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Identification and Valuation of Flexibility in Marine Systems Design

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Master Thesis in Marine Systems

for

Stud. techn. Carl Fredrik Rehn

"Identification and Valuation of Flexibility in Marine Systems Design"

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Background

Capital-intensive ocean engineering projects often involve a high degree of risk and uncertainty related to their future operating environment. Uncertainty is an intrinsic property of factors such as the state of the economy, oil prices, supply and demand, environmental regulations and technological innovations. In the shipping and offshore markets, much of the focus on handling uncertainty has been on an operational level, often by using derivatives to hedge risk. However, system designers have recently begun to address the need for other methods for handling uncertainty, such as by designing flexible solutions that can continue to deliver value in many alternative operating contexts by focusing on exploiting opportunities and mitigating downside risks.

The focus in this project is to address how one can better handle uncertainties by flexibility, through means of properly identifying and valuing flexible design alternatives. Further, as these methods are not properly established in the industry, there is a need for addressing how flexibility can be quantitatively assessed, and how an analysis framework can serve as a base of communication between key non-technical and technical players in the industry.

In the fall of 2014, a project thesis with the topic “Comparing Models Capturing the Value of Flexibility in Ocean Engineering Systems” was written as a an introduction project to the master thesis. The master thesis deadline is September 14th 2015, which is later than normal. This is because the author is on a department sponsored integrated PhD program and has undertaken coursework the spring of 2015.

Primary Objective

The primary objective of this thesis is to discuss and compare methods for identifying and valuing flexibility for applications in marine systems design, and through an illustrative study present a generic approach for quantifying the added value obtained by flexibility.

Scope of Work

The candidate should presumably cover the following main points:

1. Present an introduction of relevant topics for handling uncertainty in marine systems design, such as flexibility, real options theory, responsive system comparison method and epoch-era analysis.

2. Present and discuss a framework for identifying and quantifying the value of flexibility. This includes discussing the following areas:
   (a) Methods for estimating and modelling the future.
   (b) Methods for identifying which types of flexibility that are relevant for a design.
   (c) Methods for choosing between flexible designs, by valuation and quantification of flexibility.
   (d) Approaches for choosing which methods to use when.

3. Present an illustrative case study where the framework for flexibility identification and valuation is demonstrated.

4. Discuss and conclude on the methods for flexibility analysis, and on their use in marine systems design.

Modus Operandi

Professor Stein Ove Erikstad and Professor Bjørn Egil Asbjørnslett will be the supervisors at NTNU. The work shall follow the NTNU guidelines for Master thesis work. The workload shall correspond to 30 credits.

Stein Ove Erikstad
Professor/Main Supervisor

Preface

This thesis is the final part of my Master of Science degree with specialization in Marine Systems Design at the department of Marine Technology (IMT) at the Norwegian University of Science and Technology (NTNU). The work has been entirely written at NTNU during the spring and summer of 2015. The workload corresponds to 30 ECTS.

The master thesis builds on work done in the project thesis written in the fall of 2014, with the topic "Comparing Models Capturing the Value of Flexibility in Ocean Engineering Systems".

During the fall semester of 2014, I also started an integrated Ph.D. program at the same department at NTNU. Even though this master thesis stands alone, it is intended to serve as an introduction to the following years of my Ph.D. research at NTNU.

Trondheim, Norway, September 2015

Carl Fredrik Rehn

Acknowledgement

I would like to thank my supervisors, professor Stein Ove Erikstad and professor Bjørn Egil Asbjørnslett, for providing relevant literature and valuable advice during the autumn semester of 2014 and spring semester of 2015. Furthermore, I would like to thank Océane Balland for guidance and advice on the topic and professor Marvin Rausand for providing a free NTNU thesis LaTeX template online.

I would also like to thank interview objects at DNV GL, including Ketil Aamnes, Per Marius Berrefjord, Arnstein Eknes, Martin Wold, Magnus Lande and Torill Osberg for valuable thoughts and feedback.

Thank you,

Carl Fredrik Rehn

Summary

Marine systems, typically related to transport services and offshore petroleum projects, are often complex and involve a high degree of uncertainty related to their future operating context. Uncertain factors, such as oil prices and changing environmental regulations, are usually highly influential for the performance of these projects and introduce risks for investors in the capital-intensive maritime industry.

This thesis investigates how flexibility can be considered at the design stage for handling uncertainty for marine systems, in contrast to traditional post-design operational methods. Flexibility opens up for both reducing the downside risk and taking advantage of upside possibilities, hence increasing the expected value of a design. Even though real options analysis represents an established approach for analysing flexibility, it may be inappropriate for more complex systems. To better structure options for marine systems design, a differentiation is made between more traditional, operational "on" options, and more complex, technical "in" options. Choosing the right method for analysis is ambiguous, therefore multiple approaches for identifying and valuing relevant flexibilities are discussed in this thesis. Identification methods include interviews and different systems engineering platforms for exploring how designs respond to changing contextual parameters. Valuation approaches include traditional analytical, lattice and Monte Carlo simulation methods for pricing real options, and more novel tradespace evaluation techniques.

A generic framework for flexibility analysis is presented, serving as a stepwise approach to quantifying flexibility and as a means of communication between analysts and decision makers, both technical and non-technical. The flexibility analysis framework is illustrated through a case study of a large container ship design. By using screening methods to identify candidate flexibilities such as capacity expansion and fuel-switching, and Monte Carlo simulations for valuation, it was found that flexibility increases the profitability index by 27%, on a $200 million investment. Furthermore, it was demonstrated that screening and simulation methods are appropriate for the use in design of large commercial deep-sea marine transportation systems.

From an established real options valuation side, it is obvious that strategic flexibility has value, however, for non-standard applications typically involving complex "in" options, it is more ambiguous how to proceed. Even though system analysts recognise the value of flexibility, there is still a need for further research since flexibility rarely is seen in the maritime industry.

Sammendrag

Marine systemer, typisk relatert til transport og offshore petroleumsprosjekter, er ofte komplekse og har en høy grad av usikkerhet knyttet til deres fremtidige operasjonsomgivelser. Usikre faktorer, som for eksempel oljepriser og skiftende miljøreguleringer, er vanligvis svært innflytelsesrike for verdien av disse prosjektene og introduserer risiko for investorer i den kapitalintensive maritime industrien.

Denne oppgaven undersøker hvordan fleksibilitet kan betraktes på prosjekteringsstadiet for håndtering av usikkerhet for marine systemer, i motsetning til tradisjonelle operasjonelle metoder for å forsikre mot risiko. Fleksibilitet åpner opp for både å redusere nedsiderisiko og utnytte oppsidemuligheter, og kan dermed øke den forventede verdien til et prosjekt. Selv om realopsjonsanalyse representerer en etablert metode for å analysere fleksibilitet, kan den være lite egnet for mer komplekse systemer. For å bedre strukturere opsjoner i prosjektering av marine systemer, kan man skille mellom mer tradisjonelle, operasjonelle "på" opsjoner, og mer komplekse, tekniske "i" opsjoner. Hvordan man skal gå frem for å velge riktig metode for analyse kan være uklart, derfor er flere tilnærminger for å identifisere og verdsette fleksibilitet diskutert i denne avhandlingen. Identifiseringsmetoder omfatter intervjuer og ulike systemtekniske plattformer for å utforske hvordan et design reagerer på skiftende kontekstuelle parametere. Metoder for verdsetting inkluderer analytiske, trær og Monte Carlo simuleringer for realopsjoner, og nyere tekniske metoder relatert til utforskning av designrom.

Et generisk rammeverk for fleksibilitetsanalyse er presentert, som fungerer som en trinnvis tilnærming til kvantifisering av fleksibilitet i tillegg til et middel for kommunikasjon mellom analytikere og beslutningstakere, både tekniske og ikke-tekniske. Rammeverket for fleksibilitetsanalyse er illustrert gjennom en illustrativ studie av et stort containerskip. Ved å bruke utvelgingsmetoder for å identifisere fleksible kandidater som kapasitetsutvidelsesopsjoner og drivstoffbytteopsjoner, og Monte Carlo-simuleringer for verdivurdering, ble det funnet at fleksibilitet øker lønnsomheten med 27%, på en $200 millioner investering. Videre ble det vist at utvelgings- og simuleringsmetoder er egnet for bruk ved prosjektering av store kommersielle marine transportsystemer.

Fra en etablert realopsjonsside er det åpenbart at strategisk fleksibilitet har verdi, men for mer utradisjonelle applikasjoner som typisk involverer komplekse "i" opsjoner, er det mer tvetydig hvordan man skal går frem. Selv om verdien av fleksibilitet er anerkjent av analytikere, er det fortsatt behov for ytterligere forskning siden fleksibilitet i design sjelden er sett i den maritime næringen.

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Chapter 1

Introduction

This first chapter provides an introduction to the topic of handling uncertainty by flexibility in marine systems design, a background literature survey, the main objectives of the thesis, research limitations and the approach for answering the objectives, before briefly summarising how the rest of the thesis is structured.

1.1 Introduction

When designing ocean engineering systems, such as ships, rigs and aquaculture installations, there is a considerable amount of risk and uncertainty related to key aspects of the systems' future operating context. Uncertainty is an intrinsic property of factors such as the state of the economy, oil prices, supply and demand, environmental regulations and technological innovations. Traditional design methods do not explicitly take this into consideration, but system design practise has begun to address the need for methods for handling uncertainty, resulting in robust or flexible system designs.

> *Few will argue that these are not interesting times for the shipping industry. Freight rates have risen to unprecedented levels and have increased by almost 300 per cent over the period from 2003 to mid-2008. This increase in freight rates was followed by a corresponding drop of 95 per cent over the last quarter of 2008.*
>
> Alizadeh and Nomikos (2009)

Managers in the maritime industries have always tried to handle risks on their capital-intensive assets, but the methods used are typically on the operational level. That is, managers incorporate measures to hedge against risk for a given design, by the use of established market mechanisms such as forwards, futures and other derivatives. In contrast, the focus in this thesis will rather be on investigating how one can handle relevant uncertainties at the design level of the system, with focus on incorporation of flexibility. This involves both optimizing for the more certain near future scenarios, while still incorporating enough flexibility for the more uncertain long-term use of the design. Flexibility in design enables systems to deliver value in many alternative operating contexts by focusing on exploiting opportunities and mitigating downside risks.

The central point is that not considering uncertainties when designing marine systems may lead to suboptimal solutions, or even catastrophic system failures. Real options analysis has traditionally been applied to systems to assess post-design managerial flexibility. More recently, applications of real options theory have been applied to the quantification of flexibility in system design, involving more complex real options that touch upon both technical engineering elements and managerial strategies.

1.2 Background

Quantitative methods for risk management were probably first used in the financial sector for designing portfolios with different risk profiles. This was taken further for pricing financial options, where significant contributions have been developed such as the famous Black-Scholes analytical formula (Black and Scholes, 1973) for pricing European style options. Lattice methods for pricing options were developed based on the similar terminology (Cox et al., 1979). Nelson and Ramaswamy (1990) expand on the lattice theory with a model for incorporating stochastic mean-reverting processes. In later years Monte Carlo simulation (MCS) methods have been developed for pricing a wide variety of options. McDonald (2003) provides a general overview of pricing of derivatives.

Financial methods for managing risk were later applied on "real" investment projects, using real options analysis. The term was coined down by Myers in 1977 and the framework opened up a new method for quantifying managerial flexibility. Real options, managerial flexibility, investments under uncertainty and strategies in resource allocation is discussed by Trigeorgis (1996) and Dixit and Pindyck (1994). Flexibility in dual fuel industrial boilers are discussed by Kulatilaka (1993). Real option applications in shipping was first proposed by Dixit (1988, 1989), where decisions to lay-up, enter and exit the market were evaluated. Bjerksund and Ekern (1995) discuss contingent claims evaluation of mean reverting cash flows in shipping. Several other studies extend the application of real options in shipping investments and operations, including analysis of options in shipbuilding contracts (Hoegh, 1998), real option approach for ship investment under uncertainty (Bendall and Stent, 2005) and the evaluation of market switching for combination carriers (Soedal et al., 2008). General aspects of derivatives and risk management in shipping are discussed by Alizadeh and Nomikos (2009), where they argue that the topic of applying real option analysis in shipping investment and operations has been in focus of much academic research due to the high number of strategic options available and the high potential upside.

Research on handling uncertainty in engineering systems has been provided by research groups at MIT. Implementation and valuation of flexibility in different types of engineering projects are discussed by the book by de Neufville and Scholtes (2011). Wang and Neufville (2006) and Wang (2005) separate real options "in" and "on" projects, where "in" options relate to more complex technical systems where technology is not treated as a black box. This separation is highly relevant for valuing physical real options at the design stage of engineering systems. Flexible product platforms are discussed in Suh (2005), and use of platforms and real options in large-scale engineering systems with applications to FPSOs are discussed by Kalligeros (2006). Mikaelian (2009) discusses model-based identification and valuation of options under uncertainty and Cardin (2011) presents a quantitative performance-based evaluation of a procedure for flexible design concept generations. These studies often rely on methods for representing systems such as the Design Structure Matrix (DSM), which was introduced by Don Steward in the 1970s (Steward, 1981, 1991) and are generally described by Eppinger and Browning (2012). Exploration of flexible strategies in engineering systems using screening models with applications to offshore petroleum projects is discussed by Lin (2008) and Lin et al. (2013). In a working paper by Cardin and de Neufville (2008) they discuss methods for identification and valuation of flexibility in design of engineering systems, and present a framework for choosing which method to use when. Cardin et al. (2015) present a framework for flexibility analysis for engineering design projects in practice and use it to improve the lifecycle performance for an on-shore LNG project design.

The Systems Engineering Advancement research initiative (SEAri) group at MIT has integrated flexibility in design and real option methods to a more complete framework for designing value robust systems under uncertainty. McManus and Hastings (2006) discuss a framework for understanding uncertainty and its mitigation and exploitation in complex systems. Ross et al. (2008b) present a system engineering approach on "ilities", such as flexibility and adaptability, to handle uncertainties in design of engineering systems. Ross and Rhodes (2008a,b) discuss Epoch-Era Analysis (EEA) as a framework for scenario planning, by combining static epochs into eras, providing a structured way to analyse a system in a changing contextual environment. The Responsive System Comparison (RSC) method presented by Ross et al. (2008a, 2009) builds on EEA and is developed with emphasis on designing value robust systems with more focus on the stakeholders. Ross (2006) presents filtered outdegree as a quantitative measure of changeability and Fitzgerald (2012) presents a Valuation Approach for Strategic Changeability (VASC). An empirical investigation of system changes to understand links between design decisions and ilities is performed by Beesemyer et al. (2012).

Erikstad and Rehn (2015) discuss state-of-the-art methods for handling uncertainty in marine systems design, with focus on flexibility valuation methods. Patricksson (2012) discusses design of semi-submersible platforms in future operating scenarios. A real options analysis for environmental compliance is discussed by Acciaro (2014). Gaspar et al. (2013, 2014, 2015) apply the EEA and RCS methods on offshore ship design applications. Further use of EEA and RSC for marine engineering applications is explored by Keane (2014) and Pettersen (2015). Real options and flexibility for design of naval ship are discussed by Gregor (2003) and Page (2012).

Stochastic optimization represents an alternative path for decision-making under uncertainty, extending on the deterministic optimization approach to problem solving by explicitly considering alternative future scenarios with corresponding probability distributions. General stochastic optimization is discussed by Birge and Louveaux (2011) and aspects of modelling with stochastic optimization, including applications to real options, is presented by King and Wallace (2012). Lund (1999) develops a stochastic dynamic optimization model for evaluating offshore petroleum projects under uncertainty, which handles both market risk and reservoir uncertainty. Wang and Neufville (2004) use stochastic mixed-integer optimization to analyse real options in engineering systems. Diez and Peri (2010) present a two-stage stochastic model for ship design optimization under uncertainty. Stochastic optimization for maritime fleet renewal problems is discussed by Pantuso (2013) and Bakkehaug et al. (2014), and for planning vessel air emission regulations compliance under uncertainty by Balland et al. (2013). Stochastic optimization is also used for the fleet renewal problem with regional emission limitations (Patricksson et al., 2015).

Methods for handling uncertainty and valuing flexibility discussed in the literature often have limited records related to marine system design, making it an interesting field to study.

1.3 Objectives

The overall goal for this thesis is to discuss and get a better understanding of how flexibility can be used to handle contextual uncertainty in design of marine systems. In order to answer this, the following objectives are to be met in this Master's thesis:

1. Present and discuss relevant methodologies for identifying and valuing flexibilities that can be applied to design of marine systems.

2. Identify a generic framework for flexibility analysis that can be used to quantify the added value of flexibility.

3. Apply the flexibility analysis framework on an illustrative case of the design of a large container vessel.

4. Discuss and conclude on the results of the methods and materials presented and their particular applicability in design of marine systems.

1.4 Limitations

The main limitation in this thesis is related to the availability of relevant market data for the case study, and to get insight into how strategic decisions are made in the industry related to the exercise of the options in the case. Since the weight in this thesis is on the methods rather than the numerical calculations, insignificant time was devoted to market research and the base-case design parameters for the container ship were for simplicity taken from the literature.

1.5 Approach

In this thesis a number of alternative approaches for handling design stage uncertainty for marine systems are evaluated, focusing on state-of-the-art methods for identification and valuation of flexibility. This will mainly involve aspects of traditional finance related real options analysis, and more recently developed methods for analysing flexibility in complex engineering systems.

The research approach in this thesis follows the traditional IMRAD organizational structure: introduction, methods, results, and discussion. Since this thesis has particular focus on the methods for analysing flexibility, the "methods" part of IMRAD is divided into parts that are analysed individually, before being synthesised to a methodological framework. Hence, after the objectives are presented in the introduction, the problem is divided into three individual theory parts presenting relevant methods for modelling the future and for identifying and valuing flexibility. Then, this material is synthesized into a generic framework for analysing flexibility in marine systems design, before an illustrative example using this framework is presented on a large container ship. In the end there are discussions and conclusions.

The flexibility analysis framework is intended to be used by maritime consultants, for example at DNV GL Maritime Advisory. The way of thinking is then: *How can maritime consultants sit down with their customers and quantitatively assess flexibility for handling uncertainty? How can an analysis framework serve as a base of communication between key non-technical and technical stakeholders, designers and consultants?*

1.6 Structure of the Report

The rest of the thesis is organized as follows:

- Chapter 2 gives an introduction to uncertainty and how flexibility in design can be used to handle uncertainty. Further, different methods for handling uncertainty is presented, including finance and real options theory, systems engineering with tradespace and design structure matrix (DSM) methods, and stochastic programming. Weight is on flexibility and real options, where real options are separated into "in" and "on" options.

