(OPEX_Daily(:,1));
%Crane attribute:
Utility_Min(3) = min(Design_Space(:,1));
Utility_Max(3) = max(Design_Space(:,1));
%Total deck area attribute:
```

```
Utility_Min(4) = min(Total_Deck_Area);
Utility_Max(4) = max(Total_Deck_Area);
%Contract availability attribute:
for e = 1:num_epochs
%IMR availability:
IMR_Utility_Min(e) = min(IMR_Availability(e,:));
IMR_Utility_Max(e) = max(IMR_Availability(e,:));
%SURF availability:
SURF_Utility_Min(e) = min(SURF_Availability(e,:));
SURF_Utility_Max(e) = max(SURF_Availability(e,:));
%LWI availability:
LWI_Utility_Min(e) = min(LWI_Availability(e,:));
LWI_Utility_Max(e) = max(LWI_Availability(e,:));
%DSV availability:
DSV_Utility_Min(e) = min(DSV_Availability(e,:));
DSV_Utility_Max(e) = max(DSV_Availability(e,:));
%Nr. of Contracts feasible attribute:
Con_Utility_Min(e) = min(Contracts_Feasible(e,:));
Con_Utility_Max(e) = max(Contracts_Feasible(e,:));
end

%Defining the utility function of each performance attribute:
for d = 1:num_designs
    Utility_CAPEX(d) = ...
    (CAPEX_Daily(d,1)-Utility_Min(1))/(Utility_Max(1)-Utility_Min(1));
    Utility_OPEX(d) = ...
        (OPEX_Daily(d,1)-Utility_Min(2))/...
        (Utility_Max(2)-Utility_Min(2));
    Utility_Crane(d) = ...
        (Design_Space(d,1)-Utility_Min(3))/...
        (Utility_Max(3)-Utility_Min(3));
    Utility_Deck_Area(d) = ...
        (Total_Deck_Area(d)-Utility_Min(4))/...
        (Utility_Max(4)-Utility_Min(4));
    for e = 1:num_epochs
        %IMR availability attribute:
        if (IMR_Utility_Max(e) > 0)
            if (IMR_Utility_Min(e) < IMR_Utility_Max(e))
                Utility_IMR(e,d) = ...
                    (IMR_Availability(e,d)-IMR_Utility_Min(e))/...
                    (IMR_Utility_Max(e)-IMR_Utility_Min(e));
            elseif (IMR_Utility_Max(e) - IMR_Utility_Min(e) == 0)
                Utility_IMR(e,d) = 1;
            end
        else
```

```
            Utility_IMR(e,d) = 0;
        end
        %SURF availability attribute:
        if (SURF_Utility_Max(e) > 0)
            if (SURF_Utility_Min(e) < SURF_Utility_Max(e))
                Utility_SURF(e,d) = ...
                    (SURF_Availability(e,d)-SURF_Utility_Min(e))/...
                    (SURF_Utility_Max(e)-SURF_Utility_Min(e));
            elseif SURF_Utility_Max(e) - SURF_Utility_Min(e) == 0
                Utility_SURF(e,d) = 1;
            end
        else
            Utility_SURF(e,d) = 0;
        end
        %LWI availability attribute:
        if (LWI_Utility_Max(e) > 0)
            if (LWI_Utility_Min(e) < LWI_Utility_Max(e))
                Utility_LWI(e,d) = ...
                    (LWI_Availability(e,d)-LWI_Utility_Min(e))/...
                    (LWI_Utility_Max(e)-LWI_Utility_Min(e));
            elseif LWI_Utility_Max(e) - LWI_Utility_Min(e) == 0
                Utility_LWI(e,d) = 1;
            end
        else
            Utility_LWI(e,d) = 0;
        end
        %DSV availability attribute:
        if (DSV_Utility_Max(e) > 0)
            if (DSV_Utility_Min(e) < DSV_Utility_Max(e))
                Utility_DSV(e,d) = ...
                    (DSV_Availability(e,d)-DSV_Utility_Min(e))/...
                    (DSV_Utility_Max(e)-DSV_Utility_Min(e));
            elseif DSV_Utility_Max(e) - DSV_Utility_Min(e) == 0
                Utility_DSV(e,d) = 1;
            end
        else
            Utility_DSV(e,d) = 0;
        end
    end
end
%The total utility of a design in an epoch is calculated by weighting the
%performance attributes equally.
for e = 1:num_epochs
    for d = 1:num_designs
        Utility(e,d) = (1/8)*(Utility_CAPEX(d) + Utility_OPEX(d) ...
```

```
            + Utility_Crane(d) + Utility_IMR(e,d) + Utility_SURF(e,d) ...
            + Utility_LWI(e,d) + Utility_DSV(e,d) + Utility_Deck_Area(d));
        if (Utility_IMR(e,d) == 0) && (Utility_SURF(e,d) == 0) && ...
            (Utility_LWI(e,d) == 0) && (Utility_DSV(e,d) == 0)
            Utility(e,d) = 0;
        end
    end
end
end
```

MultiEpoch.m

```
function [Total_Utility] = MultiEpoch(Utility,Design_Space)
%This function calculates the average utility for each design across all
%epochs weighting all epochs as equally likely to occur.

%Initializing:
[num_epochs,num_designs] = size(Utility);
[num_designs,design_vars] = size(Design_Space);
Total_Utility = zeros(num_designs,1);

%Calculates the "total" utility with equal weight on all epochs.
for i = 1:num_epochs
    for j = 1:num_designs
        Total_Utility(j) = sum(Utility(:,j))/num_epochs;
    end
end
end
```

EraConstruction.m

```
function [Era_Description_Expectations,Era_Epoch_Progression] = ...
    EraConstruction(Epoch_Space)
%This function constructs eras that are aligned with the stakeholder
%perception of future uncertainty. The output generated is a selection
%of expected epoch variable progression. The second output variable
%generated an array with the numbers for the epochs the era consists of.

%Number of alternative eras to be evaluated:
num_eras = 5;
%Initializing:
[num_epochs,epoch_vars] = size(Epoch_Space);
Era_Description_Expectations = zeros(5,epoch_vars,num_eras);
```

```
Era_Epoch_Progression = zeros(5,num_eras);

for e = 1:num_eras
    %Era nr. 1:
    if e == 1
        %1-5 years: Oil price 70$. Initial contract secured.
        Era_Epoch_Progression(1,e) = 3;
        %6-10 years: Oil price 10$. No change from initial contractual
        %requirements.
        Era_Epoch_Progression(2,e) = 1;
        %11-15 years: Oil price 40$. Tie in need.
        Era_Epoch_Progression(3,e) = 28;
        %16-20 years: Oil price 70$. 2000 meter water depth. Tie in need.
        Era_Epoch_Progression(4,e) = 51;
        %21-25 years: Oil price 100$. 2000 meter water depth. Tie in need.
        Era_Epoch_Progression(5,e) = 52;
    %Era nr. 2:
    elseif e == 2
        %1-5 years: Oil price 70$. Initial contract secured.
        Era_Epoch_Progression(1,e) = 3;
        %6-10 years: Oil price 40$. Module size increase: 250 tonnes.
        Era_Epoch_Progression(2,e) = 6;
        %11-15 years: Oil price 10$. Module size 250 tonnes.
        Era_Epoch_Progression(3,e) = 5;
        %16-20 years: Oil price 40$. Module size 250 tonnes.
        Era_Epoch_Progression(4,e) = 6;
        %21-25 years. Oil price 70$. Module size increase: 300 tonnes.
        Era_Epoch_Progression(5,e) = 11;
    %Era nr. 3:
    elseif e == 3
        %1-5 years: Oil price 70$. Initial contract secured.
        Era_Epoch_Progression(1,e) = 3;
        %6-10 years: Oil price 70$. Module size increase: 300 tonnes.
        Era_Epoch_Progression(2,e) = 11;
        %11-15 years: Oil price 40$. Module size 300 tonnes. 2000 meter
        %water depth.
        Era_Epoch_Progression(3,e) = 22;
        %16-20 years: Oil price 70$. Module size 300 tonnes. 3000 meter
        %water depth.
        Era_Epoch_Progression(4,e) = 35;
        %21-25 years. Oil price 70$. Module size 300 tonnes. 3000 meter
        %water depth. Fibre rope technology.
        Era_Epoch_Progression(5,e) = 107;
    %Era nr. 4:
    elseif e == 4
```