- Chapter 3 presents relevant approaches one can take for modelling the future. These include time series and stochastic processes for more progressive uncertainties, and methods for drastic uncertainties such as the Epoch-Era framework.

- Chapter 4 presents methods for identification of candidate design flexibilities, including interview methods, information flow methods, screening models and an approach using tradespace exploration related methods.

- Chapter 5 presents methods for valuation and quantification of design flexibilities, including analytical, tree and simulations methods for real options pricing and a relatively new valuation approach for strategic changeability (VASC).

- Chapter 6 gives an analysis framework that consists of the identification and valuation methods discussed earlier.

- Chapter 7 gives an illustrative case study of the design of flexible large container ships, in order to demonstrate the framework from Chapter 6.

- Chapter 8 provides a discussion, synthesising on the aforementioned material and a critical assessment of the proposed framework and results.

- Chapter 9 presents the conclusions of the thesis and recommendations for further work.

Chapter 2

Handling Uncertainty by Flexibility

In this chapter the foundation is set for the rest of the thesis. Uncertainty is defined and flexibility is introduced as a method to handle uncertainty in design of marine systems. Real options are presented as a framework for representing flexibility, and a separation between real options "in" and "on" projects are made. Frameworks for representing systems for incorporation of flexibility are presented, including the design structure matrix (DSM) and tradespace exploration and evaluation methods.

In terms of systems design, uncertainty is often perceived synonymous to risk, with a negative atmosphere. However, what will be emphasised in this chapter is that there are both downside and upside risks affiliated with uncertainty.

2.1 Understanding Uncertainty

McManus and Hastings (2006) define uncertainty as "things that are not known, or only known imprecisely". When designing capital-intensive ocean engineering projects, it is important to realize that the future inevitably is uncertain. Design decisions often have to be made before relevant information about the future is resolved. Uncertainty in these aspects is typically related to changes in the future operating context, as presented in Table 2.1.

Table 2.1: Examples of uncertainties in marine systems design (Erikstad and Rehn, 2015).

Field	Example
Economic	Oil price, freight rates, supply and demand.
Technology	Energy efficiency improvement and lifetime enhancement.
Regulatory	SOx/NOx emissions and ballast water treatment.
Physical	Sea ice, sea states, marine icing and extreme temperatures.

In the process of handling uncertainty in engineering design, it is of importance to classify different types of uncertainty. Uncertainties may arise from endogenous and exogenous sources, as discussed by Lin et al. (2013):

- *Endogenous uncertainty* can be actively managed by decision-makers, and depends on system designs and development plans. An example can be how a ship that is to be build will respond to waves, which can be resolved by modelling.
- *Exogenous uncertainty* is external and independent of project decisions. This can for example be market rates or fuel prices.
- *Hybrid uncertainty* can partially be influenced by decision-makers. An example is shipbuilding schedule and costs.

A representation of layers of uncertainties and decision-makers' ability to influence it is discussed by Miller et al. (2001) and illustrated in Figure 2.1.

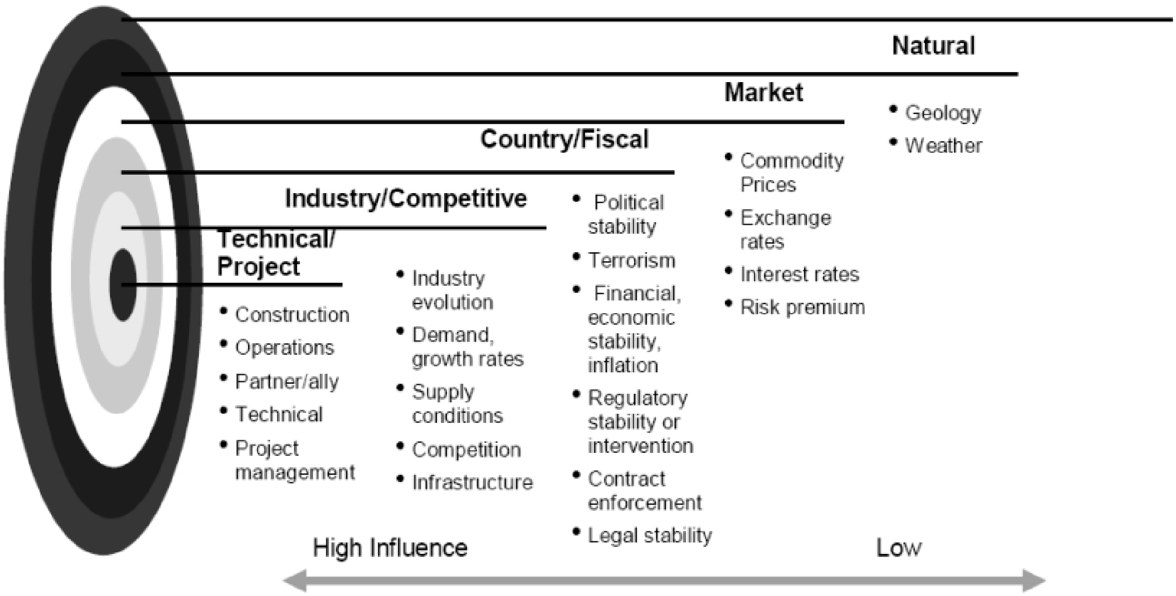


Figure 2.1: Several layers of uncertainty (Miller et al., 2001).

Uncertain parameters can be quantified by probability distributions, and is traditionally represented by corresponding statistical parameters such as the mean, standard deviation and percentile values. Simplifying and representing uncertain future contextual parameters by the assumed most likely scenario, or the mean value, can be dangerous due to *the flaw of averages.* The flaw of averages states that plans based on average inputs are wrong on average, and is a reason why we underestimate risk in the face of uncertainty (Savage, 2009). Mean values typically fail to capture important asymmetries of the distributions, which are important to include in non-linear models not to end up with over-simplified and wrong results.

This can be exemplified by a fixed ship that can only expand capacity by a certain degree if the market turns out better than expected, but on the other hand, it can take the whole downside if the market collapses. This asymmetric system behaviour is mathematically described with Jensen's inequality, which for convex functions states that the expected value is less or equal to the expected value of the function. If φ is the convex function with X as a random variable, then Jensen's inequality can be formulated as in Equation 2.1.

$$\varphi(E[X]) \leq E[\varphi(X)] \tag{2.1}$$

Instead of relying on single value forecasts of the most probable future uncertain contextual parameters, it is of importance to consider the range of possibilities that may occur. For example, market rates that may occur range from the rigid limit on one side to no particular limit on the other, since they are non-negative. As discussed by de Neufville and Scholtes (2011) and Erikstad and Rehn (2015), all historical attempts at predicting the long-term market rates have failed.

By handling uncertainty in design of ocean engineering systems, it is central to focus on value robustness. That means the ability of a system to "continue delivering stakeholder value in the face of changing contexts and needs" Ross and Rhodes (2008b). Value here is related to the preferences of the stakeholders, and is not necessarily monetary. However, for commercial capital-intensive ocean engineering projects, it typically is. This is essential in the approach on how to handle uncertainty.

Another relevant system characteristic frequently mentioned in the literature with regard to handling uncertainty is complexity. This is natural as they relate to some degree, as complex system behaviour introduce more uncertainty. Complexity is used to characterise something that is made up of parts with many interconnections, and is seen to frequently have a hierarchical structure, as discussed by Simon (1996). On a general basis, reducing complexity while still maintaining the functional requirements for a design is desirable (Suh, 1990). Rhodes and Ross (2010) decompose complex systems into five aspects: structural, behavioural, contextual, temporal and perceptual. While the structural and behavioural aspects can be assessed with traditional engineering approaches, the contextual, temporal and perceptual aspects are subject to newer and more untraditional methods. The five aspects of complexity with application to system ship design are illustrated in Figure 2.2. Aspects of handling complexity in conceptual ship design are discussed by Gaspar (2013).

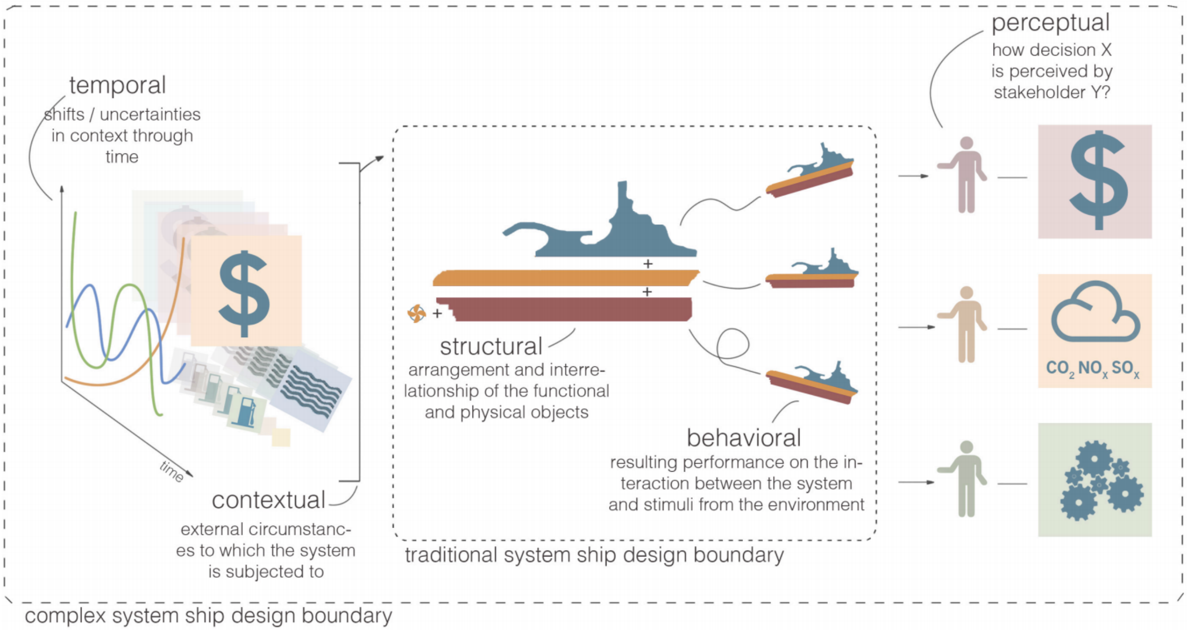


Figure 2.2: Five aspects of complexity in system ship design (Gaspar et al., 2013).

2.2 Flexibility in Engineering Design

Flexibility in design of engineering systems is one of several methods of handling uncertainty. Flexibility has several definitions and is often used on a wide range of aspects. In their paper, Saleh et al. (2009) present a survey of the use of the word "flexibility" in the literature. Related to engineering systems they find two distinct uses; flexibility in the design process and in the design itself. Flexibility in the design process can be related to customers with the requirements, and the designers with the constraints. In-design flexibility has several definitions, and is related to the ability of the system to respond to change and to perform different functions, typically not included in the initial requirements definition. In-design flexibility is in focus in this thesis.

A systems engineering approach is central in this thesis, with focus in "ilities", such as flexibility and adaptability, as discussed by McManus et al. (2007) and Ross et al. (2008b). In this context, the authors define *flexibility* to be the ability of a system to be changed by a system-external change agent. *Adaptability* is closely related, and is the ability of a system to be changed by a system-internal change agent. Flexibility and adaptability are both types of *changeability*, which is defined as the ability of a system to alter its form - and consequently its function - at an acceptable level of resource expenditure.

Flexibility enables a design to take advantage of new opportunities and to avoid downside risks, hence increasing the expected value. However, flexibility usually comes with an initial cost. Flexibility in design in can be considered as an active method of creating value, contrasting the standard passive robust design approach. According to de Neufville and Scholtes

(2011) flexible designs fall into three major categories, as described in Table 2.2.

Table 2.2: Three types of flexible marine designs (de Neufville and Scholtes, 2011; Erikstad and Rehn, 2015).

Flexibility	Example
Change in size	A design might be modular to permit easy addition of capacity. A modular design might also facilitate contraction of capacity. An example can be a cruise ship that can expand its length by adding a module in the middle.
Change in function	The system might permit users to remove or add function. An example can be a container ship that can change between types of containers, such as refrigerating containers and normal containers. Another example is a multifunctional ocean construction vessel (OCV).
Accident protection	Systems normally feature a range of ways to protect against accidents. An example can be to have propulsion and navigation redundancy on a ship.

2.3 Finance, Real Options and Flexibility

For systems with stakeholders preferences that include profit and costs, a normal approach of valuing flexibility involve assessing its effects on the cash flows, and the perceived present value of the cash flows. Typical metrics for assessing discounted-cash-flows (DCF) include net present value (NPV) and internal rate of return (IRR). Traditionally, the NPV method stands out as a common engineering design measure, with the usual goal of maximizing the NPV given numerous constraints. NPV is typically defined as:

$$NPV = \sum_{t=0}^{N} \frac{R_t - C_t}{(1+r)^t} \tag{2.2}$$

Where R_t and C_t are the revenue and costs in period t discounted at r, with t representing the project time periods from 0 to N. However, the traditional static NPV method is in most occasions inadequate for project valuation, as it fails to accurately capture values in an uncertain environment. This can be solved by introducing real options. As illustrated in Figure 2.3, real options analysis (ROA), or real options valuation (ROV), include factors such as cash flow volatility and managerial flexibility.

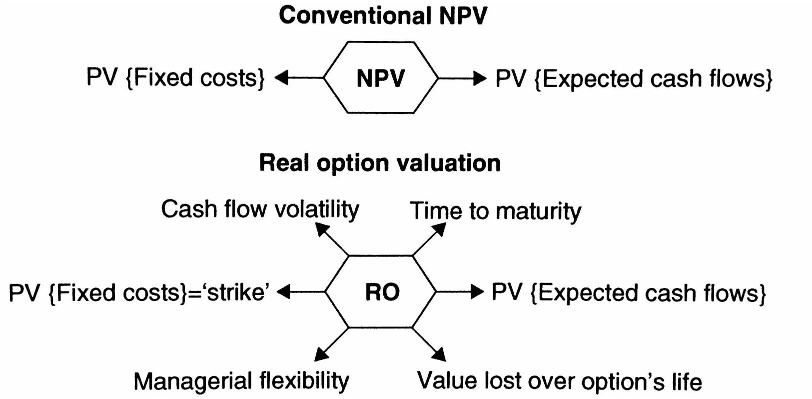


Figure 2.3: Drivers of NPV and real option valuation techniques (Cuthbertson and Nitzsche, 2001).

Options are traditionally related to finance, and represent the right, but not obligation, to buy or sell an underlying instrument at a defined price on, or before, a specific date. Options introduce flexibility, as it enables the owner to postpone decisions. This right is worth an option premium. There are numerous types and classes of options. Put options represent the right to sell and call options represent the right to buy. American options can be exercised at any date before the date of maturity and European options can only be exercised at their date of maturity. Perpetual options do not have a time limit, and this option type is typically more relevant than what many may think. For example according to his biographer Alice Schroeder (Schroeder, 2009), Warren Buffett views cash as a call option with no expiration date. That is because for him, having cash represents the flexibility to make strategic investments in assets and increase its value, with no particular time limit. Additionally there are several types of more exotic options, including Asian options, Bermuda options, compound options, gap options and barrier options, which will not be explained further here.

Real options are financial option analogy used on real assets or projects, and the term was coined by Stewart Myers in 1977. Real options open up for evaluation of managerial flexibility for project investments. For example, the investment cost of a project can represent the strike price an option, and the present value of an investment project can represent the price of the underlying instrument. However, there are also numerous important differences between financial and real options, as presented in Table 2.3.

Table 2.3: Options and real options characteristics (Alizadeh and Nomikos, 2009).

Determinant	Financial option	Real option
General characteristics	Clear	Unclear
Replication	Wide	Unique
Tradeable	Yes	No
Time to maturity	Short	Long
Underlying values	Smaller	Higher
Management influence	None	High

When it comes to design of engineering systems, real options represent a proactive approach for handling risks, where the focus is on maximizing reward. This is in contrast to the typical conventional reactive design approach, where the focus rather on minimizing risks. This is illustrated in Table 2.4.

Table 2.4: Real options approach to systems design differs from the conventional approach in how it faces risk (de Neufville, 2003).

	Reactive attitude	Proactive attitude
Minimize risk	Conventional	
Maximize reward		Real options

2.4 Separating Real Options "In" and "On" Projects

A important differentiation between types of real options can be made by the introduction of real options "in" and "on" projects (Wang and Neufville, 2004). Real options "on" projects are financial options applied on technical things, without focusing on technicalities. An example of an "on" option can be the option to lay up a ship. Real options "in" projects are options that are created by changing the design of the technical system. This can for example be the option to install a large crane on an offshore ship, which will have implications for numerous of technical properties of the system, such as stability, a reduced deck area and for internal power distribution and production.

Table 2.5: Characteristics of real options "in" and "on" projects (Pettersen, 2015).

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

This differentiation is of particular relevance when it comes to the method used to value real options. While traditional option valuation methods are applicable for "on" options, "in" option pricing typically require more novel approaches focusing on their behaviour in complex systems.

Traditional shipping real options presented in Table 2.6 can be categorised as "on" options. These options are more related to operations, and not the physical structure of the vessels themselves. For example, a company may expand its fleet by buying another ship, which can be characterised as an "on" option. While the expansion of the capacity of one ship alone is related to the physical structure of the ship and can be characterised as an "in" option.

Table 2.6: Examples of "on" real options in shipping (Alizadeh and Nomikos, 2009).

"On" option	Description
Abandon	Option to sell the assets and exit the market, which can be valuable when the market is volatile and there is substantial uncertainty about its future direction.
Expand fleet	Option to expand in operational and investment projects introduces the flexibility to have limited involvement initially, and to increase the involvement once the conditions are right.
Lay-up	Option to stop operating the vessel temporarily is perhaps one of the most relevant options for shipowners, and is normally exercised when an asset is not profitable.
Delay	Option to delay certain decisions and projects. For example, if local market imbalances occur, the actors experiencing the downside from this effect can wait for more favourable market conditions before fixing a contract.
Other	Options may also be embedded in contracts, which are often used without proper valuation. Without going in details, these can for example be time-charter (TC) extensions, newbuilding options, purchase options on TC contracts or options related to debt.

Table 2.7: Examples of "in" real options in shipping.

"In" option	Description
Expand capacity	Option to physically expand the capacity of a particular ship by retrofit, such as midship elongation.
Switch scope	Option to switch between different modes of operation or between different chartering contracts offers a certain level of flexibility ship operators and charterers.
Switch fuel	Option to alter or change the fuel and engine systems. This may be to change from normal diesel (MGO) to liquefied natural gas (LNG), which involves different fuel tanks, cryogenic systems and other engine properties.
Capability retrofit	Option to add or change the capabilities of the ship, for example by the installation of an crane or ROV systems on an offshore construction vessel.