```
        %1-5 years: Oil price 70$. Initial contract secured.
        Era_Epoch_Progression(1,e) = 3;
        %6-10 years: Oil price 100$. 3000 meter water depth.
        Era_Epoch_Progression(2,e) = 12;
        %11-15 years: Oil price 70$. Module size increase: 300 tonnes.
        %3000 meter water depth. Tie in need.
        Era_Epoch_Progression(3,e) = 70;
        %16-20 years: Oil price 70$. Module size 300 tonnes.
        %3000 meter water depth. Tie in need. Fibre rope technology.
        Era_Epoch_Progression(4,e) = 143;
        %21-25 years. Oil price 40$. Module size 300 tonnes.
        %3000 meter water depth. Fibre rope technology.
        Era_Epoch_Progression(5,e) = 106;
    %Era nr. 5:
    elseif e == 5
        %1-5 years: Oil price 70$. Initial contract secured.
        Era_Epoch_Progression(1,e) = 3;
        %6-10 years: Oil price 100$. Module size increase: 300 tonnes. Tie
        %in need.
        Era_Epoch_Progression(2,e) = 72;
        %11-15 years: Oil price 10$. Module size decrease: 250 tonnes. Tie
        %in need.
        Era_Epoch_Progression(3,e) = 65;
        %16-20 years: Oil price 40$. Module size 250 tonnes. 2000 meter
        %water depth. Tie in need.
        Era_Epoch_Progression(4,e) = 54;
        %21-25 years. Oil price 40$. Module size 200 tonnes. 3000 meter
        %water depth. Tie in need.
        Era_Epoch_Progression(5,e) = 50;
    end
end

%Generates the epoch variables as they evolve through each of the eras
%specified.
for i = 1:5
    for j = 1:epoch_vars
        for e = 1:num_eras
            Era_Description_Expectations(i,j,e) = ...
                Epoch_Space(Era_Epoch_Progression(i,e),j);
        end
    end
end
end
```

MultiEpochEraAnalysis.m

```
function [Utility_Era,Total_Utility_Era] = MultiEpochEraAnalysis...
    (Utility,Era_Epoch_Progression)
%This function calculates the utility for each design weighting all epochs
%in each era, thus finding the total utility of a design through an era.

%Initializing:
[num_epochs,num_designs] = size(Utility);
[num_periods,num_eras] = size(Era_Epoch_Progression);
Utility_Era = zeros(num_eras,num_designs);
Total_Utility_Era = zeros(1,num_designs);

%Calculates the "total utility" for each design for each era:
for i = 1:num_eras
    for d = 1:num_designs
        for e = 1:num_periods
            Utility_Era(i,d) = ...
                sum(Utility(Era_Epoch_Progression(:,i),d))/num_periods;
        end
    end
end
%Calculates the total weighted utility for all designs accounting for
%all eras:
for d = 1:num_designs
    Total_Utility_Era(d) = mean2(Utility_Era(:,d));
end
end
```

Pareto.m

```
function [Total_Pareto_Set,Total_Pareto_Set_Eras,Pareto_Set_Eras,...
    Pareto_Set,Pareto_Trace] = Pareto...
    (Utility,CAPEX_Total,Total_Utility,Utility_Era,Total_Utility_Era)
%This function identifies the Pareto frontier for the tradespaces of each
%epoch.

%Initializing:
[num_epochs,num_designs] = size(Utility);
[num_eras,num_designs] = size(Utility_Era);

%For each epoch:
```

```
for e = 1:num_epochs
    %Condition for while loop:
    i = 0;
    %The first element in the Pareto array:
    k = 1;
    while i == 0
        %Finding the maximum utility element.
        [a,b] = max(Utility(e,:));
        %Adding point design to Pareto array.
        Pareto_Set(e,k) = b;
        %Setting current max utility to -1 to avoid rechecking.
        Utility(e,b) = -1;
        %Setting utility of all elements with a larger cost to -1.
        for j = 1:num_designs
            if CAPEX_Total(j) >= CAPEX_Total(b)
                Utility(e,j) = -1;
            end
        end
        %Exiting while loop when the lowest cost is reached or the max
        %utility is 0.
        if (CAPEX_Total(b) == min(CAPEX_Total(:))) || (max(Utility(e,:)) == 0)
            i = 1;
        end
        %For finding next element in Pareto array.
        k = k+1;
    end
end
%Same procedure for multi-epoch (total utility):
%Condition for while loop:
i = 0;
%The first element in the Pareto array:
l = 1;
while i == 0
    %Finding the maximum utility element.
    [c,d] = max(Total_Utility(:));
    %Adding point design to Pareto array.
    Total_Pareto_Set(l) = d;
    %Setting current max utility to -1 to avoid rechecking.
    Total_Utility(d) = -1;
    %Setting utility of all elements with a larger cost to -1.
    for j = 1:num_designs
        if CAPEX_Total(j) >= CAPEX_Total(d)
            Total_Utility(j) = -1;
        end
    end
```

```
    %Exiting while loop when the lowest cost is reached.
    if (CAPEX_Total(d) == min(CAPEX_Total(:))) || ...
            (max(Total_Utility(:)) == 0)
        i = 1;
    end
    %For finding next element in Pareto array.
    l = l+1;
end

for q = 1:num_eras
%Same procedure for utility of each era:
%Condition for while loop:
i = 0;
%The first element in the Pareto array:
m = 1;
while i == 0
    %Finding the maximum utility element.
    [e,f] = max(Utility_Era(q,:));
    %Adding point design to Pareto array.
    Pareto_Set_Eras(q,m) = f;
    %Setting current max utility to -1 to avoid rechecking.
    Utility_Era(q,f) = -1;
    %Setting utility of all elements with a larger cost to -1.
    for j = 1:num_designs
        if CAPEX_Total(j) >= CAPEX_Total(f)
            Utility_Era(q,j) = -1;
        end
    end
    %Exiting while loop when the lowest cost is reached or the max
    %utility is 0.
        if (CAPEX_Total(f) == min(CAPEX_Total(:))) || ...
            (max(Utility_Era(q,:)) == 0)
        i = 1;
    end
    %For finding next element in Pareto array.
    m = m+1;
end
end

%Same procedure for multi-era (total utility weighting all eras equally):
%Condition for while loop:
i = 0;
%The first element in the Pareto array:
s = 1;
while i == 0
```

```
    %Finding the maximum utility element.
    [g,h] = max(Total_Utility_Era(:));
    %Adding point design to Pareto array.
    Total_Pareto_Set_Eras(s) = h;
    %Setting current max utility to -1 to avoid rechecking.
    Total_Utility_Era(h) = -1;
    %Setting utility of all elements with a larger cost to -1.
    for j = 1:num_designs
        if CAPEX_Total(j) >= CAPEX_Total(h)
            Total_Utility_Era(j) = -1;
        end
    end
    %Exiting while loop when the lowest cost is reached or the max
    %utility is 0.
    if (CAPEX_Total(h) == min(CAPEX_Total(:))) || ...
            (max(Total_Utility_Era(:)) == 0)
        i = 1;
    end
    %For finding next element in Pareto array.
    s = s+1;
end

%Finding the Pareto Trace (frequency of occurence of Pareto optimality):
trace = unique(Pareto_Set);
Pareto_Trace_temp = [trace,histc(Pareto_Set(:),trace)];
Pareto_Trace = [Pareto_Trace_temp(:,1), Pareto_Trace_temp(:,2)/num_epochs];

end
```

E.2 MATLAB Files for Life Cycle Path Analysis with Flexibility

This section provides the MATLAB code for the scripts and functions relating to Step 7 in the Responsive Systems Comparison method. This script is run for designs found passively value robust in the preceding steps.

LifecycleModel.m

```
%This script performs the life cycle path analysis (Step 7 of the RSC
%method).

%% Step 7 of RSC: Lifecycle path analysis with flexibility.
%Selecting era for current Monte Carlo simulation run:
```

```
[era] = MonteCarloEra(n);

%Monte Carlo simulation of time charter (day) rates:
Time_Charter_Contract = MonteCarloTimeCharter...
    (Time_Charter_Rates,T_life,T_con,n,dT,MR_rate,StD,...
    OPEX_Daily,era,Era_Epoch_Progression,All_Contracts_Availability);

%Calculating ENPV for design "Design_Selected": Inflexible design valuation.
[NPV_Vessel_Inflexible,Contract_Inflexible,Mean_NPV_Inflexible] ...
    = InflexibleVesselNPV(Era_Epoch_Progression,...
    All_Contracts,era,Design_Selected,T_con,Time_Charter_Contract,...
    CAPEX_Daily,OPEX_Daily,r_discount);

%Defining transition costs and rules:
[Transition,Transition_Cost] = TransitionRules...
    (Design_Space,Total_Deck_Area,CAPEX_DV,Design_Variables,...
    T_life,T_con,cost_factor_remove,cost_factor_install);

%Calculating ENPV for design "Design_Selected": Flexible design valuation.
%Assuming transitions are allowed according to transition rules.
[NPV_Vessel_Flexible,Contract_Flex,Design_Transition,...
    Mean_NPV_Flexible] = FlexibleVesselNPV(Design_Selected,...
    All_Contracts,Era_Epoch_Progression,era,Transition,Transition_Cost,...
    T_con,Time_Charter_Contract,CAPEX_Daily,OPEX_Daily,r_discount);
```

MonteCarloEra.m

```
function [era] = MonteCarloEra(n)
%This function specifies which era occurs for each simulation run.