As presented in Table 2.7, "in" options in marine systems design in other words typically involve retrofit, that is rebuilding the ship after it already has been in operation. The expand option is related to both "in" and "on" option types. However, the differences are that for "on" expand options, this is typically related to expanding the fleet, while "in" expand options typically are related to physically expanding the capacity of a particular ship. Both types of options relate to decreasing the downside and increasing the upside potential of investments, hence increasing the expected value. However, one can argue that the "in" options focus more on increasing the upside, while "on" options typically relate more to reducing the downside. This is in line the characteristic trend of flexibility in design, where the focus is on maximizing reward instead of minimizing risks.

2.5 Systems Engineering and Flexibility

It is not always that the real options approach for assessing flexibility to handle uncertainty is the most appropriate one. For real options "on" projects, real option analysis (ROA) is a good approach. However, for real options "in" projects, it can be discussed whether a real options approach appropriate. This is particularly for more complicated stakeholder preferences, which not only focus on monetary values.

There are several approaches that can be taken at handling uncertainty by flexibility for systems engineering, including general topics involving architecture, modelling, simulation, system dynamics, reliability and simulations. We will in this section briefly introduce relevant systems engineering topics including the Design Structure Matrix (DSM) and tradespace exploration and evaluation methods. First of all some relevant systems engineering terms are described in Table 2.8.

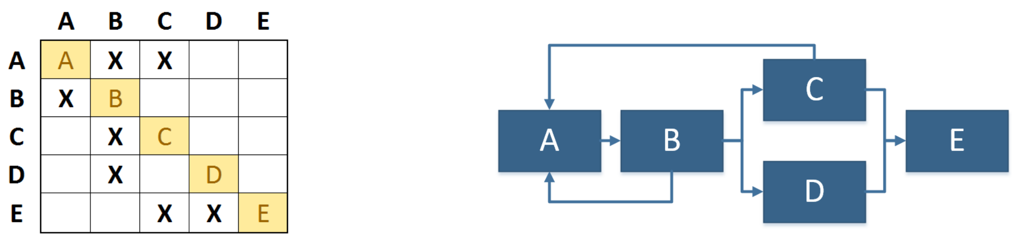
Table 2.8: Relevant systems engineering glossary descriptions (Ross and Hastings, 2005).

Word	Description
Attribute	A decision-maker-perceived metric that reflects how well a decision maker-defined objective is met.
Design variables	A set of variables that are designer-controlled quantitative parameters that reflect an aspect of a concept.
Tradespace	A space spanned by the complete set of design variables, representing the space of possible design options.
Utility	A dimensionless parameter that reflects the "perceived value under uncertainty" of an attribute.
Value	A metric that captures the "goodness" of something to a stakeholder.
Context	The characteristics of the environment of a system.

Design Structure Matrix (DSM)

The Design Structure Matrix (DSM) introduced by Don Steward in the 1970s (Steward, 1981, 1991) is a simple form of representing a system in a matrix. The method is useful for design of complex systems, but is also used in aspects of project management and organizational architecture.

The DSM is a square matrix, where system components are represented by rows and columns, and linkages between the components are represented by the off-diagonal cells. This set-up provides a means of efficiently illustrating patterns between system elements, such as for information flows, modules and for identification of feedback loops. This way of representing systems opens up for using matrix-based analysis techniques, which can improve the structure of the system. An example of a DSM with its equivalent flow chart is given in Figure 2.4.



(a) (b)

Figure 2.4: Example of a design structure matrix (DSM) for a system with components A-E (a), and its equivalent flowchart (b).

The Engineering Systems Matrix (ESM), introduced by Bartolomei (2007), extend the traditional DSM and include the whole end-to-end model of a socio-technical engineering system. Through adding of system drivers and stakeholders DSMs, the ESM model includes social, environmental and managerial aspects.

Using DSM as a base for system representation is relevant when it comes to design of flexible systems. By for example investigating how change propagates through the DMS in a complex system, one can better understand the dynamics and provide design support for how to handle uncertainty. DSM is used by Kalligeros (2006) for studying platforms and real options in large-scale engineering systems, with applications to preliminary design of floating production, storage and offloading (FPSO) vessels.

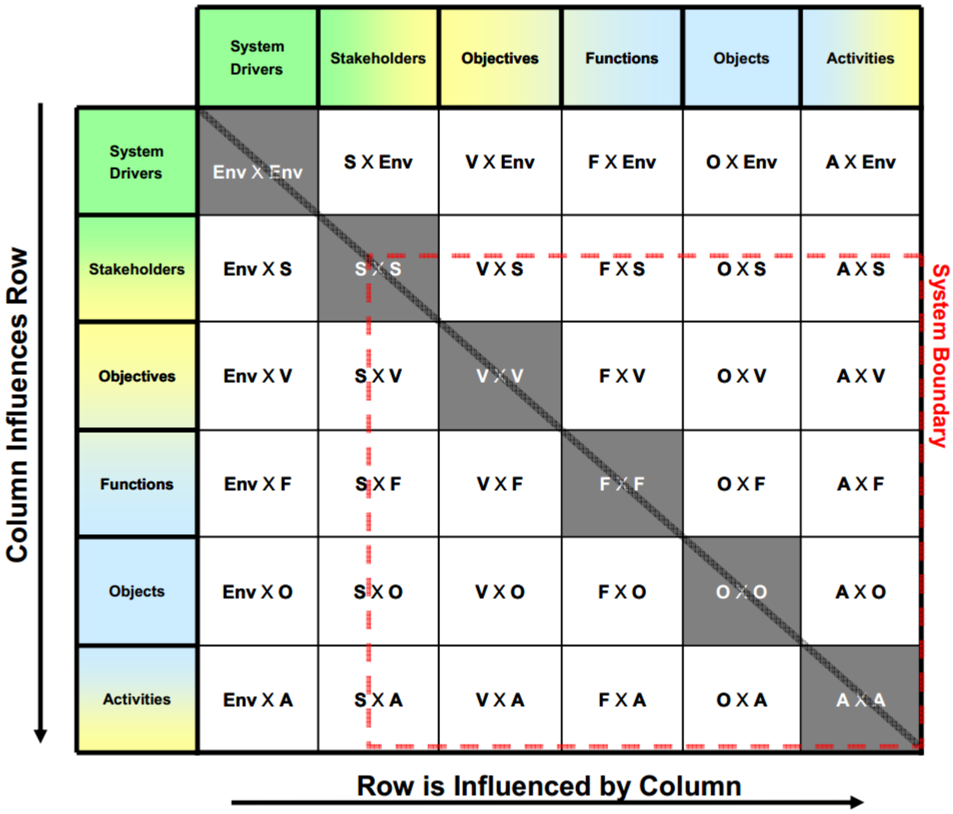


Figure 2.5: Engineering Systems Matrix (ESM) representation example (Bartolomei, 2007).

Tradespace Exploration and Evaluation Methods

Tradespace exploration represents an approach to comparing large number of system designs. As illustrated in Figure 2.6, the development of tradespaces typically involve assessing numerous design alternatives in terms of cost and value (utility) during the concept exploration phase. This process includes the mapping between design parameters representing the physical design and the performance space, where attributes represent the perceived values by the decision-makers.

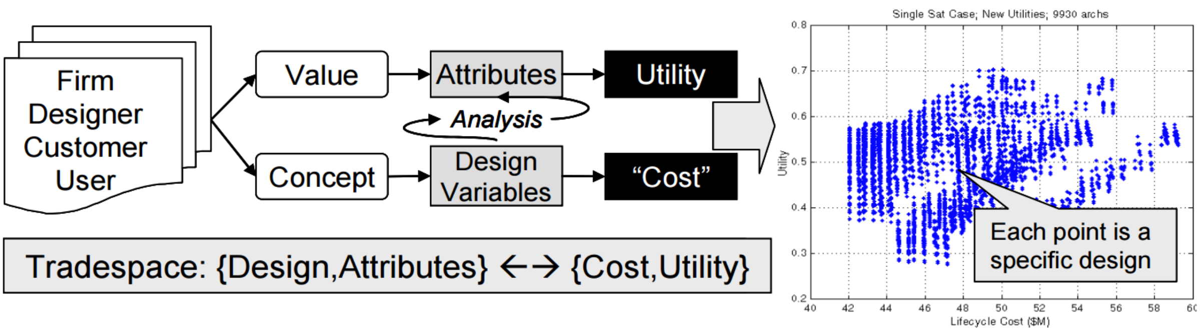


Figure 2.6: A tradespace is a representation of design parameters and stakeholder perceived value evaluated in terms of utility and cost (Ross and Hastings, 2006).

Each point in a tradespace plot represents a unique design choice. A Pareto set characterises those designs that have the highest utility and lowest cost. Designs that have these characteristics are often said to be on the Pareto front, and choosing among these designs involves making cost-utility trade-offs. Designs that are not on the Pareto front are called dominated designs. When facing uncertain operating contexts with changing parameters, or changing preferences, a tradespace may change completely, as illustrated in Figure 2.7. As one can see in the figure, the coloured points representing three designs did not shift in the same direction, nor with the same magnitude, upon the same change in preferences, illustrating that some design options are more sensitive to changes than others are.

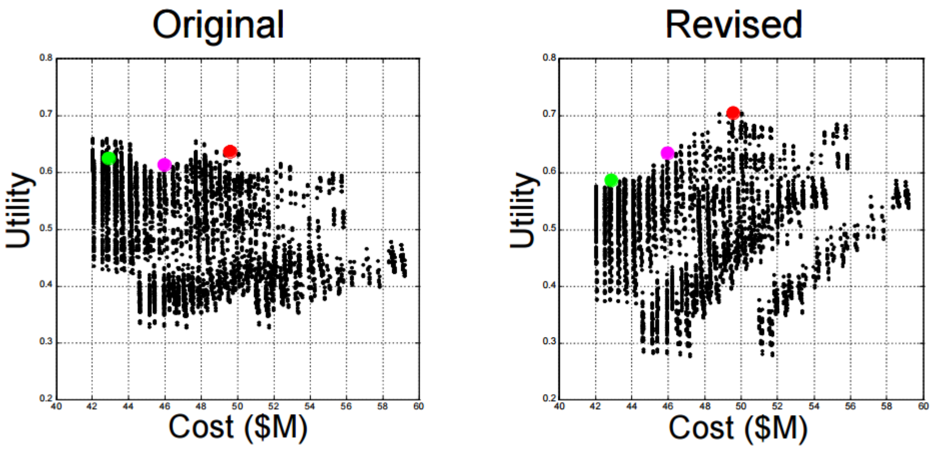


Figure 2.7: Example in changes in preferences reflected in tradespace shifts (Ross and Hastings, 2005).

Considering each design in a tradespace as a potential starting or ending state for change, this framework can be used to assess changeability. By representing change specifications with start and end states, and transition paths between these states, a traditional tradespace can become a *tradespace network*, illustrated in Figure 2.8. By the use of a tradespace network model, design states and transition paths can be represented as points and arcs.

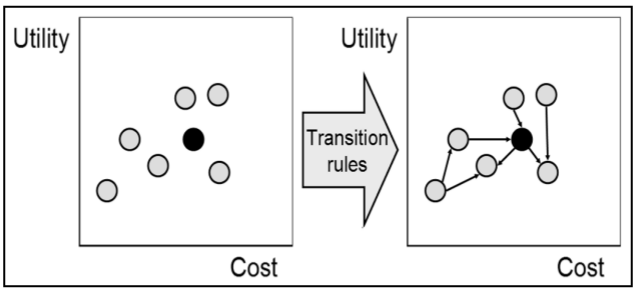


Figure 2.8: Point designs in a tradespace can be linked as a network via transitions rules to assess changeability (Ross and Rhodes, 2008b).

An agent-mechanism-effect framework can be used for describing change events (Ross et al., 2008b) and to provide means to clarify and define different types of "ilities". Figure 2.9 illustrates these three elements. The *change agent* is what initiates a system change, the *change* *mechanism* is the means by which the system is able to change and the *change effect* represents the difference between the starting and ending state of the system.

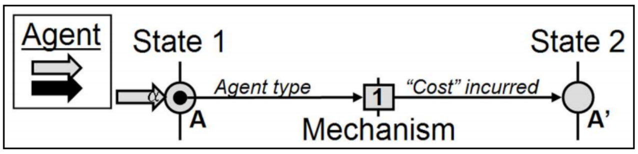


Figure 2.9: Agent-mechanism-effect framework (Ross et al., 2008b)

The change mechanisms of a system may be defined through *transition rules*, as illustrated in the network model in Figure 2.8. The change effect defines what kind of changeability the transition rules offer. By the introduction of transition rules for a system design, different types of designs that may change can be identified. Hence, this approach represents a way to identify and quantify changeability that can be of relevance for handling uncertainty in systems design.

Some particular approaches are developed using this framework, including Multi-Attribute Tradespace Exploration (MATE), Epoch-Era Analysis (EEA) and the Responsive System Comparison Method (RSC), developed by system engineering researchers at MIT. These emerging methods are particularly interesting because they are subject of ongoing research and development. For example, EEA and RSC have been used in research on marine systems recently (Gaspar, 2013; Pettersen, 2015).

Epoch-Era Analysis (EEA)

Epoch-Era Analysis (EEA) is a structured approach for clarifying the effects of changing contexts over time have on the perceived value of a system (Ross and Rhodes, 2008a). An *epoch* is a fixed period of contexts and needs in which a system operates, and is characterized using a fixed set of *epoch variables*. These variables can define anything that can have a potential effect on the usage and value of the system, such as market rates, weather patterns, political scenarios and financial situations, and are typically related to exogenous uncertainty factors. A complete set of epochs can then be assembled into *eras*. These ordered sequences of epochs then create a description of the progression of contexts and needs over time. This is illustrated in Figure 2.10. The epoch-era framework provides a base for performing value delivery analysis for systems operating in changing conditions.

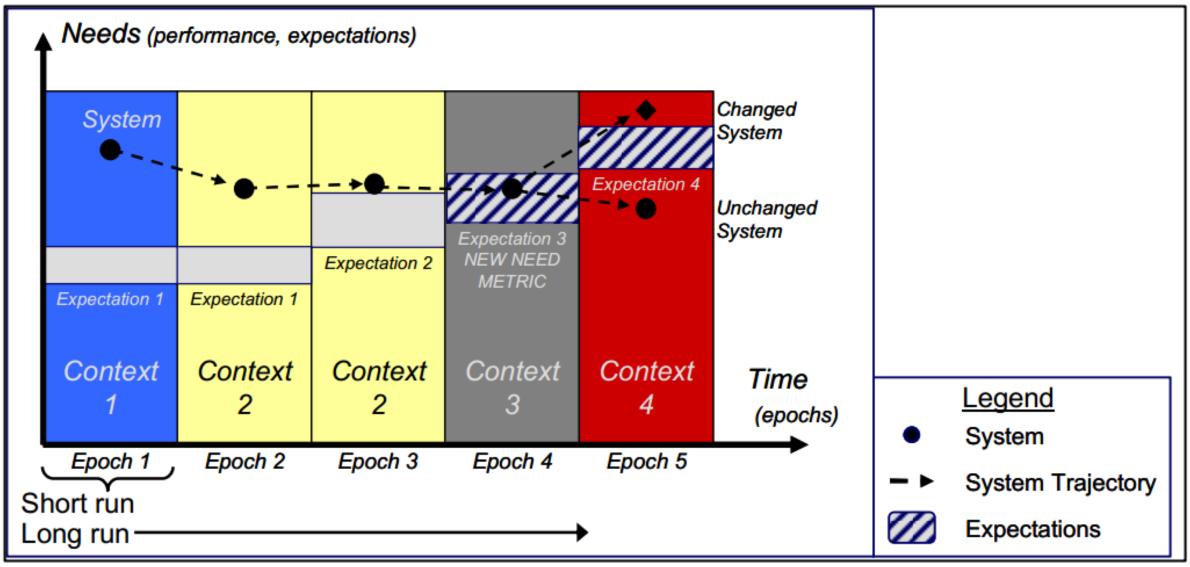


Figure 2.10: Epoch-Era Analysis, system needs vs. expectations across epochs (Ross and Rhodes, 2008a).

Responsive System Comparison Method (RSC)

The Responsive System Comparison Method (RSC) is a set of processes, including MATE and EEA, used for gaining insight into developing value robust systems (Ross et al., 2009). The method includes system concept generation, evaluation and selection. By the use of RSC one can analyse a variety of system designs across changing contexts and needs. The goal of the method is to generate knowledge about trade-offs, compromises, and risks to a project and identify concepts that are active or passive value robust. According to Rhodes and Ross (2010), the strength of the method is that it enables dialogue and knowledge building between stakeholders and system developers.

With reference to the process flowchart illustration in Figure 2.11, the seven steps of the RSC method the following way:

1. **Value-Driven Context Definition** - Identify overall problem / needs statement.
2. **Value-Driven Design Formulation** - Elicit stakeholder needs statements (attributes) and formulate system solution concepts (design variables).
3. **Epoch Characterization** - Parametrize the range of contextual uncertainties (epochs) under consideration.
4. **Design Tradespace Evaluation** - Gain an understanding, via modelling and simulation, of how key system concepts and trades (design variables) fulfil the overall value-space (attributes) in response to contextual uncertainties (epochs).
5. **Multi-Epoch Analysis** - Identify value robust system designs across changing contexts and needs.
6. **Era Construction** - Develop era timelines from the set of enumerated epochs.

7. **Lifecycle Path Analysis** - Develop near- and long-term system value delivery strategies in response to time-dependent contextual uncertainties (described via era timelines).