%Initializing:
era = zeros(1,n);
%Monte Carlo loop:
for i = 1:n
    %Determines which era "e" will occur, with equal probabilities.
    r = rand();
    if r <= 0.2
        era(i) = 1;
    elseif r > 0.2 && r <= 0.4
        era(i) = 2;
    elseif r > 0.4 && r <= 0.6
        era(i) = 3;
    elseif r > 0.6 && r <= 0.8
        era(i) = 4;
```

```
    elseif r > 0.8 && r <= 1
        era(i) = 5;
    end
end
end
```

MonteCarloTimeCharter.m

```
function Time_Charter_Contract = MonteCarloTimeCharter...
    (Time_Charter_Rates,T_life,T_con,n,dT,MR_rate,StD,...
    OPEX_Daily,era,Era_Epoch_Progression,All_Contracts_Availability)
%This function simulates the time charter rates for the vessels (day rate),
%based on a mean reverting process.

%Initializing:
markets = length(Time_Charter_Rates);
Time_Charter_Simulated = zeros(n,markets,T_life);
d_Time_Charter = zeros(n,markets,T_life);
Time_Charter_Mean = zeros(markets,T_life);
Time_Charter_Contract = zeros(n,markets,T_life);

%Monte Carlo loop:
for i = 1:n
    %Generating TC rates for each market.
    for m = 1:markets
        %Yearly income from time charter rates:
        Time_Charter_Simulated(i,m,1) = Time_Charter_Rates(m);
        %Mean time charter rate.
        Time_Charter_Mean(m,1) = Time_Charter_Rates(m);
        %Simulating time charter rates according to a mean reverting
        %process:
        for t = 2:dT:T_life
            Time_Charter_Mean(m,t) = Time_Charter_Mean(m,t-1);
            %Change in time charter is a mean reverting process:
            d_Time_Charter(i,m,t-1) = MR_rate(m)*(Time_Charter_Mean(m,t-1) ...
                - Time_Charter_Simulated(i,m,t-1))*dT ...
                + StD(m)*normrnd(0,StD(m));
            %Adding the change in time charter to the previous rate.
            Time_Charter_Simulated(i,m,t) = ...
                (d_Time_Charter(i,m,t-1) + ...
                Time_Charter_Simulated(i,m,t-1));
        end
        for t = 1:T_life
            %Specifies which period each year belongs to.
```

```
            if (t < T_con+1)
                tt = 1;
            elseif (t >= T_con+1) && (t < 2*T_con+1)
                tt = 2;
            elseif (t >= 2*T_con+1) && (t < 3*T_con+1)
                tt = 3;
            elseif (t >= 3*T_con+1) && (t < 4*T_con+1)
                tt = 4;
            elseif (t >= 4*T_con+1) && (t < 5*T_con+1)
                tt = 5;
            end
            %Time charter is agreed for five years.
            if ((t == 1) || (t == T_con+1) || (t == 2*T_con+1) || ...
                    (t == 3*T_con+1) || (t == 4*T_con+1))
                %Accounting for the probability of winning a contract.
                %Also accounting for lay up when TC are below OPEX.
                if ((rand() > (All_Contracts_Availability...
                        (Era_Epoch_Progression(tt,era(i)),m))/...
                        max(All_Contracts_Availability...
                        (Era_Epoch_Progression(tt,:),m)))) || ...
                        (Time_Charter_Simulated(i,m,t) ...
                        < min(OPEX_Daily(:)))
                    Time_Charter_Contract(i,m,t) = 0;
                else
                    Time_Charter_Contract(i,m,t) = ...
                        Time_Charter_Simulated(i,m,t);
                end
            else
                Time_Charter_Contract(i,m,t) = ...
                    Time_Charter_Contract(i,m,t-1);
            end
        end
    end
end
end
```

MonteCarloNPV.m

```
function [NPV_Epoch_Inflex] = MonteCarloNPV(T_con,Time_Charter_Contract,...
    CAPEX_Daily,OPEX_Daily,r_discount,Design_Space)
%This function calculates the NPV that can be achieved for an INFLEXIBLE
%vessel in each market in each epoch in an era.

%Initializing:
```

```matlab
num_periods = 5;
[num_designs,design_vars] = size(Design_Space);
[n,markets,T_life] = size(Time_Charter_Contract);
NPV_Epoch_Inflex = zeros(n,markets,num_designs,num_periods);

%Monte Carlo loop:
for i = 1:n
    for d = 1:num_designs
        for m = 1:markets
            for t = 1:T_life
                %Finding NPV for each contract period, market and design.
                if t < T_con+1
                    NPV_Epoch_Inflex(i,m,d,1) = ...
                        (350*Time_Charter_Contract(i,m,t) ...
                        - 365*(CAPEX_Daily(d,t) + OPEX_Daily(d,t)))/...
                        (1+r_discount) + NPV_Epoch_Inflex(i,m,d,1);
                elseif t >= T_con+1 && t < 2*T_con+1
                    NPV_Epoch_Inflex(i,m,d,2) = ...
                        (350*Time_Charter_Contract(i,m,t) ...
                        - 365*(CAPEX_Daily(d,t) + OPEX_Daily(d,t)))/...
                        (1+r_discount) + NPV_Epoch_Inflex(i,m,d,2);
                elseif t >= 2*T_con+1 && t < 3*T_con+1
                    NPV_Epoch_Inflex(i,m,d,3) = ...
                        (350*Time_Charter_Contract(i,m,t) ...
                        - 365*(CAPEX_Daily(d,t) + OPEX_Daily(d,t)))/...
                        (1+r_discount) + NPV_Epoch_Inflex(i,m,d,3);
                elseif t >= 3*T_con+1 && t < 4*T_con+1
                    NPV_Epoch_Inflex(i,m,d,4) = ...
                        (350*Time_Charter_Contract(i,m,t) ...
                        - 365*(CAPEX_Daily(d,t) + OPEX_Daily(d,t)))/...
                        (1+r_discount) + NPV_Epoch_Inflex(i,m,d,4);
                elseif t >= 4*T_con+1 && t < 5*T_con+1
                    NPV_Epoch_Inflex(i,m,d,5) = ...
                        (350*Time_Charter_Contract(i,m,t) ...
                        - 365*(CAPEX_Daily(d,t) + OPEX_Daily(d,t)))/...
                        (1+r_discount) + NPV_Epoch_Inflex(i,m,d,5);
                end
            end
        end
    end
end
end
```

InflexibleVesselNPV.m

```
function [NPV_Vessel_Inflexible,Contract_Inflex,Mean_NPV_Inflexible] ...
    = InflexibleVesselNPV(Era_Epoch_Progression,All_Contracts,era,...
    Design_Selected,T_con,Time_Charter_Contract,CAPEX_Daily,OPEX_Daily,...
    r_discount)
%This function calculates the net present value of one selected vessel
%over its lifetime, given that it is not allowed to change.

%Initializing:
[n,markets,T_life] = size(Time_Charter_Contract);
[num_epochs,num_designs,markets] = size(All_Contracts);
[num_periods,num_eras] = size(Era_Epoch_Progression);
NPV_Vessel_Inflexible = zeros(1,n);
NPV_Epoch_Inflex = zeros(n,markets,num_designs,num_periods);
Contract_Inflex = zeros(num_periods,n);
%Current design selection:
d = Design_Selected;

%Monte Carlo loop:
for i = 1:n
    %First contract is a certain IMR contract!
    for t = 1:T_con
        NPV_Vessel_Inflexible(i) = (350*Time_Charter_Contract(i,1,t) ...
            - 365*(CAPEX_Daily(Design_Selected,t) ...
            + OPEX_Daily(Design_Selected)))/(r_discount) ...
            + NPV_Vessel_Inflexible(i);
    end
    Contract_Inflex(1,i) = 1;
    %Evaluating NPV for vessel d assuming that the vessel can not be
    %changed.
    for t = (T_con+1):T_life
        %Matches year and contract period.
        if (t >= T_con+1) && (t < 2*T_con+1)
            tt = 2;
        elseif (t >= 2*T_con+1) && (t < 3*T_con+1)
            tt = 3;
        elseif (t > 3*T_con+1) && (t < 4*T_con+1)
            tt = 4;
        elseif (t > 4*T_con+1) && (t < 5*T_con+1)
            tt = 5;
        end
        %Calculating the NPV for each epoch for design d in each market.
        for m = 1:markets
```

```
            %NPV if contract is feasible.
            if (All_Contracts(Era_Epoch_Progression(tt,era(i)),d,m) == 1)
                NPV_Epoch_Inflex(i,m,d,tt) = ...
                    (350*Time_Charter_Contract(i,m,t) ...
                    - 365*(CAPEX_Daily(d,t) + OPEX_Daily(d)))/...
                    (1+r_discount) + NPV_Epoch_Inflex(i,m,d,tt);
            %NPV if contract is infeasible.
            else
                NPV_Epoch_Inflex(i,m,d,tt) = ...
                    - 365*(CAPEX_Daily(d,t) + OPEX_Daily(d))/...
                    (1+r_discount) + NPV_Epoch_Inflex(i,m,d,tt);
            end
        end
    end
    %Selecting most profitable contract for current epoch:
    for tt = 2:num_periods
        [Current_NPV_Epoch(i,tt),Contract_Inflex(tt,i)] ...
            = max(NPV_Epoch_Inflex(i,:,d,tt));
        if (All_Contracts(Era_Epoch_Progression(tt,era(i)),d,...
                Contract_Inflex(tt,i)) == 0)
            Contract_Inflex(tt,i) = 0;
        end
        NPV_Vessel_Inflexible(i) = ...
            NPV_Vessel_Inflexible(i) + Current_NPV_Epoch(i,tt);
    end
end