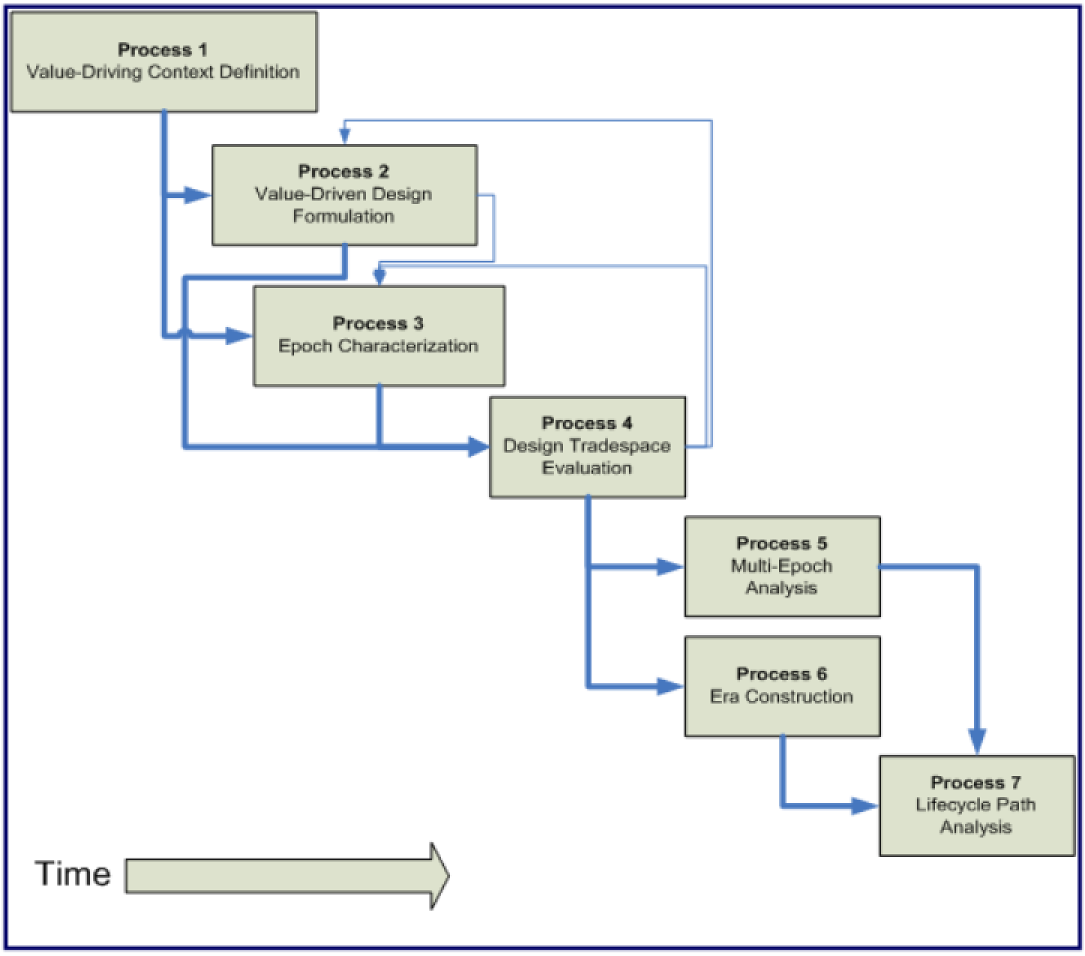


Figure 2.11: Responsive system comparison method (RSC) flowchart (Ross et al., 2009).

2.6 Stochastic Optimization and Flexibility

Mathematical optimization in general represents a framework used to find the best set of elements from some set of alternatives. Stochastic optimization becomes relevant when some of the data elements in the program are best described using random variables, and represents a relevant framework for solving problems that involve uncertainty.

Stochastic optimization traces its roots back to the introduction of recourse models in the 1950s by Dantzig. Recourse involves making some decision before uncertainty is resolved. According to Birge and Louveaux (2011), a classic two-stage stochastic linear problem with fixed recourse can be generalized on the following form:

$$\begin{aligned}
\min \quad & z = c^T x + E_\xi[\min q(\omega)^T y(\omega)] && (2.3)\\
\text{s.t.} \quad & Ax = b && (2.4)\\
& T(\omega)x + W y(\omega) = h(\omega) && (2.5)\\
& x \geq 0,\ y(\omega) \geq 0 && (2.6)
\end{aligned}$$

where 2.3 represents the objective function minimizing the costs, and consists of a deterministic and stochastic part for the two-stage problem. The first stage is deterministic, represented in the objective function as costs c^T and decisions variables x. In the second stage a number of random events $\omega \in \Omega$ may realize, represented in the objective function as the expected value E_ξ of a function minimizing the stochastic costs $q(\omega)$ for the second stage decision variables $y(\omega)$. ξ is a random vector consisting of all the elements in ω. 2.4 is the deterministic constraint and 2.5 is the stochastic constraint. $T(\omega)$ is an uncertain parameter related to the first stage decision and W represents a the fixed recourse in the second stage. 2.6 is a constraint for securing non-negative variables.

Two relevant measures for stochastic problems are the expected value of perfect information (EVPI) and the value of stochastic solution (VSS). EVPI measures the value of having complete information about the future, and can be interpreted as the loss of value due to the presence of uncertainty. VSS is obtained by subtracting the value of the stochastic solution from the value obtained from solving the problem using the expected value of the random variables, and represents the value of knowing and using the distributions of future outcomes.

The flow of information is central in stochastic programming. Which information is known when? Scenario trees are great tools for representing relevant information flow. In many cases, two-stage programs represent an appropriate framework for modelling, for example for an investment, where the first stage is typically to make the investment and the second is to operate this in an uncertain future context (King and Wallace, 2012).

Stochastic optimization and real options theory share the idea of finding the optimal strategies to satisfy stakeholders. An example may be from the real option of abandonment of an offshore oil well. Deterministically this is when the discounted future profits equal the cost of abandonment. However, uncertainty in the future oil prices can introduce additional profit, and impose an option value on the well. From a stochastic optimization point of view, this option value is included in the notion of recourse actions, which embody the potential to respond when information has been resolved (King and Wallace, 2012).

King and Wallace (2012) discuss the use of stochastic programming with relations to real options. They argue that the main difference between the fields is that in traditional options theory you can only value structures already defined, not find them, while with stochastic programming you can value total solutions which may contain options, but finding them must be done manually. However, for simple problems, one may price design flexibility (real options) that is clearly defined in a stochastic program by changing the input variables (cost of the real option) and see when the optimal stochastic solution changes between inflexible and flexible design. This is discussed by Erikstad and Rehn (2015).

Stochastic programming has been used for marine systems design problems, typically for fleet renewal problems and for emission compliance under uncertainty (Pantuso, 2013; Balland et al., 2013; Patricksson et al., 2015). However, in this thesis stochastic programming is not followed up in detail as a framework for flexibility identification and valuation in marine systems design.

Chapter 3

Approaches for Modelling the Future

In this chapter, we focus on the challenge of estimating and modelling what may happen in the future. This is particularly relevant for the methods discussed in Chapter 4 and 5 for flexibility identification and valuation. Topics discussed include scenario thinking, Epoch-Era for scenario generation and the application and use of time series and stochastic processes. Stochastic processes are typically used for valuation of real options.

3.1 Modelling the Future for Marine Systems

The maritime industry is often considered one of the most volatile, where the actors are subject to substantial business and financial risks. These risks originate from fluctuations in the different factors affecting the cash flows and hence the performance of the assets, such as bunker prices, market rates, the price of the vessels, interest rates and exchange rates. Therefore, it is important to have a good understanding of risk and its dynamics for effectively handling uncertainty and managing risks. Alizadeh and Nomikos (2009) present a profound discussion on different statistical tools traditionally used for modelling risk and the dynamics of volatility with applications to shipping, including complex methods such as generalized autoregressive conditional heteroskedasticity (ARCH) and generalized ARCH (GARCH) models. In this chapter, we do not go deep in these types of statistical measures, but rather present some ways to model uncertain parameters, with focus on stochastic processes.

For applications to systems design, Cardin and de Neufville (2008) differentiate between two types of uncertainties affecting systems: progressive and drastic. Progressive sources of uncertainty evolve slowly and steadily in time, and examples are market rates and fuel prices. Drastic sources of uncertainty are characterised by sudden jumps, such as induced by sudden political shifts and natural catastrophes. This differentiation is of particular relevance when it comes to the frameworks used for modelling relevant uncertainties.

Another aspect of modelling the future is that, given that the model theoretically is correct, it must also be understood and perceived as logical by the key decision-makers. For example, explaining about complex correlated stochastic processes simulated thousands of times to non-technical decision-makers will probably make the analysis less valuable for these players. The surface of the Epoch-Era method may also be perceived this way since it is new and typically uses technical terminology. Therefore, when it comes to modelling the future, it is important to also take this into consideration. Perhaps for certain situations the best approach is to initially involve the key stakeholders, and explicitly consider a handful of scenarios of how the future will resolve.

When it comes to modelling the future, typically by estimating distributions of future possibilities, de Neufville and Scholtes (2011) present an approach for system designers. In addition to identifying the most important factors and analysing historical data and trend-breakers, the approach involves assessing the inaccuracy of the forecast. This is particularly interesting, and involves being realistic towards our ability to predict the future. For example by evaluating the inaccuracy of relevant prior predictions, we can get an indication on how well we can hope to execute the next project.

3.2 Scenario Thinking

Scenario thinking is something humans do all the time. Our strategic scenario-planning centre, or the brain, is constantly interpreting signals from the environment, and combined with prior experience it projects future trajectories for us to navigate and make the best decisions in the purpose of our reaching our goal. This, for example, enables us to successfully walk down a crowded street, or to navigate a sailboat in a windy sea with obstacles such as islands and other more unpredictable human-controlled boats. Successfully managing these situations require training and experience in order to intuitively, or even subconsciously, evaluate alternative strategies for different scenarios and draw conclusions. For simple day-to-day tasks, this may often be subject to intuition, but for more complex problems, such as the design of an engineering system, we have limited experience and need to explicitly consider scenario analysis.

There is no particular definition of scenario and scenario planning, but according to Lindgren and Bandhold (2002), a scenario is not a forecast or a vision, but a well-worked answer to the question "What can conceivably happen?" Or: "What would happen if...?". Further, they describe scenario planning as an effective strategic planning tool for medium to long-term planning under uncertainty conditions.

Modern scenario planning is often credited to Herman Kahn through his work for the US Military and the RAND Corporation (Research ANd Development) in the 1950s with the "future-now thinking". In the industry, Pierre Wack at Royal Dutch Shell was one of the first to use scenario planning as part of their process for generating and evaluating strategic options (Wack, 1985). He characterized scenario planning as "the gentle art of reperceiving". Consequently, Royal Dutch Shell has been consistently better in their oil forecasts than other major oil companies, and has been the first to see overcapacity in the tanker and petrochemical business, according to Schoemaker (1995). In his paper, discussing scenario planning as a strategic tool for thinking, Schoemaker (1995) concludes that when contemplating the future, it is particularly useful to consider these three classes of knowledge:

1. Things we know we know.
2. Things we know we don't know.
3. Things we don't know we don't know.

Furthermore, these three classes are subject to biases, as we typically are overconfident in our over- and under-predictions and that we have a tendency to look for confirming evidence for our intuition. In particular, for the two latter classes, Schoemaker (1995) argues that this is where scenario planning excels, as it essentially is a study of our collective ignorance.

Scenario planning may be of particular relevance for design of complex systems, as it serves as a way to handle complexity and uncertainty. For example by recognizing that many uncertain factors in a complex system can combine in ways to generate surprising results, for example due to nonlinearities and feedback loops, one may gain better insight in the nature of the system. Scenario planning serves as a applicable and powerful approach to identify contextual opportunities and challenges.

3.3 Epoch-Era

The framework of Epoch-Era in Epoch-Era Analysis, as introduced in Chapter 2.5, is basically a way of generating scenarios. An *epoch* is a fixed period of contexts and needs in which a system operates, and a complete set of epochs can then be assembled into *eras*. An *era* then represents a system life with varying contexts and needs. These ordered sequences of epochs then create a description of the progression of contexts and needs over time.

An era can be considered as a scenario for a system over its lifetime, with varying contexts and needs. However, there is a difference. The "key difference between eras and typical "scenarios" is that eras include the path dependence of the context, while typically scenarios only consider starting and ending contexts." - Ross and Rhodes (2010).

While stochastic processes represent a good way of statistically modelling time series, epoch characterization and era construction are particularly good for considering exogenous uncertainties related to categories such as policy, funding, infrastructure, technology and environment.

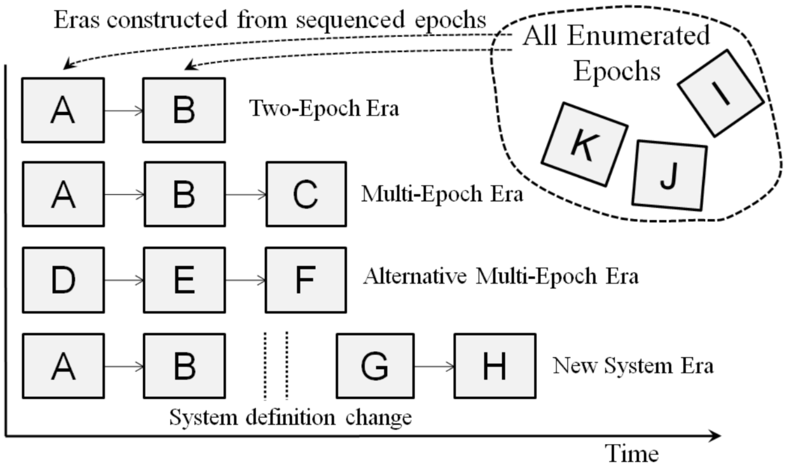


Figure 3.1: Assemblies of epochs construct eras spanning a system lifecycle define alternative future value expectations and contexts (Rader et al., 2010).

There are several methods for constructing eras, and two common ways are by narrative and numerical procedures. The narrative ways typically involve "hand-picking" epochs to fit imagined scenarios. The numerical ways involve computer algorithms for epoch assembly, by processes or by iterating on the prior epochs. According to Ross and Rhodes (2010), era construction generally involves four activities: specify era duration, characterise epoch durations, establish epoch ordering logic and construct eras. Furthermore, epoch ordering in the construction of eras, together with change strategies, may affect timing of design change decisions. Fulcoly et al. (2012) introduce a framework for assessing this, called epoch syncopation framework (ESF).

3.4 Time Series and Stochastic Processes

When it comes to analysing and collecting data over time and using it to model the future, central topics are time series and stochastic processes.

Time Series

A time series is a simply a sequence of discrete data points in time, and examples can be of the oil price, ship market prices, ocean tides or interest rates. Time series are used in a variety of fields, such as statistics, finance, pattern recognition, econometrics, engineering (particularly in control engineering) and basically any field of science involved in temporal measurements.

Time series analysis involve analysing data in time series for the purpose of extracting valuable statistical characteristics, often for the interest of making educated guesses on the future development of a temporal variable. This is often called time series forecasting.

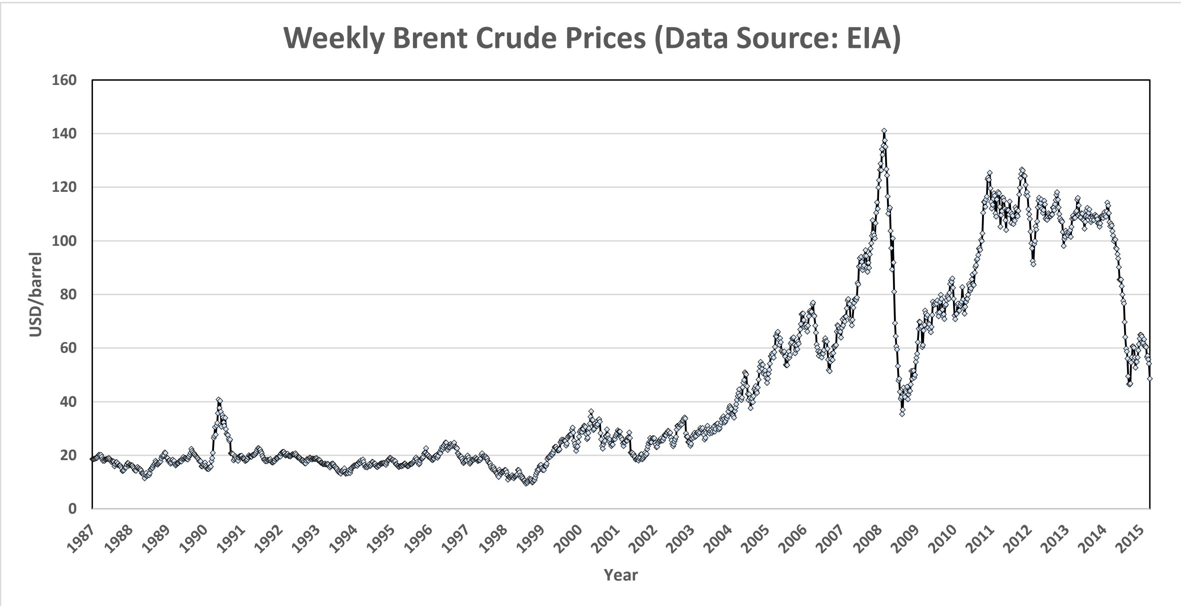


Figure 3.2: Example of daily Brent crude price time series, data source EIA [1].

Stochastic Processes

A stochastic process, in contrast to a deterministic process, is a term used to describe random variables for the representation of its evolution over time. They can be in continuous or discrete time. One can say that stochastic processes are statistical models for time series. Stochastic processes can be used in several frameworks for generating scenarios, for example by Monte Carlo simulation. In the following, some often-used stochastic processes are presented and discussed.

Four Relevant Stochastic Processes

Geometric Brownian motion

Geometric Brownian motion (GBM) is a stochastic process in which the logarithm of the

[1]EIA: U.S. Energy Information Administration `http://www.eia.gov/dnav/pet/pet_pri_spt_s1_w.htm`, accessed August 18. 2015.

underlying asset follows a Brownian (or Wiener) motion with drift. The process is well-suited for modelling non-negative asset prices. S is said to follow a GBM if it satisfies the following stochastic differential equation (here represented in continuous time):

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

Where σ is volatility of S_t, μ is the drift, dt is the time increment and W_t is a Wiener process/Brownian motion. Some important properties of GBM are that the expected value is only dependent on the drift and the time period, and that the percentage change of the underlying is random and independent of the past movements. GBM is used in the famous Black-Scholes option pricing formula, to model stock price behaviour.

Autoregressive motion
An autoregressive (AR) model is a type of a random process, where the output variable depends on its own previous values. AR models are a special case of the more general autoregressive-moving-average (ARMA) model of time series. The AR model was introduced by Yule and Walker in the 1930s. A linear AR model of order p is for a random variable S is defined as:

$$S_t = c + \sum_{i=1}^{p} \varphi_i S_{t-i} + \epsilon_t \tag{3.2}$$

Where S_t is the variable at time t, c is a model constant, $\varphi_i, ..., \varphi_p$ are model parameters, and ϵ_t is white (random) noise. Due to the variables' state dependency on prior states, AR models can be used to model market momentum and market cycles.

Mean-reverting process
A stochastic process with mean-reversion (MR) tends to centre around some long-term mean value. There are several types of mean-reverting processes. One frequently used version was introduced by Ornstein and Uhlenbeck in the 1930s, called an Ornstein-Uhlenbeck (OU) process, which can be considered as a modification to the GBM model. A stochastic process S_t follows an Ornstein-Uhlenbeck process if it satisfies the following stochastic differential equation (here in continuous time):

$$dS_t = \kappa(\bar{S} - S_t)dt + \sigma dW_t \tag{3.3}$$

Where κ is the rate of mean-reversion, $\bar{S}$ is the long-term average value for mean-reversion, σ is volatility of S_t, dt is the time increment and W_t is a Wiener process or Brownian motion. Mean reversion is of particular relevance for modelling for example commodity markets, since it accounts for an important principle of market equilibrium, and its related time lags.

Jump-diffusion process
The jump-diffusion process, as introduced by Merton (1976), is a stochastic process where

the return of the underlying follows a Brownian motion with drift punctuated by jumps. The frequency of the arrival of these jumps can be described by a Poisson process. The characteristics of this process is that it can represent a distribution with high skewness and leptokurtosis - typically observed in financial time series. The underlying S_t is said to follow a jump diffusion process if it satisfies the following differential equation (here in continuous time):

$$\frac{dS_t}{S_t} = \mu dt + \sigma dW_t + (J-1)dN(t) \tag{3.4}$$

Where μ is the drift, dt is the time increment, σ is volatility of S_t and W_t is a Wiener process or Brownian motion. J is the multiplicative jump size and $N(t)$ is the number of jumps that occurred up to time t, typically assumed to follow a Poisson process. The jump size may of course follow any distribution, but is often assigned a lognormal distribution.

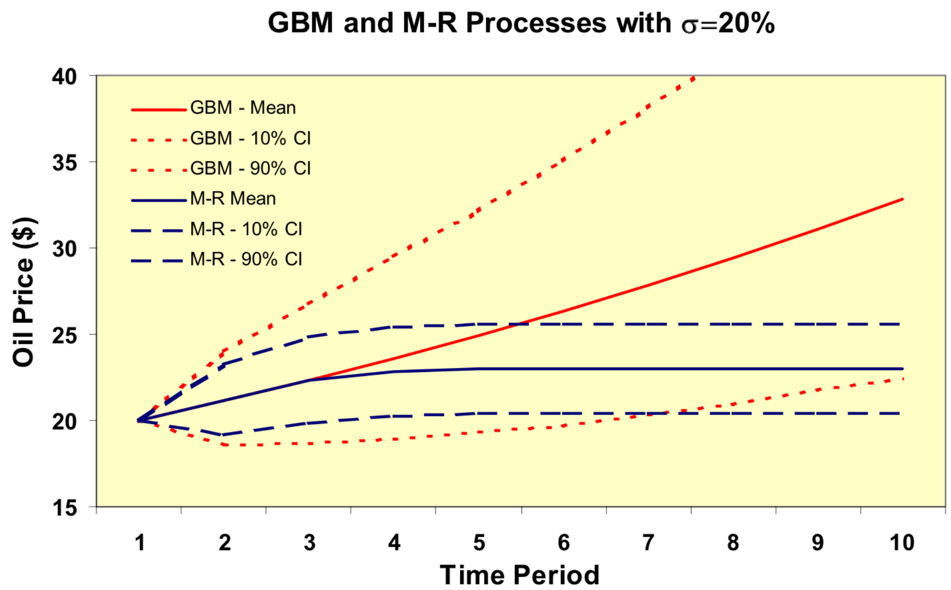


Figure 3.3: Illustration of the development of geometrical Brownian motion (GBM) and mean reverting (M-R) processes (CI=confidence interval) (Hahn, 2005).

Modelling Correlated Uncertain Parameters

In the case of Monte Carlo simulation of correlated parameters, it is important to make certain steps when it comes to the modelling. This typically involves explicitly modelling their pairwise correlations in a correlation matrix, and performing a Cholesky decomposition on this to make a lower triangular matrix that can be applied to a vector of uncorrelated samples to produce a sample vector of with the correct covariance properties of the system being modelled. We will not go in detail on this, but it may be relevant for e.g. for simulating the oil price and the market rates (which probably tends to correlate) for a model for designing offshore ships.

Short-term/long-term model for commodity prices

For time series of commodity prices fluctuations often tend to follow a long-term stochastic process, with short-term variations. Schwartz and Smith (2000) present a two-factor stochastic price model for commodity prices, with short-term mean-reversion and uncertainty in the long-term equilibrium level to which the prices revert. Jafarizadeh and Bratvold (2012) discuss this model for the modelling of the oil-price in order to analyse oilfield abandonment flexibility. They argue that the two-factor model provides advantages over simpler models, but still is simple enough to be communicated to decision-makers who do not have expertise in the field.

S-Curve Function

The s-curve function, also called the sigmoid function or the logistic curve, is a mathematical function that has the "S" shape. This characteristic shape of this function is relevant for modelling a technological lifecycle. That is, starting with a period of low activity, followed by a period of rapid growth that eventually flattens out as the market is mature or saturated. The sigmoid function *S(t)* can be represented by the following simple formula:

$$S(t) = \frac{1}{1+e^{-t}} \tag{3.5}$$

The s-curve function can be relevant for modelling markets and demands, and is perhaps of particular relevance for system design in emerging markets. In these cases, one can model stochastic parameters that follow an s-curve pattern. For example, Cardin et al. (2015) model liquefied natural gas (LNG) demand as a s-curved function in their analysis of a flexible LNG plant design. This is illustrated in Figure 3.4.

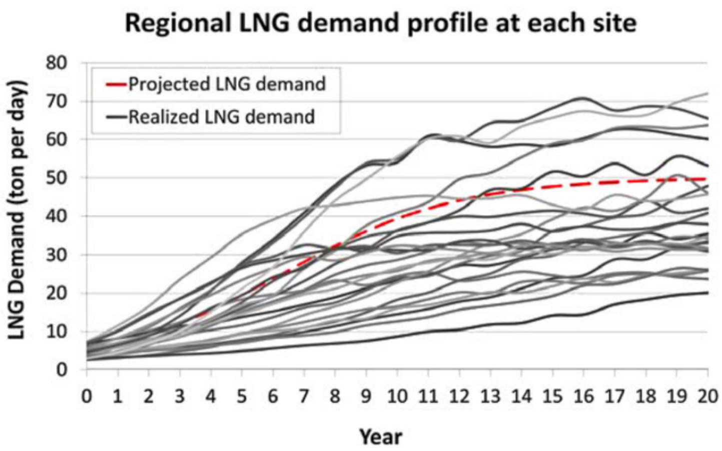


Figure 3.4: Example of an s-curve function for modelling the demand for LNG (Cardin et al., 2015).

Chapter 4

Flexibility Identification

In this chapter, we will discuss methods for identifying candidate design flexibilities in design of marine systems. This include interview methods, information flow methods, screening methods and tradespace methods for changeability identification.

In order to implement good flexibilities in designs for handling uncertainties, the right candidate design flexibilities must be identified. Relevant questions can be: How should we implement flexibility? What parts of the system should be flexible and how flexible should they be? It is not obvious which types flexible design options that will add the most value to a project, and it depends on several factors such as the nature of the system, the kind and intensity of uncertainties and the costs of implementation.

de Neufville and Scholtes (2011)

The type of flexibility that is of relevance for these methods is mainly the "in" option type, discussed in Chapter 2.4. This is not the types of flexibility that one almost always can apply to marine systems, such as the shut down or lay-up options that reduces the downside of the expected system performance. The "in" options that are of interest are usually embedded in the technicalities in the design, and are often non-obvious and difficult to consider intuitively. Furthermore, since "in" options typically have complex technological ramifications, they usually do not have particular value unless they are strategically considered in the early stages of the design process. Hence, methods for identifying these types of flexibilities early are highly relevant.

The organization of the content in this chapter is inspired by Cardin and de Neufville (2008), where they categorize relevant methods in: interview, information-flow and screening methods. Particular weight is put on screening methods, based on discussion by de Neufville (2003). Additionally, we present a discussion on a relevant tradespace exploration approach.

4.1 Interview Method

Perhaps the simplest approach to identifying candidate flexibilities in design of engineering systems is through interviews with subject matter experts (SME). SMEs may be experienced managers, engineers or system operators. Such interviews may help to understand how systems respond to different types of changes, and in particular for exogenous changes in the operating context. It may particularly help for understanding more about the non-intuitive sides of the system dynamics. Furthermore, interviews of managers can help to better understanding the preferences of the stakeholders, and if these preferences are subject to change when facing changing operating contexts. A drawback with the interview method is that the information may be subject to biases, however, qualitative research methods may be appropriate for handling these (Silbey, 2003).

Other, more systematic, technical methods for identifying flexibility in engineering systems presented below often incorporate interview methods for the development of the system and its interconnections. This includes for example change propagation analysis (CPA) method and sensitivity design structure matrix (sDSM).

A characteristic of many shipping companies is that the decision-making team often is relatively small compared to other larger corporations. Hence, understanding their risk profile and strategic behaviour is of importance in order to understand how the system performs over time for the stakeholders, and in general for better modelling of the system.

4.2 Information-Flow Methods

Engineering systems can be represented as interactions between components, stakeholders and users. By observing the properties of the information flow between the components of a system, candidate flexibilities can be identified. Such methodologies are categorised by Cardin and de Neufville (2008) as information-flow methods. These methods typically build on design structure matrix (DSM) methodologies for representing systems, as introduced in Chapter 2.5. This includes also includes the Engineering Systems Matrix (ESM) that extends the more technical DSM to include aspects of the social, managerial and environmental domains.

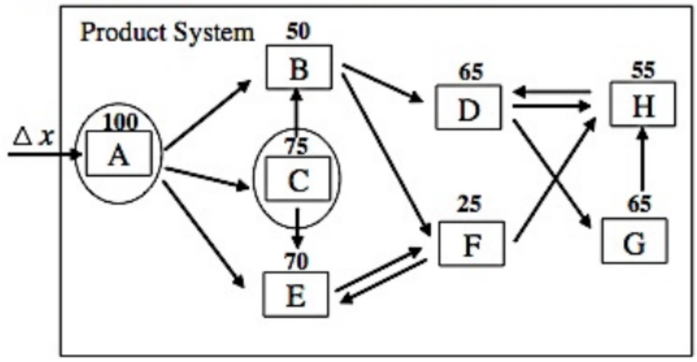
Change Propagation Analysis (CPA)

Change Propagating Analysis (CPA) is method for quantifying and measuring how change propagates in a system (Eckert et al., 2004). For using CPA the system should be represented as an interconnected network, typically using the DSM. The Change Propagation index (CPI) for a component then illustrates how it affects the change information in the network, as it expresses the difference of change information that comes in and out from all the connected components (Suh, 2005). For a system with n components, component i has its CPI_i as given by Equation 4.1.

$$CPI_i = \sum_{j=1}^{n} \Delta E_{j,i} - \sum_{k=1}^{n} \Delta E_{i,k} = \Delta E_{out,i} - \Delta E_{in,i} \tag{4.1}$$

If the CPI<0, the component receives more change that it absorbs, and it is called an *absorber*. A component with CPI=0 is neutral and is called a *carrier* and a component with CPI>0 is called a *multiplier*.

Multiplier: A, C Carrier: B, D, F, G Absorber/Constant: E, H



Propagating Change / Receiving Change

	A	B	C	D	E	F	G	H	ΔE_{in}
A									0
B	1		1						2
C	1								1
D		1						1	2
E	1		1			1			3
F		1			1				2
G				1					1
H				1		1	1		3
ΔE_{out}	3	2	2	2	1	2	1	1	
CPI	3	0	1	0	-1	0	0	-2	
Class	M	C	M	C	A	C	C	A	

Figure 4.1: Change propagation analysis (CPA) due to Δx for a system (Suh et al., 2007).

Change multipliers are good candidates of incorporating flexibility in engineering systems, as discussed by Suh et al. (2007). According to Cardin and de Neufville (2008), flexibility can be incorporated as a buffer component to reduce the number of components affected by the change, or the amount they have to change and their associated costs.

As a variation of the CPI as a change measure, Giffin et al. (2009) propose the normalized CPI (nCPI). This measure indicates the normalized levels of change multiplication and absorption between system components. nCPI expresses the relative strength of each area on the absorber-multiplier spectrum between -1 and +1. If the total change affecting component i

is given by $C_{in}(i)$ and the total changes originating from this component is given by $C_{out}(i)$ then nCPi can be given as:

$$nCPI_i = \frac{C_{out}(i) - C_{in}(i)}{C_{out}(i) + C_{in}(i)} \tag{4.2}$$

Sensitivity Design Structure Matrix (sDSM)

A sensitivity design structure matrix (sDSM) is a square matrix where the off-diagonal entries in row *i* and column *j* represent the partial derivative for the output of task *i* to the output task *j*: $sDSM(i,j) = \partial x_i / \partial x_j$ (Yassine and Falkenburg, 1999). These partial derivatives matrix elements can also be normalized: $nsDSM(i,j) = (\partial x_i / \partial x_j)(x_j / x_i)$ (Kalligeros, 2006). That is, entry (*i,j*) represents the percentage change in variable *i* caused by a percentage change i variable *j*. nsDSM is illustrated in Figure 4.2, where both design variables and functional requirements are included.

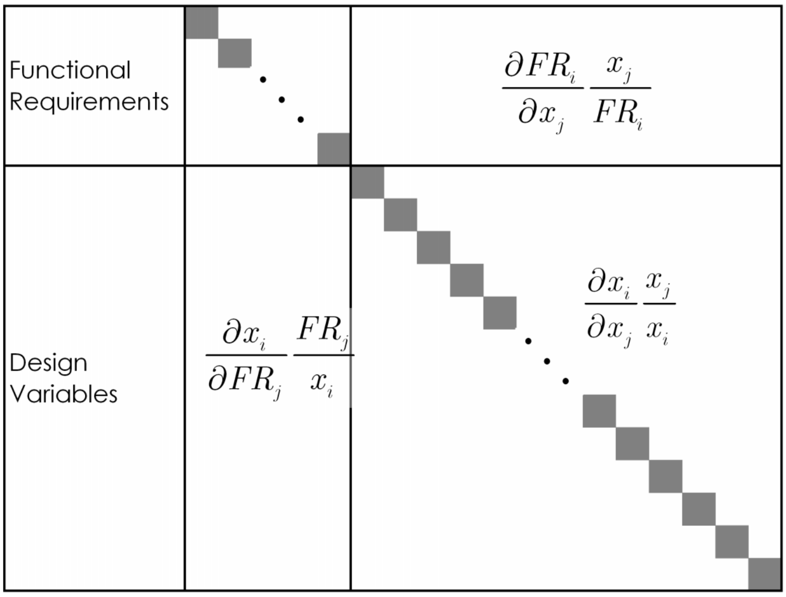


Figure 4.2: Normalized sensitivity design structure matrix (nsDSM) (including extended exogenous functional requirements) approach for identifying flexibility (Kalligeros, 2006).

With the sDSM framework, one can explore system components that are, and are not, sensitive to exogenous changes. Standard components that are not sensitive to changes constitute a platform for which variant designs can be created, and sensitive components are potential areas to introduce flexibility.

Kalligeros (2006) uses an *Invariant Design Rules algorithm* to partition the sDSM and identify alternative standardized design platform alternatives, with components are insensitive to changes in functional requirements. Then sDSM can serve as a useful way to search the design space for areas where flexibility may be built into the system to reduce the cost of switching between relevant design variants. Kalligeros (2006) investigates the methodology on the design of floating production storage and offloading (FPSO) units.

For example for offshore vessels, standard elements such as the hotel, bridge, engines and deck area may serve as a platform used for a variety of designs with specifications for particular offshore segments such as a heavy lift crane, ROVs, module handling tower or a saturated diving system.

4.3 Screening Methods

Screening models are simple, conceptual, low-fidelity representations of the performance of a system that are used to screen out the most important design variables and candidate design flexibilities. The concept of screening models have a long history in engineering design, where one of the first major publications is by Jacoby and Loucks (1972). More recently, Wang (2005) discusses screening models as a concept to identify real options "in" engineering systems. A overview of screening methods is presented in the book by de Neufville and Scholtes (2011), where the authors argue that the use of screening methods is the recommended approach for identifying the most valuable kinds of flexibilities for a system. This chapter is inspired by chapter 5 in their book.

In contrast to slow high-fidelity models, screening models need to be fast so that they can evaluate system performance for different configurations in many scenarios. In that way, screening models can be used to find a short list of attractive configurations and operations of complex systems. After the most relevant candidate designs are found, they can later be investigated in detail. Screening models filter out interesting possibilities, hence their name. This process is illustrated in Figure 4.3.

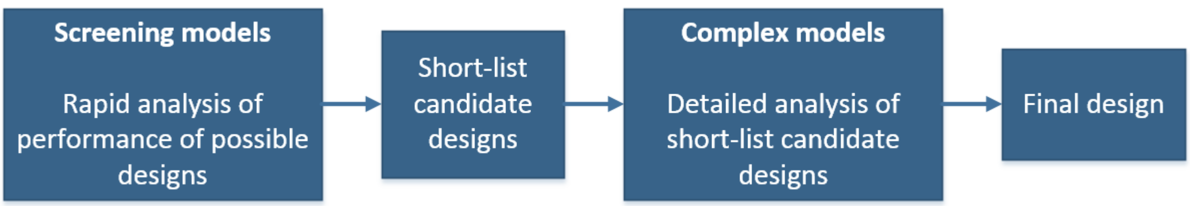


Figure 4.3: Screening models precede and complement detailed models (de Neufville and Scholtes, 2011).

Developing Screening Models

According to de Neufville and Scholtes (2011), there are three generic types of screening models: *bottom-up, simulator* and *top-down.* These methods represent different paths that analysts can take to develop screening models, and in practice, combinations of the methods may be used.

Bottom-up models

The bottom-up screening model strategy involves building simplified versions of the system by the understanding of the parts. These models are more common since they build directly on existing technical knowledge and hence are easier to develop.

Professionals may already have a set of models that describe a system and often have developed ways to coordinate these models into a functional suite. This can bring together knowledge about technical possibilities, environmental factors and the project economics. These packages of models may offer starting points for the development of screening models. For example for a marine system, an integrated system model may include the following three parts:

- A technical model describing the details of the many elements that comprise the isolated design itself, such as the floating ship, including sub-models such as the size of fuel tanks, cargo capacity and functional capabilities.
- A system environment model would describe the relevant details of the important systems that interact with the design, for example, fuel prices and availabilities, market rates and environmental regulations.
- A performance model, typically measuring the economic performance as NPV for the total system, including cash flows, capital expenses, and operating costs.

One can go from these typically existing, more complex, integrated system models to screening models by for example simplifying model inputs and reducing the time step. It is of importance not to simplify too much, and keep the details that are critical for the system behaviour.

Simulator models

Simulator models focus on producing the outputs of a complex system from the inputs, ignoring the inner workings of a process and hence treating the technical considerations as a black box. They can be considered as a statistical exercise with curve fitting, which involves finding a set of outputs corresponding to a set of inputs to create a simple functional relationship reproducing the dynamics. This is a two-step process, first on finding the most important variables and then fitting a simple function to a series of model responses.

Mathematically, simulator models can be referred to as "responsive surface models", since the value of a system can be represented as a function of n relevant parameters, which yields a surface in an n-dimentional hyperspace.