%Computing mean NPV for inflexible design:
Mean_NPV_Inflexible = mean2(NPV_Vessel_Inflexible);
end
```

TransitionRules.m

```
function [Transition,Transition_Cost] = TransitionRules...
    (Design_Space,Total_Deck_Area,CAPEX_DV,Design_Variables,...
    T_life,T_con,cost_factor_remove,cost_factor_install)
%This function generates a NxN matrix defining whether a transition is
%allowed. It calculates the costs for making such transitions.

%Initializing:
[levels,design_vars] = size(Design_Variables);
num_periods = T_life/T_con;
[num_designs,design_vars] = size(Design_Space);
Transition = zeros(num_designs);
```

```
Transition_Cost = zeros(num_designs,num_designs,num_periods);
Transition_Cost_Temp = zeros(num_designs,num_designs,T_life);

%Defines which transitions from DESIGN i to j, are feasible.
for i = 1:num_designs
    for j = 1:num_designs
        %Transition is possible if the total deck area remains the same.
        if Total_Deck_Area(i) == Total_Deck_Area(j)
            Transition(i,j) = 1;
        end
    end
end
%Calculates the costs of making a transition from DESIGN i to DESIGN j:
for i = 1:num_designs
    for j = 1:num_designs
        if Transition(i,j) == 1
            for k = 1:design_vars
                if Design_Space(i,k) ~= Design_Space(j,k)
                    %The cost of transitioning between designs.
                    for l = 1:levels
                        if (Design_Space(i,k) == Design_Variables(l,k))
                            Transition_Cost_Temp(i,j,1) ...
                                = cost_factor_remove*CAPEX_DV(l,k) ...
                                + Transition_Cost_Temp(i,j,1);
                        elseif (Design_Space(j,k) == Design_Variables(l,k))
                            Transition_Cost_Temp(i,j,1) ...
                                = cost_factor_install*CAPEX_DV(l,k) ...
                                + Transition_Cost_Temp(i,j,1);
                        end
                    end
                end
            end
        %Setting transition costs to infinity for illegal transitions.
        else
            Transition_Cost_Temp(i,j,:) = inf;
        end
        for t = 2:T_life
            Transition_Cost_Temp(i,j,t) = Transition_Cost_Temp(i,j,t-1);
        end
        %Defines the transitions at the times transition is possible:
        Transition_Cost(i,j,1) = Transition_Cost_Temp(i,j,1);
        Transition_Cost(i,j,2) = Transition_Cost_Temp(i,j,T_con+1);
        Transition_Cost(i,j,3) = Transition_Cost_Temp(i,j,2*T_con+1);
        Transition_Cost(i,j,4) = Transition_Cost_Temp(i,j,3*T_con+1);
        Transition_Cost(i,j,5) = Transition_Cost_Temp(i,j,4*T_con+1);
```

```
    end
end
end
```

FlexibleVesselNPV.m

```
function [NPV_Vessel_Flexible,Contract_Flex,Design_Transition,...
    Mean_NPV_Flexible] = FlexibleVesselNPV(Design_Selected,...
    All_Contracts,Era_Epoch_Progression,era,Transition,Transition_Cost,...
    T_con,Time_Charter_Contract,CAPEX_Daily,OPEX_Daily,r_discount)
%This function calculates the expected NPV for a vessel for which
%flexibility can be exercised according to some transition rules.