According to de Neufville and Scholtes (2011), there are two ways of developing simulator models: *direct* and *indirect*. The direct approach ignores the interior mechanisms of the system, focusing only on replicating the output and mimicking the overall results of the detailed model. The direct approach is particularly relevant because of its ease of development and use. The indirect approach first focuses on the outputs of the system parts and uses these to to build a complete system model. The indirect approach requires a deeper understanding of different aspects of the elements of the model. However, this may also mean that its result may provide a deeper understanding of the system performance.

An example of simulator direct approach for an offshore oil platform is presented in de Neufville and Scholtes (2011). Designers of deep-water oil and gas platforms usually have detailed models of the aspects of platform design, the oil and gas field and the project economics. These models may take days to run. In the process of creating the screening model, principal drivers of value first are identified. These can for example be the size of the field, the price of oil and the size of the offshore oil platform. The detailed model can then be used to find the system value for different combinations of the value drivers. A statistical curve fitting can then be done for the best fit for an equation. A linear or non-linear value function can be identified, as exemplified below:

$$\begin{array}{ll} \text{Linear:} & \text{Value} = a(\text{size of field}) + b(\text{capacity of platform}) + c(\text{price of oil}) + \text{e} \\ \text{Non-linear:} & \text{Value} = \text{e}(\text{size of field})^{a} \cdot (\text{capacity of platform})^{b} \cdot (\text{price of oil})^{c} \end{array}$$

An indirect approach on the offshore oil and gas field could involve creating simplified models for different detailed sub-models of the system. This could be for a technical model of the platform, a model describing the dynamics of the oil in the field, and an economics model calculating the NPV (Lin, 2008).

Another valuable aspect of simulator models is that they allow the users to explore the overall behaviour of a system, to see if it makes sense. In that way, one can use them as test on integrated models. de Neufville and Scholtes (2011) present one example of this related to oil filed development, where a research team used a simple simulator model to find that the integrated model that the designers used had major flaws leading to costly design errors. This was in particular by the use of economics of scale. By looking at the relationship between the cost and capacity of the system, they found that the economics of scale for the project were "too good to be true" compared to other empirical data, resulting in wrong and costly over-dimensioning of the design.

Top-down screening models

Top-down screening models show how a system's major parts influence and interact with each other over time, and these models provide an overall view of a system. Two types of investigation is required to develop top-down screening models. First, one has to identify chains of physical interactions, to see how changes in one area affect operation in another. Then one has to develop an understanding of how the humans in the system react to these physical changes. Therefore, a good top-down model in general requires an understanding of both the behavioural and mechanical aspects of the system.

Top-down models are of particular relevance when systems involve feedback between components over time, typically introduced by delayed responses. For example, an offshore supply ship owner may have a base of loyal customers, which will cause a time lag in the loss of sales if the company fails to maintain its competitiveness.

Using Screening Models for Flexibility Identification

Screening models can be used to identify flexible design candidates in three ways: *conceptual, optimization and patterned search*, according to de Neufville and Scholtes (2011). The best approach depends on the problem, but in practice, several methods may be used on the same project.

Conceptual Approach

The conceptual approach for identifying candidate flexibilities builds on the simplicity of the developed screening model, and is useful in getting designers and decision-makers to think outside the box. By focusing on an overall perspective of the system, one can easier see interactions between components. This can help experts in each particular field to see how their performance depends on that of others, and to see beyond their immediate responsibilities. This opens up for exploring design opportunities and candidate flexibilities.

An example of a conceptual approach for the design of an offshore oil platform is discussed by Lin (2008). The initial focus was on the platform design alone, but a larger view of the situation indicated that the way the subsea wellheads connected with each other significantly affected the performance of the platform. By introducing subsea tiebacks between the wellheads in the design, the expected value increased by 78 percent.

Optimization Approach

According to de Neufville and Scholtes (2011), the optimization approach works best when applied to a system that is represented by a single model. Relevant fields may particularly be those represented by a network of flows, such as supply chain networks and maritime logistic chains. The single model situations that are applicable for optimization approaches are in contrast to other common fields. This can for example be for the offshore oil platform design situation, which typically has a oil and gas field model, a model for the operation of the platform and a model for the economic performance.

Optimization procedures typically involve methods such as linear programming, dynamic programming or heuristic search. The procedure of identifying candidate flexibilities by optimization can be done by first optimizing the design for one set of contextual conditions. These can be estimates of future market rates and fuel prices, typically chosen as the mean of the range of scenarios. Secondly, the optimization process has to be repeated for several values of the contextual conditions, to see how the optimal solution changes. Then one can observe which elements of the optimal design that change upon contextual change. These are the ones that are relevant for implementing design flexibility.

Patterned Search

The patterned search method involves exploring different types of designs with guidance from conceptual methods familiar to the design team, or from comparable projects. Patterned search differs from optimization, as it is not directed by a set of clear mathematical procedures that lead to the optimal solution. However, the different search methods can be represented mathematically in patterned search, which differentiates the method from the conceptual approach. Focusing on different standard alternatives that can provide flexibility is central for patterned search as there is no specific guidance. Some standard alternatives of patterned search is discussed below.

- **Phased design** - By dividing an expansion into several phases, the managers can limit capacity if the expansion turns out to be unnecessary, and time the expansion according to how the future resolves.

- **Modular design** - Subdividing systems into smaller parts that can be independently designed and used in different systems. This "plug-and-play" method allows for adding features through simple connections. Modular designs can be seen in the shipbuilding (Erikstad, 2009), and in terms of the modular transport parcels of the container transport.

- **Design for expansion** - Systems designed with the built-in capacity to expand in size. An example of this is midship elongation, which was done on the cruise ship MV Balmoral in 2008.

- **Platform design** - Designing with a platform on which designers can create different designs later. This can be an offshore ship that has a hull that is strengthened, so that different systems can be installed later.
- **Shell design** - Designing with extra capacity for use in the future, that is not used immediately. The case here is typically that designers agree that there is a need for the capacity, but do not want to commit to expensive completions before they get more information.

4.4 Tradespace Methods for Changeability Identification

Ross et al. (2011) present a method using Epoch-Era Analysis to identify changeability in system design. They use the tradespace network model and agent-mechanism-effect framework discussed in Chapter 2.5. By the use of the tradespace network model, design states and transition paths can be represented as points and arcs. The number of outgoing arcs from a particular design is called the outdegree of the design. By applying a stakeholder relevant perceived cost threshold for the transitions, the filtered outdegree (f-OD) is defined (Figure 4.4). Filtered outdegree then becomes a quantified measure of changeability (Ross, 2006; Ross et al., 2008b). This is further described in Chapter 5.4.

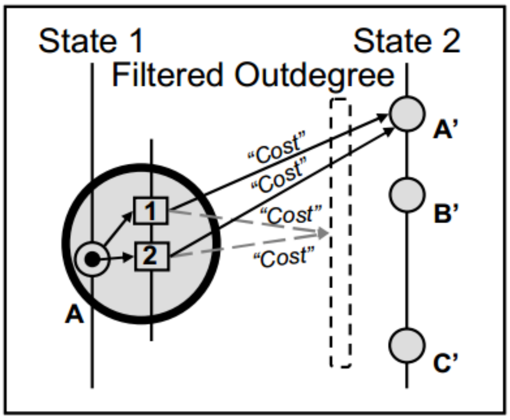


Figure 4.4: Filtered outdegree as a measure of changeability (Ross and Rhodes, 2008b).

Ross et al. (2011) describe a five-step procedure for identifying valuable changeability in system design. However, the method requires a proper construction of an Epoch-Era analysis (EEA) first. This means that several candidate designs are considered in various future scenarios, where different designs have different perceived value, already are generated. The five-step method then proceeds as follows:

1. **Selection of designs.** The first step is selecting the designs of interest, and it is recommended that the number of relevant designs does not exceed ten.

2. **Calculation of changeability value.** - Changeability value metrics represent measures that assign a particular value to a design, using some means of representing the value of executing an available design transition option from that design. Relevant value metrics can for example be NPV or value weighted filtered outdegree.

3. **Aggregation of frequency distributions.** This step involves presenting the calculated changeability values as frequency distributions, for each design in each epoch. Representations can be either of one design in all epochs or one epoch for all designs. The goal of this step is to give graphs that provide an immediate and intuitive understanding of the available changeability.

4. **Cross-Epoch Statistical Breakdown.** The fourth step involves breaking down the distributions into respective statistics, such as the minimum, maximum, median and relevant percentiles. The shapes of the distributions are lost in this step, but the results make up a basis for comparisons of designs and epochs.

5. **Stochastic Era Analysis.** The final step involves stochastic sampling of epochs for era assembly, that is *era construction*. This is to better understand which, and how often, change mechanisms that would be used in operation of each design.

To clarify, this five-step approach represents a framework for post-processing data already created by an EEA. It is intended to help identifying candidate design changeabilities between design alternatives by better illustrating their differences. Hence, it can help the strategic decision-makers in the design process.

Chapter 5

Flexibility Valuation and Quantification

In this chapter, we will present different methods for quantifying the value of flexibility for applications in marine systems design. This involves methods pricing real options including analytical solutions, tree building methods and Monte Carlo simulation. Additionally, insight in flexibility quantification from a systems engineering perspective is discussed, where we discuss the valuation approach for strategic changeability (VASC).

The traditional real option pricing methods discussed are originally used for pricing "on" options. However, the focus in this chapter is more on "in" options. Since "in" options are more complex that "on" options, they typically require more generic methods for pricing, such as Monte Carlo simulations.

The best metric used for flexibility valuation is dependent on the preferences of the stakeholders. A monetary preference is probably most common for engineering systems, and in particular for commercial marine systems. Hence, a preferred value metric is often the net present value (NPV). From the financial side of pricing options, a monetary view is also natural. Therefore, for simple "on" options traditional option pricing methods, such as Black-Scholes or Binomial lattice, are applicable. However, when flexibility gets more of the characteristics in the "in" options category, as introduced in Chapters 2.3 and 2.4, the ambiguous translation of pricing parameters may then render these traditional pricing methods inappropriate. This is even amplified when the value of flexibility is represented by other non-monetary stakeholder preferences.

Some may argue that all other metrics in the end often can be translated into how they affect the cash flows and the NPV, especially for commercial systems. However, not all systems are for commercial use, such as for example the coastguard or the construction of search and rescue vessels. For these examples, the value may be in their agility and the number of different scopes they can be used for, perhaps for a given budget. Other cases are for the development of human spaceflight projects at NASA (Hawes and Duffey, 2008), where performance, safety and costs are central topics of interest, or for design of flexible naval ships that do not generate any positive cash flows (Knight, 2014). For these applications typically involving "in" options, more novel methods for quantifying the value are of interest. Relevant methods here are typically Monte Carlo simulations and the newer tradespace related approach (VASC), where systems engineering is central.

Some of the methods discussed in this chapter are inspired by the state-of-the art paper by Erikstad and Rehn (2015), where they compare methods for flexibility valuation. However, in this chapter some methods are added together with more discussion.

5.1 Analytical Solutions

Generally speaking, analytical solutions are exact solutions to equations describing some relevant parameters or variables, for the purpose of calculating the value of something. In terms of pricing options, analytical solutions have great applications, representing exact solutions to differential equations expressing the change in option value with respect to the relevant variables. Compared with other methods for pricing options, analytical solutions have the advantage of being quick and easy to understand and use, and that they are computationally easy. However, for non-standard options, finding analytical solutions can quickly become very difficult.

The most famous analytical option-pricing model is the Black-Scholes / Black-Scholes-Merton (BSM) option pricing model (Black and Scholes, 1973; Merton, 1973). They were the first to show that options could be priced by the construction of a risk free hedge, by dynamically managing a simple risk-free portfolio consisting of the underlying asset and cash. Traditionally, geometrical Brownian motion (GBM) is used for the modelling of the underlying value in BSM, and introducing other stochastic processes or properties quickly makes analytical solutions very complicated.

Despite their rather complicated nature, analytical (real) option-pricing models have been developed for applications to freight markets. For example, Soedal et al. (2008) propose an analytical solution for combination carriers able to switch between markets. Their model is an Ornstein-Uhlenbeck mean-reverting version of a standard entry-exit model with stochastic prices.

Since analytical solutions directly represent how different model variables and parameters affect each other, they serve as a good tool to better understand the problem of analysis. For example, one can relatively easy see for which combinations of volatility and underlying value a real option should be exercised, or for which combinations it is more valuable to wait. In the following, we will briefly discuss the Black-Scholes formula, and a simple approach to pricing perpetual options.

Black-Scholes formula

The Black-Scholes formulas for European put and call options are, as described by McDonald (2003):

$$BS_{call} = Se^{-\delta T}N(d_1) - Ke^{-rT}N(d_2) \tag{5.1}$$

$$BS_{put} = Ke^{-rT}N(-d_2) - Se^{-\delta T}N(-d_1) \tag{5.2}$$

Where S is the current price of the underlying, δ is continuously compounded dividend rate, K is the strike price, r is the continuously compounded risk-free interest rate, σ is the volatility of the underlying, T is the time to expiration and $N(d)$ represents the cumulative normal distribution function as a function of the variable d given by:

$$d_1 = \frac{ln(\frac{S}{K}) + (r - \delta + \frac{\sigma^2}{2})T}{\sigma\sqrt{T}} \quad and \quad d_2 = d_1 - \sigma\sqrt{T} \tag{5.3}$$

Analytical solution for perpetual options

Another relevant application of the analytical solution form is for perpetual options, that is options that never expire. When it comes to analytically pricing perpetual American options, an extension of the Black-Scholes formula was developed by Merton (1973). The approach as, as described in McDonald (2003), is first, by using the same notation as above, define h_1 and h_2:

$$h_1 = \frac{1}{2} - \frac{r-\delta}{\sigma^2} + \sqrt{(\frac{r-\delta}{\sigma^2} - \frac{1}{2})^2 + \frac{2r}{\sigma^2}} \tag{5.4}$$

$$h_2 = \frac{1}{2} - \frac{r-\delta}{\sigma^2} - \sqrt{(\frac{r-\delta}{\sigma^2} - \frac{1}{2})^2 + \frac{2r}{\sigma^2}} \tag{5.5}$$

The value of a perpetual American call (AC) option, with a strike price K that is exercised when $S \geq H_c$ is:

$$AC_{perpetual} = (H_c - K)\left(\frac{S}{H_c}\right)^{h_1} \tag{5.6}$$

Where H_c is given by:

$$H_c = K\left(\frac{h_1}{h_1 - 1}\right) \tag{5.7}$$

The value of a perpetual American put (AP) option, with a strike price K that is exercised when $S \leq H_p$ is:

$$AP_{perpetual} = (K - H_p)\left(\frac{S}{H_p}\right)^{h_2} \tag{5.8}$$

Where H_p is given by:

$$H_p = K\left(\frac{h_2}{h_2 - 1}\right) \tag{5.9}$$

5.2 Tree Building Methodologies

Tree building methodologies represent a framework for building scenarios as discrete steps into branches developing something that looks like a tree, where strategic measures can be made accordingly. Probabilities are often assigned to the scenarios, and applications include decision trees and option-pricing trees.

There are several classes of trees. One of the most common trees is the binomial tree, which has two scenarios going out of each state, but extensions to multinomial trees are possible. In terms of the sequential branching, the simpler trees recombine into what often is called a lattice. This means that if you move up and down, or down and up, over a two-step process, the end state has the same value as the start sate. This makes the enumeration of total possible states much lower, hence easing the computational power required. In Figure 5.1, a binomial recombining tree and lattice is illustrated. However, as seen with the a-d illustration of the end states in this particular figure, both the tree and the lattice are recombining.

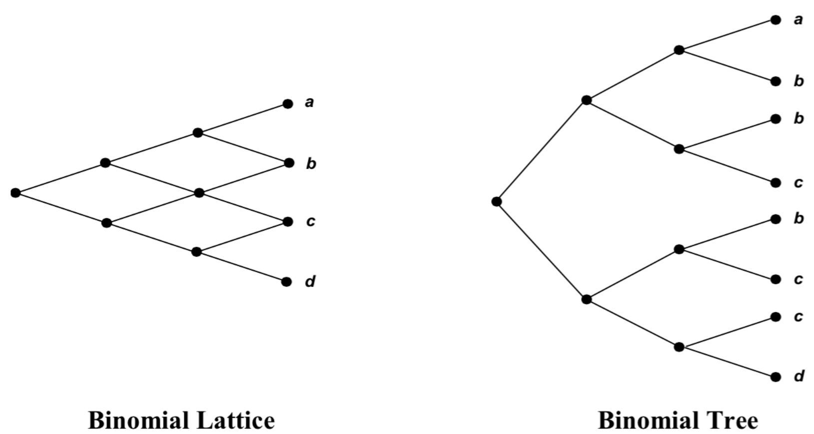


Figure 5.1: Recombining binomial lattice and tree (Hahn, 2005).

Option Pricing Trees

For pricing options, and real options, tree-building methodologies are widely used and is particularly relevant for pricing American style options. The nature of the tree framework makes it great for some applications of option pricing, but when the underlying stochastic processes become complicated, such as for handling path dependence, the tree methods usually cannot be easily adapted.

Binomial option pricing model

Probably the most famous tree method for pricing options is the binomial lattice option-pricing model (BOPM), introduced by Cox et al. (1979). The method shows similarities to the Black-Scholes-Merton model, as it also is based on the principle of creating a risk-neutral portfolio consisting of the option and the underlying asset, which in this case is assumed to follow a binomial process. The construction of a binomial price tree is illustrated in Figure 5.2.

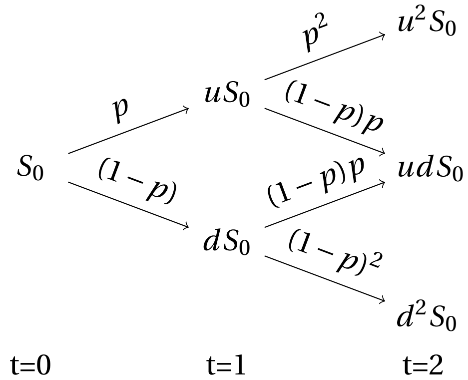


Figure 5.2: Two period recombining binomial lattice.

Here, the value of the underlying asset S is assumed to follow a two-step, binomial, discrete development with time steps Δt. The stochastic process is characterised as a geometrical Brownian motion (GBM). At each step, the value can increase by a multiple of u or decrease with a multiple $d = 1/u$, with corresponding probabilities of p and $q = (1-p)$. These parameters are given by the following formulas:

$$u = e^{\sigma\sqrt{\Delta t}} \tag{5.10}$$

$$d = e^{-\sigma\sqrt{\Delta t}} \tag{5.11}$$

$$p = \frac{e^{r\Delta t} - d}{u - d} \tag{5.12}$$

Where r is the risk-free interest rate and σ is the standard deviation of the underlying asset. The method can be easily extended to include dividends δ. A developed value tree typically provides initial conditions for the price tree, which is solved backwards with strategic actions made depending on what kind of option that is to be priced. For example, for an American option, this involves evaluating if the option is to be exercised or not, in each node. In this process, probabilities and discount rates are used to end up with a present value of an option.