%Initializing:
[n,markets,T_life] = size(Time_Charter_Contract);
[num_epochs,num_designs,markets] = size(All_Contracts);
[num_periods,num_eras] = size(Era_Epoch_Progression);
NPV_Vessel_Flexible = zeros(1,n);
Contract_Flex = zeros(num_periods,n);
Design_Transition = Design_Selected*ones(num_periods,n);
NPV_Epoch_Flex = zeros(n,markets,num_designs,num_periods);

%Monte Carlo loop:
for i = 1:n
    %First contract certain IMR contract:
    for t = 1:T_con
        NPV_Vessel_Flexible(i) = (350*Time_Charter_Contract(i,1,t) ...
            - 365*(CAPEX_Daily(Design_Selected,t) ...
            + OPEX_Daily(Design_Selected)))/(r_discount) ...
            + NPV_Vessel_Flexible(i);
    end
    Contract_Flex(1,i) = 1;
    d = Design_Selected;
    %Later contracts:
    for t = (T_con+1):T_life
        %Matches year and contract period.
        if (t >= T_con+1) && (t < 2*T_con+1)
            tt = 2;
        elseif (t >= 2*T_con+1) && (t < 3*T_con+1)
            tt = 3;
        elseif (t > 3*T_con+1) && (t < 4*T_con+1)
            tt = 4;
        elseif (t > 4*T_con+1) && (t < 5*T_con+1)
            tt = 5;
```

```
        end
        %Current design is the one transitioned into.
        d = Design_Transition(tt-1,i);
        for j = 1:num_designs
            for m = 1:markets
                %Can never make a transition that would not be allowed from
                %the initial design.
                if Transition(Design_Selected,j) == 0
                    NPV_Epoch_Flex(i,m,j,tt) = -inf;
                elseif Transition(Design_Selected,j) == 1
                    %The case that design d is infeasible for a market m.
                    %Check the opportunity for transitioning:
                    if (All_Contracts(Era_Epoch_Progression(tt,era(i)),...
                            d,m) == 0)
                        %If contract m is unavailable for design j:
                        if (All_Contracts(Era_Epoch_Progression...
                                (tt,era(i)),j,m) == 0)
                            NPV_Epoch_Flex(i,m,j,tt) = -inf;
                        %If contract m is available for design j:
                        elseif (All_Contracts(Era_Epoch_Progression...
                                (tt,era(i)),j,m) == 1)
                            %Accounting for the time taken to exercise
                            %options:
                            Nr_Days_Operative = 330;
                            %Calculating NPV for epoch:
                            NPV_Epoch_Flex(i,m,j,tt) ...
                                = (Nr_Days_Operative*...
                                Time_Charter_Contract(i,m,t) ...
                                - 365*(CAPEX_Daily(Design_Selected,t) ...
                                + OPEX_Daily(j)) ...
                                - Transition_Cost(d,j,tt))...
                                /(1+r_discount) + NPV_Epoch_Flex(i,m,j,tt);
                        end
                    %The case that design d is feasible for a market m.
                    elseif (All_Contracts(Era_Epoch_Progression...
                            (tt,era(i)),d,m) == 1)
                        %If contract m is unavailable for design j:
                        if (All_Contracts(Era_Epoch_Progression...
                                (tt,era(i)),j,m) == 0)
                            NPV_Epoch_Flex(i,m,j,tt) = -inf;
                        %If contract m is available for design j:
                        elseif (All_Contracts(Era_Epoch_Progression...
                                (tt,era(i)),j,m) == 1)
                            %Days operative dependent on whether changes
                            %are made:
```

```
                            if j == d;
                                Nr_Days_Operative = 350;
                            else
                                Nr_Days_Operative = 330;
                            end
                            %Calculating NPV for epoch:
                            NPV_Epoch_Flex(i,m,j,tt) ...
                                = (Nr_Days_Operative*...
                                Time_Charter_Contract(i,m,t) ...
                                - 365*(CAPEX_Daily(Design_Selected,t) ...
                                + OPEX_Daily(j)) ...
                                - Transition_Cost(d,j,tt))...
                                /(1+r_discount) + ...
                                NPV_Epoch_Flex(i,m,j,tt);
                        end
                    end
                end
            end
            %Maximizing NPV with regards to market.
            Current_NPV_Epoch(i,j,tt) = max(NPV_Epoch_Flex(i,:,j,tt));
        end
        %Finding the design (transition) giving this NPV.
        [NPV(tt,i),Design_Transition(tt,i)] = ...
            max(Current_NPV_Epoch(i,:,tt));
        %Identifying the contract that gives this NPV.
        for m = 1:markets
            if NPV(tt,i) == NPV_Epoch_Flex(i,m,Design_Transition(tt,i),tt)
                Contract_Flex(tt,i) = m;
            end
            for j = 1:num_designs
                NPV_Epoch_Flex(i,m,j,tt) = 0;
            end
        end
        NPV_Vessel_Flexible(i) = NPV(tt,i) + NPV_Vessel_Flexible(i);
    end
end
%Calculating the mean NPV for the flexible design:
Mean_NPV_Flexible = mean2(NPV_Vessel_Flexible(:));
end
```