For path-independent trees, there are several paths one can take and still end up in the same state. As mentioned, this makes the computational process much easier, but for some real options, it may be an over-simplification of reality and may not hold (Wang and Neufville, 2004). This is particularly for "in" options, with high technical complexity.

The traditional binomial lattice method presented above applies geometrical Brownian motion (GBM) as the stochastic process for describing the underlying asset movement. However, developing generic tree pricing methods when considering other stochastic processes can be rather difficult.

Mean-reversion binomial lattice
An example of a stochastic process that may be of relevance for real option pricing is mean-reversion. To model this in a binomial lattice, Nelson and Ramaswamy (1990) proposed a one-factor approximation to the Ornstein-Uhlenbeck mean-reverting process.

With the same parametric notation as for the binomial lattice process, the model can be described as follows (Hahn, 2005):

Up move:

$$S_t^+ = S + \sqrt{\Delta t \sigma} \tag{5.13}$$

Down move:

$$S_t^- = S - \sqrt{\Delta t \sigma} \tag{5.14}$$

Probability for up move:

$$q_i = max\Big(0, min\Big(1, (\frac{1}{2} + \sqrt{\Delta t}\frac{\kappa(\bar{S} - S_t)}{2\sigma})\Big)\Big) \tag{5.15}$$

Probability for down move:

$$1 - q_i \tag{5.16}$$

Where S_t is the underlying asset price at time step t, σ is the process volatility, κ is the mean reversion coefficient and $\bar{S}$ is the log of the long-term mean price. Log is used since it is often assumed that asset prices follow a log-normal distribution.

Decision Trees

A relevant usage of trees for assessing flexibility is by decision trees, often related to the field of decision analysis. Decision analysis (DA) is a methodology and framework for facilitating decisions in a formal manner, and the term was coined by Ronald A. Howard in 1966.

As described in Skinner (2009), a decision tree is "a sequential graphical representation of decisions and uncertainties which represent all paths the decision-maker might follow through time." Decision tree construction include elements such as decision nodes (typically squares), chance nodes (circles) and end nodes (triangles), and branches between the alternatives and for the outcomes. Decision trees are perhaps of particular interest for incorporation and valuation of design flexibility when it comes to the assessment of decision rules - for the strategic managerial process of exercising real options.

An example of a two-stage decision tree used for valuing flexibility is illustrated in Figure 5.3 (Cardin and de Neufville, 2008). The tree has nine possible outcomes, with corresponding values V_i. Paths 1 to 6 are related to the flexible design, with some kind of flexibility can be exercised, such as lay-up, abandon or capacity expansion. Paths 7 to 9 are related to the inflexible design, here operations continue as they are. The circular nodes with a C inside are chance nodes - relating to some uncertain event or information, and the square nodes with a D inside are decision nodes.

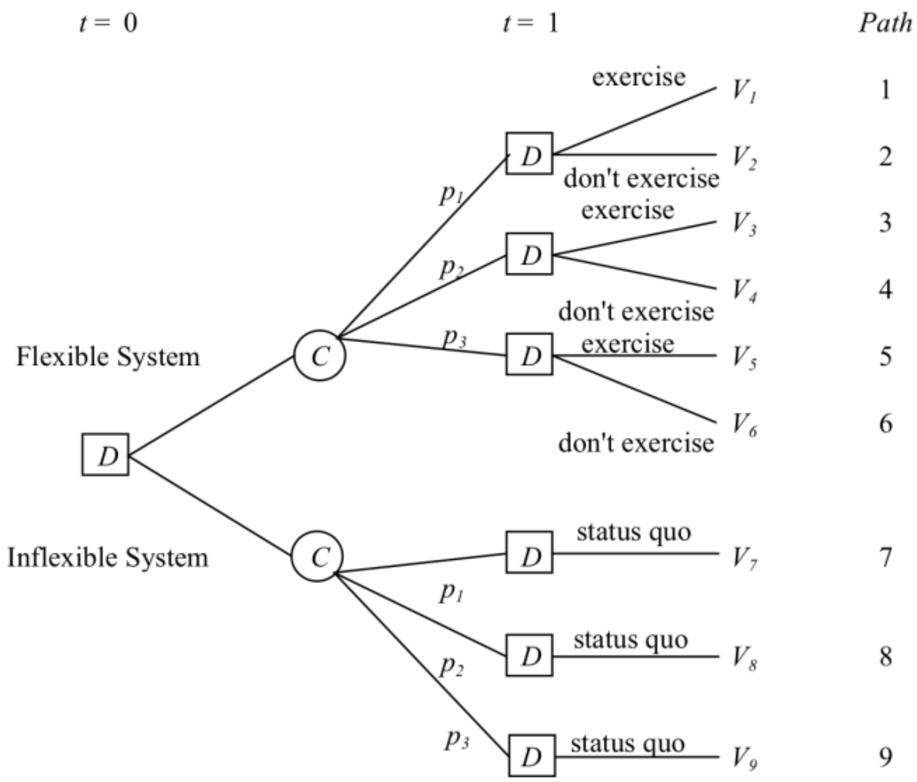


Figure 5.3: Example of a tree structure for valuing flexibility using decision analysis (Cardin and de Neufville, 2008).

In the case of Figure 5.3, flexibility analysis is done by first pruning the tree, which involves selecting the paths that correspond to the decision strategies with the highest expected outcome value, and removing the others. The value of flexibility can then be calculated by subtracting the expected inflexible value from the flexible value. Due to the nature of the methodology, it can be of particular relevance when it comes to valuing combined real options, discussed in Chapter 5.5.

5.3 Simulations

Simulation methodologies comprise a generic framework for solving various sorts of problems, and are highly relevant for valuing flexibility in system design. In particular for option-pricing, Monte Carlo simulation enables us to solve relatively complex path-dependent problems much more easily than by other common methods.

Monte Carlo Simulation (MCS)

Monte Carlo methods for simulation are a broad class of algorithms that involve repeated random sampling for obtaining numerical results, introduced by Metropolis and Ulam in the 1940s. This method opens up for numerically solving problems that are difficult to solve analytically. As Rader et al. (2010) put it, "MCS seeks to answer the question: *What is the expected outcome distribution given known systematic uncertainties?*". The Monte Carlo simulation process is illustrated in Figure 5.4.

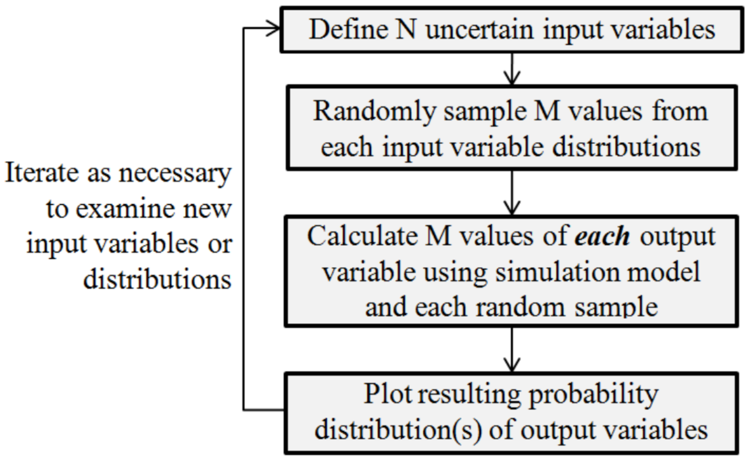


Figure 5.4: The Monte Carlo simulation (MCS) process (Rader et al., 2010).

For pricing real options, MCS is used for generating scenarios by drawing random numbers from probability distributions representing uncertain variables, to simulate possible paths asset values or other parameters can take over time. Two thousand scenarios generated by a MCS is illustrated in Figure 5.5. For each scenario, relevant strategic actions are made depending on the type of option and management strategy, resulting in the corresponding system performance. By doing this multiple times, a performance distribution can be generated. For real options in system designs, one typically finds the expected net present value (ENPV) for a project with and without the real option. The value of flexibility is then the difference between these values, as illustrated in Equation 5.17.

$$E(V) = E(NPV_{flex}) - E(NPV_{rigid}) \tag{5.17}$$

Pricing real options, MCS represents a flexible framework to approximate the value of real options, compared to for example binomial lattice or analytical solutions. This is because the method can more easily accommodate various non-standard stochastic processes and path-independence. de Neufville and Scholtes (2011) argue that MCS is the preferable method valuing flexibility in engineering design.

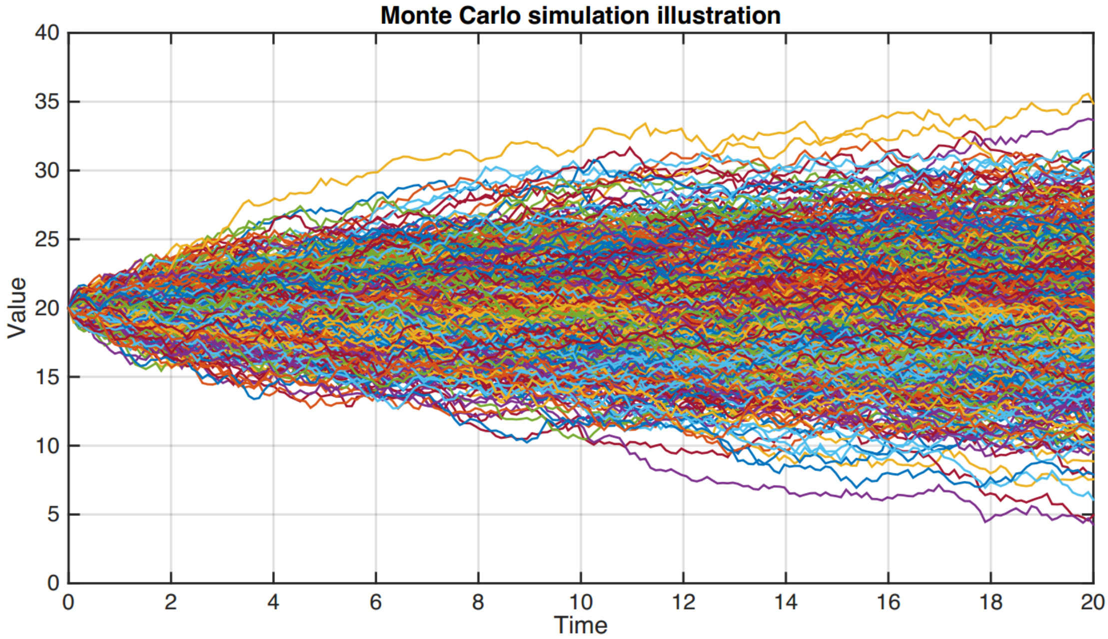


Figure 5.5: Example of 2000 scenarios generated by the Monte Carlo simulation method.

For implementing and valuing flexibility in design of engineering systems, Monte Carlo simulation opens up for an easy method to incorporate different types of decision rules. This can typically be by the use of "IF", "ELSE" and "THEN" programming statements. For example "IF: Two consecutive years with negative cash flows" "THEN: Exercise the *lay-up* option." "ELSE: Continue as usual." Due to the nature of the simulation framework it is typically much easier to implement, compared to the other methods, and furthermore, one can easier analyse the effects of different decision rules and hence consider more practical management strategies.

5.4 Tradespace Methods for Changeability Quantification

Central in the tradespace evaluation and exploration framework is the concept of changeability quantification, as briefly introduced in Chapter 4.4. Changeability quantification, or "ility" quantification, involves both understanding which designs that are more changeable than others and the perceived value of this for the relevant stakeholders. This approach to design for changeability can be considered a complementary approach to real options (Ross et al., 2008b).

Quantifying Changeability

This framework builds on the agent-mechanism-effect tradespace network representation, presented in Chapter 2.5, with system design states and transition paths represented as points and arcs in the network (Ross et al., 2008b). Each arc represents a transition with a related cost, involving both time and money. Each transition resulting in a viable change event has an "acceptability-threshold" for the time and money spent by the decision-makers.

The number of outgoing arcs from a design is called the *outdegree* of the design. The number of outgoing arcs that have a cost lower than the relevant threshold value is defined as the *filtered outdegree* (f-OD). Filtered outdegree then becomes a quantified measure of changeability (Ross, 2006; Ross et al., 2008b). This is summarised in Figure 5.6. The filtered outdegree approach may also be used on other "ilities".

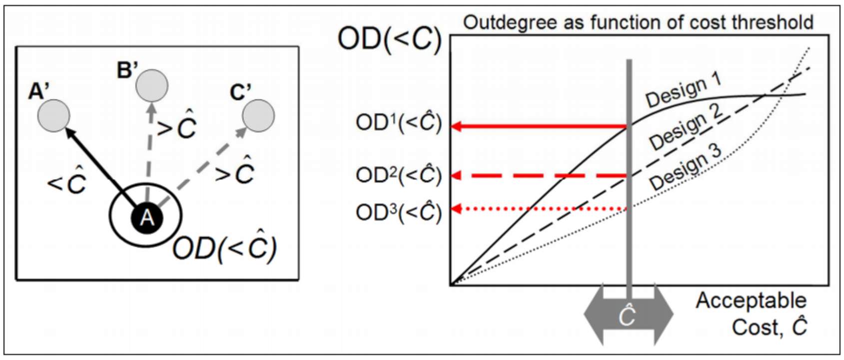


Figure 5.6: (OD = outdegree) Filtered outdegree as a measure of changeability Ross et al. (2008b).

What is changeable for one decision-maker may not be perceived as changeable for another, since different stakeholders often have different risk attitudes and different perceptions of value. Due to the nature of the threshold value, capturing the nature of the resources spent, the filtered outdegree method captures the relativity in the perceived changeability of various designs.

There are also modified versions of f-OD. For example, Viscito and Ross (2009) introduce *value-weighted filtered outdegree* as an approach to modify filtered outdegree into a value metric. This method weights the outgoing arcs by the sign of their effect in utility, thus differentiating between positive and negative value changes.

Valuation Approach for Strategic Changeability (VASC)

Building on Epoch-Era as an analysis framework, real options and the filtered outdegree method as a changeability quantification measure, Fitzgerald (2012) introduces the valuation approach for strategic changeability (VASC).

VASC tries to meet some particular challenges with a general framework. According to Fitzgerald et al. (2012), these are related to what they call *magnitude value, counting value* and *strategies*. The value of changeability can be characterised by magnitude and counting value. Magnitude value relates to the level of performance improvement derived from the change. Counting value relates to the quantity of changeability, as there is more value in having multiple outgoing arcs, as this increases the probability that a desirable change is available. The authors argue that prior methods do not properly account for the combination of these aspects, which is what is desired with VASC. For the clarification of the tension between magnitude and counting value, the concept of strategy (or rule execution strategy) is proposed to capture that value is derived from changeability only through executed changes. Fitzgerald et al. (2012) define strategy to be a statement of how and when a stakeholder plans to execute any changeability options in the system. By the concept of strategy, the burden of enumerating all possible end states is reduced as only "good enough" end states show changeability value.

Figure 5.7: "Best" path selection determined by different strategies (Fitzgerald et al., 2012).

Value Metrics

Fitzgerald et al. (2012) also discuss the use of different metrics in the VASC framework. The goals for the metrics are that they should be independent of the considered alternatives and that they should be universal in scale across contexts. The reason why this is included in such detail is that these metrics all represents approaches to quantifying flexibility, serving the objectives of this thesis. The relevant metrics the authors present are the following, mostly in their own notation and words:

- **Filtered Outdegree (FOD)** - As described earlier, this metric scores designs based on their number of outgoing arcs, filtered by a threshold cost.

$$FOD(d,\bar{C}) = \sum_{j}^{N} \sum_{numrules}^{k} H(T_{d,j,k}), \forall T_{d,j,k} \leq \bar{C} \tag{5.18}$$

$\bar{C}$ is the acceptable cost threshold, N is the number of designs, k i a given transition rule, j is a given destination design from d, $T_{d,k,j}$ is a matrix of costs for the transition from d to j using rule k, and H represents the Heaviside function.

- **Fuzzy Pareto Number (FPN)** - This is defined as the minimum required fuzziness for a design (d) to be included in the K% fuzzy Pareto set (P_K). FPN is defined in each design in each epoch and can be interpreted as a measure of cost efficiency.

$$FPN(d) = min\{K| \subset P_K\} \tag{5.19}$$

A fuzzy Pareto set opens up for a margin of deviation from the true Pareto front and is defined as a percentage of the range of the data. A FPN of 10% means that the design is within 10% of total cost-efficiency in that epoch. In this way one can also include the satisficing designs, performing well but not best.

- **(Fuzzy) Normalized Pareto Trace (NPT/fNPT)** - This metric measures the fraction of the epochs in the epoch space for which a design is Pareto efficient, that is non-dominated in utility and cost. In this way, the metric targets passive value robustness.

$$NPT(d) = \sum_{epochs} 1\{FPN(d) = 0\} \div N_{epochs} \tag{5.20}$$

$$fNPT(d,K) = \sum_{epochs} 1\{FPN(d) \leq K\} \div N_{epochs} \tag{5.21}$$

- **Effective NPT / Effective fNPT (eNPT/efNPT)** - Measures changeability-enabled "effective" robustness, by calculating NPT and fNPT for a design considering its end state (d^*) determined by a strategy, rather than its own position.

$$eNPT(d) = \sum_{epochs} 1\{FPN(d^*) = 0\} \div N_{epochs} \tag{5.22}$$

$$efNPT(d,K) = \sum_{epochs} 1\{FPN(d^*) \leq K\} \div N_{epochs} \tag{5.23}$$

- **Fuzzy Pareto Shift (FPS)** - Calculated as the difference in FPN of the start and end states, and evaluates the magnitude of the strategy-selected change path in each epoch. It measures the efficiency improvement or decline caused by the executed changes.

$$FPS(d) = FPN(d) - FPN(d*) \tag{5.24}$$

- **Available Rank Improvement (ARI)** - Takes a defined epoch and scores each change mechanism (r) for each design in terms of how many other designs can be surpassed in rank-order utility via that change mechanism. d^r is the set of designs reachable by d through r. The metric is useful for comparing the relative value of different design mechanisms.

$$ARI(r,d) = Rank(d) - min\{Rand(d^r)\} \tag{5.25}$$

- **Lifecycle FPN statistics** - The current FPN can be tracked at all times when simulating an era, and this data can be processed at the end of each sample era to find the best, worst and average FPN over the system's lifecycle. Average FPN can be of particular interest when comparing different designs' aggregate lifetime efficiency.
- **Rule Usage Likelihoods** - The number of usages of each change mechanism during an era simulation can also be of interest for design comparisons. This enables for comparisons of relative frequency, and the likelihood of different change events.
- **"Going Rate" tradeoffs** - By comparing initial costs to any lifetime value metric, the "going rate" for additional changeability can be calculated. This is for designs that differ only by their inclusion of a given mechanism.

Five steps of the VASC procedure

The VASC process is a five step procedure, described by Fitzgerald et al. (2012) as following:

1. **Set up data for Epoch-Era Analysis** - The first step involves implementing the case into the Epoch-Era framework. This includes identifying input data like design variables, stakeholder preferences, relevant attributes, change mechanisms and context variables, and outputs such as transition matrices, design/epoch lists and Fuzzy Pareto Numbers for each design/epoch pair.
2. **Identify designs of interest** - The second step involves identifying relevant designs for further detailed exploration, and is necessary in order to reduce the computation time. This also involves screening measures such as (fuzzy) Normalized Pareto Trace for value robust designs and filtered outdegree for highly changeable designs.
3. **Define Rule Usage Strategies** - By defining strategies, one specifies the logic behaviour of the system condition over time and identifies the change mechanism options that should be executed. This step involves determining the set of possible rule usage strategies, defining strategies for change mechanism execution in each epoch and for

each design/epoch pair to determine the most desirable end state. The outputs include the realized end states and transition costs for all relevant combinations of design, epoch and strategy.

4. **Conduct Multi-Epoch Changeability Analysis** - In this step a multi-epoch changeability analysis is conducted, considering possible contexts the system could be used in. This step involves calculation of metrics such as Effective NPT and Effective Fuzzy NPT, Fuzzy Pareto Shift and Available Rank Increase. The outputs include relevant information on when, why and how designs of interest are changing within epochs and the value of these changes. Additionally, one can identify particularly valuable change mechanisms and designs that rely on a single change mechanism of high relative value.

5. **Conduct Era Simulation and Analysis** - The last step is an era analysis, that gives important design lifecycle performance information and helps identify valuable change mechanisms. Activities include simulations of numerous eras for each design. The outputs from this step include statistical data on the related usage and likelihood of change mechanisms, and on the utility provided and design efficiencies. In this way, one can compare different strategies and change mechanism usages for each design.

5.5 Other Aspects of Flexibility Valuation

Optimal Exercise and Triggering Rules

A critical aspect of the implementation and valuation of flexibility in engineering design is how to decide when to exercise the flexibility and how to do this optimally. For classical financial options, the traditional approach is to choose the outcome with the highest expected value through backwards induction. This has roots in dynamic programming and the Bellman equation.

However, for methods valuing complex "in" options for systems design, making a framework that in each node calculates the expected value of each outcome of a decision can quickly be complicated. This is particularly for path dependent options, where a complete enumeration of the tree can become very computationally heavy. A practical approach often used to decide when to exercise these "in" options is by the implementation of decision rules, as briefly discussed in Chapter 5.3. Simulation methods serve as an appropriate framework for implementation of decision rules such as "IF", "ELSE" and "THEN", describing the actions and consequences of the decisions. In a practical simulation model, these are typically implemented as a function of for example the year-to-year profits or the momentum of the market situation. As discussed earlier, the marine industry is highly volatile, and typically goes through defined cycles (Stopford, 2009). For example, where a management team think they are in the cycle, can serve as a triggering rule for several flexible strategies, such as to expand when they are past a cycle trough, and to sell or when they are past a cycle peak.

However, there are methods developed for ensuring a more optimal nature of option exercise in the simulation pricing approach. For example the least-squares Monte Carlo (LSMC) method (Longstaff and Schwartz, 2001), originally developed for valuing American options, aims at better estimating the conditional expected payoff to the option holder for continuation, by simulating lots of paths and performing a regression analysis on the resulting option values.

Compound Options - Options on Options

Options on options, also called compound options, arise when for example facing the decision about if you want to make the ship flexible from day one, or to prepare the ship to be able to become flexible in the future if needed. The latter can then be considered as a compound option, as it gives the opportunity to postpones the decision about investing in flexibility at a later stage. In this case, flexibility is considered as an option itself, for example as the option to switch between markets.

Compound real options are of particular interest when there is significant uncertainty about the usage of the flexibility. For example, for the case with building a ship prepared for a conversion to be able to run on either LNG or HFO. Typically, on the route there may not be available bunkering stations for LNG, which for short-term considerations makes the value of the flexibility of switching very low. However, this may change in the future.

Combined Options

When analysing system flexibility, there are often multiple real options that are relevant for valuation. This can typically be related to both expanding and abandoning projects. If one values these two options for themselves, one can end up with the wrong value of them combined. This is because if one exercises the abandon option, one also gives up the expansion option. Therefore, it is important to consider this when valuing multiple options for system designs. The problem can be solved easily, depending on the method for real option valuation. For the binomial tree method, one has to consider both value trees in each node when calculating the price tree backwards, to find the optimal decision strategy. For Monte Carlo simulation methods, one has to consider this in the decision rules that are designed to replicate the strategic actions made by the management team.

Game Theoretic Applications

The main source of uncertainty in traditional real options analysis (ROA) is typically related to the market, such as for commodity prices. However, these variables may in fact also depend on other aspects - in particular the actions of competitors. Traditional ROA assumes the competition to be exogenous, but for real options that to some degree are shared with others the exercise decisions for one player can influence option values for another player. In these situations, traditional ROA is not sufficient for pricing real options, and game theoretic extensions are necessary (van der Wijst, 2013).

Game theory is the study of strategic interactive decision-making - involving behaviour in situations where the players' choices depend on the choices of the other players, and was introduced in "Theory of Games and Economic Behavior" by Von Neumann and Morgenstern in the 1940s. Real options and game theory is linked by Smit and Trigeorgis (2004). Related to marine system design, multidisciplinary decision-making based on game theory in ship preliminary design is discussed by Liang et al. (2009).

Economies of Scale

An important factor regarding flexibility is Economies of Scale (EoS), which is the per unit cost advantages obtained due to large scales of operation or production. EoS is important because it drives designers to initially build large, which is in contrast to design for flexibility. A representation of economies of scale is by the cost function (Cardin et al., 2015):

$$\text{CAPEX of fixed design} = \text{capacity}^{\alpha} \tag{5.26}$$

Where α is the economies of scale factor, where a lower α yields greater economies of scale.

Discount Rates and the Time value of Money

The discount rate r in the Discounted Cash Flow (DCF) models represents the time value of money. What is of interest is that higher discount rates make short-term cash flows more valuable and long-term cash flows less valuable. Therefore, it provides a counterbalance to economies of scale, and increases the attractiveness of flexible measures that decrease the initial investment costs.

The traditional methods used for pricing financial options use the risk free interest rate for discounting the values from the risk neutral space. That is, for example for the binomial process, the up and down probabilities are risk-neutral. If another discount rate is used, such as the opportunity cost of capital for the relevant segment, the values that are discounted are the real values. The latter method is more often seen in the complex "in" options pricing methods.

Learning Effects

Learning effects refers to the idea that the cost of flexibility, or typically modularity, is reduced with the number of units produced (de Neufville and Scholtes, 2011; Cardin et al., 2015). This is because of the common conception that we gain experience of doing something the more we do it, thereby "learning" to be more productive. A way of representing modular CAPEX is by Equation 5.27 (Cardin et al., 2015).

$$U_i = U_1 \cdot i^{\beta} \tag{5.27}$$

Where U_1 and U_i represent the CAPEX of the first and ith modules. β is the slope of the learning curve - for example determined by empirical data. For clarification, for a learning rate L, β can be calculated by Equation 5.28 (Cardin et al., 2015).

$$\beta = \log(100\% - L\%) \div \log(2) \tag{5.28}$$

The learning effect phenomenon, together with the time value of money, encourages for flexible design, as opposed to the concept of economies of scale. This is because learning makes the cost of small modular increments of capacity more profitable, compared with building larger units.

Chapter 6

Framework for Flexibility Analysis

The intentions of this chapter are to synthesise the material presented earlier on methods for identification and valuation of flexibility, and present a practical approach for analysing flexibility in design of marine systems. This involves first summarising the benefits and drawbacks of the different methods for identification and valuation of flexibility discussed earlier, before an approach for selecting "which method to use when" is presented. This again involves classifying the systems with particular criteria to see the main characteristics, and matching them with the properties of the different analysis methods. In the end, a practical stepwise generic approach for analysing flexibility for design of marine systems is presented, comprising both deterministic and stochastic analyses. Focusing on analysis of real options "in" system design is a red line through the past methodological discussions, and is also the focus in this chapter.

6.1 Summary of Identification and Valuation Methods

There are several methods for identification and valuation of flexibility. In the following, brief summaries of the different methods are presented, discussing benefits and drawbacks.

Table 6.1: Summary of the most relevant flexibility identification and valuation methods discussed in this thesis.

Identification Methods	Valuation Methods
Interview	Analytical
Information flow (CPA, sDSM)	Tree methods (Binomial lattice, decision trees)
Screening	Simulation
Tradespace methods	VASC

Abbreviations in Table 6.1: CPA: change propagation analysis, sDSM: sensitivity design structure matrix.

Table 6.2: Pros and cons with the discussed flexibility identification methods (adapted from Cardin and de Neufville (2008)).

Method	Benefits	Drawbacks
Interview	Basic and intuitive method. Can be a good starting point for using more technical methods.	Information needs to be translated to another medium for further analysis. Interviews can be biased.
Information Flow	Provides a good representation of the system and interconnections between components, and allows for technical analysis through CPA and sDSM, and environmental aspects through ESM.	Most applicable for technical audience. Applied so far on platform developments, and it is not clear how to use on systems with more frequent adaptations. Do not consider optimal conditions for exercise, only look at design representation.
Screening	Computationally efficient for exploring the design space for valuable design configurations. Can be used with transparency to be easily understood by decision makers.	Can be difficult to find appropriate sets of exogenous factors for screening, and some of the sub-methods require technically trained audience. Generally does not guarantee that the optimal solutions are found.
Tradespace	Provide means of better communication with stakeholders by focusing on their preferences and their understanding of the system and context. Good for systems with mixed stakeholder preferences.	The methods themselves are relatively new and may seem complicated for non-technical audience.

Table 6.3: Benefits and drawbacks with valuation methods (adapted from Cardin and de Neufville (2008)).

Method	Benefits	Drawbacks
Analytic	Can provide quick valuations for simple standard options, and are often recognised by non-technical decision-makers. Useful when there are standard distributions representing the progressive uncertainties.	For non-standard options, analytical methods quickly become very complicated, if not impossible, and may require high mathematical expertise.
Tree	Recombination of the trees can simplify to e.g. a binomial lattice can provide relatively simple and useful means for pricing real options that are not too complicated in nature. Decision trees is useful for evaluating events with sudden changes in uncertainty, e.g. by regulations. The illustrativeness of a tree can help for explicitly looking at particular decisions.	Assumptions made for standard approaches with binomial lattice may not hold for complicated engineering applications. Binomial lattice requires understanding of financial options theory, and the method does not handle well multiple sources of uncertainty. Decision tree analysis may become difficult to handle for large complex problems.
Simulation	Good at handling large and complex problems, with multiple sources of uncertainties. A vast array of design and decision rules may be implemented. Simulation outcomes are typically distributions, with more embedded information of the risks. Method is usually easy to understand.	For large problems, simulations may be computationally heavy. Implementation of simulation procedures require computer coding skills and is usually for technically trained people. Difficult to guarantee optimal option exercise, resulting in suboptimal option values.
VASC	For quantifying flexibility, this framework is good for mixed preferences. By generating future realizations with stakeholders, for example by the narrative approach, it serves as a method that may easily be explained to a non-technical audience, without going into statistics.	Narrative approach for scenario generation with the epoch-era framework may move towards wishful and unrealistic thinking. The methodology itself is relatively new and technical, and may therefore be less relevant for a non-technical audience.

6.2 Choosing Which Method to Use When

The approach for selecting "which method to use when", is built on Cardin and de Neufville (2008). They present five criteria for classifying systems to help select the appropriate method for identification and valuation: main area of flexibility, frequency of exercise, intended audience, intensity of LCC and nature of uncertainty. Two more criteria are added: stakeholder preferences and system complexity. This is mainly because they help characterise the tradespace related methods.

Criteria for Method Selection

- **The main area of flexibility**
  The main area of flexibility criterion is based on the type of activity the system is involved in, and is typically related to "**operations**" or to the "**physical structure**" of the system. For example, a fleet of container ships can have flexibility in their operations by varying their routes and the size of the fleet and ships. A single offshore ship can for example have physical flexibility when it can be retrofitted, for example with a large crane, to take on other types of contracts.

- **Frequency of exercise**
  The frequency of exercise criterion is how often the flexibility is expected to be used, and is characterised as **frequent** or **infrequent**.

- **Intended audience**
  The intended audience criterion is important, as the point of the analysis typically is to communicate design ideas from an analyst to an intended audience. The intended audience can be divided into "**technical**" and "**non-technical**" groups. For example, it can be of little value to try to communicate highly technical models to an audience with no qualified training or technical background.

- **Intensity of lifecycle cost**
  The intensity of lifecycle cost (LCC) criterion refers to the total expenses of ownership throughout the life of a system. This can be related to research and development (R&D), capital expenditures (CAPEX), operational costs (OPEX) and costs of acquiring flexibility. The LCC intensity is divided into "**high**" and "**low**". This is relevant for the analysis method, because for a high intensity LCC project, the investors typically may be interested in a more detailed analysis than for a low intensity LCC project.

- **Nature of uncertainty**
  The nature of uncertainty criterion characterises different types of uncertainties that affect the system and is relevant for choosing which method to use. Two natures of uncertainties are defined as "**progressive**" and "**drastic**". Progressive sources of uncertainty evolve slowly in time, examples are market rates, fuel prices and cargo demand.

Drastic sources of uncertainty are characterized by sudden jumps, such as regulatory changes, political shifts and natural catastrophes. This is of high relevance to what kind of model that is applicable for the flexibility analysis and for the value of flexibility.

- **Stakeholder preference**
  The stakeholder preference criterion characterises different types of design objectives, and for modelling purposes, it can be divided into the two segments "**monetary**" and "**mixed**". Monetary is for stakeholders most interested in profit, and mixed is when the focus is more on aspects such as safety, multi-capability, emissions, reliability and availability. Mixed preferences are often also related to money, but can be related to problems of creating the best design for a given budget.

- **System complexity**
  The system complexity is relevant for what type of modelling framework that is of relevance, and it is divided into "**high**" and "**low**". Systems with lower complexity, often related to "on" options, can typically be modelled with simpler models than that of more complex systems, typically related to "in" options.

The different criteria and two characteristics for each are summed up in Table 6.4.

Table 6.4: Guidance criteria (adapted from Cardin and de Neufville (2008)).

Guidance criteria	Characteristic	Characteristic
Main area of flexibility	Operations	Physical
Frequency of exercise	Frequent	Infrequent
Intended audience	Technical	Non-technical
Intensity of lifecycle cost	High	Low
Nature of uncertainty	Progressive	Drastic
Stakeholder preference	Mixed	Monetary
System complexity	High	Low

Method Selection Matrix

The purpose of the above discussed guidance criteria is to describe a system so that one more easily can decide on which analytical tools to use for identifying and valuing flexibility. In Figure 6.1, each analytical tool is described in terms of these criteria. In reality, different tools may be used in different contexts for various problems. This table only indicate effective and appropriate usages for the identification and valuation methods. The selection framework is built on work by Cardin and de Neufville (2008).

Methods		Guidance criteria						
		Main area of flexibility	Frequency of exercise	Intended audience	Intensity of LCC	Nature of uncertainty	Stakeholder preference	System complexity
Identify	Interview	Physical structure / operations	Infrequent / frequent	Technical / non-technical	High / low	Progressive / drastic	Monetary / mixed	High / low
	Information flow	Physical structure	Infrequent	Technical	High	Progressive / drastic	Monetary / mixed	High
	Screening	Physical structure / operations	Frequent	Technical / non-technical	High / low	Progressive	Monetary / mixed	High / low
	Tradespace	Physical structure	Infrequent	Technical	High	Drastic	Mixed	High
Value	Analytical	Operations	Infrequent	Technical / non-technical	Low	Progressive	Monetary	Low
	Tree method	Physical structure / operations	Infrequent / frequent	Technical / non-technical	High / low	Progressive	Monetary / mixed	Low
	Simulation	Physical structure / operations	Frequent	Technical / non-technical	High / low	Progressive / drastic	Monetary / mixed	Low / high
	VASC	Physical structure	Infrequent	Technical	High	Drastic	Mixed	High

Figure 6.1: Framework for choosing among the discussed methods for flexibility identification and valuation (adapted from Cardin and de Neufville (2008)).

6.3 Flexibility Analysis Framework

The proposed method for analysing design flexibility is based on a procedure presented in Cardin et al. (2013, 2015). They propose a practical and effective approach to implement and communicate possible value improvements for large scale, capital-intensive projects under market uncertainty. Their four-step process include first a deterministic analysis, then introduce uncertainty in the model before assessing flexible design options. In the end they perform a sensitivity analysis. This is illustrated in the attached figure in Appendix C.1.

What is of particular interest with their method lies in that it helps building acceptance among decision-makers by the way it develops an understanding of the drivers of flexibility. Furthermore, also discussed by Cardin et al. (2015), an important problem with the development and usage of flexibility in engineering design is that decision-makers often have not understood the value of flexibility, or accepted the concept, even though system analysts have. This is perhaps even more important in a capital-intensive and conservative marine business. It is therefore of focus to use a framework that propose good solutions that also are credible.

In an attempt to make this framework more as a generic decision support tool for marine system designers, their framework is extended to a six step process as illustrated in Figure 6.2. A starting step is added where the goal of the analysis has to explicitly be defined. Further, the step that incorporates flexibility in the design is more emphasised, where a separation between "in" and "on" options analysis is made.

Six Step Process for Flexibility Analysis

Step 1: Problem Definition

As with any problem solving method, the first step involves clearly defining the goals of the analysis and identifying the stakeholder preferences. This first step makes the rest of the analysis framework less ambiguous.

Step 2: Deterministic Analysis

This step is about creating a basic deterministic valuation model for the fixed design problem as a benchmark. The goal with this is to understand the key system components that influence performance. The model ideally incorporates all the relevant inputs, constraints and outputs in order to obtain the correct discounted net values of the system for any assumed possible scenario. An often-used metric for project evaluation is the net present value (NPV). The benchmark model is of the usual deterministic case of fixed specifications with no uncertainties.

Step 3: Uncertainty Analysis

In this step, the important uncertain parameters affecting the model are identified. This can be done with sensitivity analyses, which typically are illustrated with tornado diagrams. Conducting interviews with relevant experts also serves as a good approach.

Step 4: Stochastic Analysis

In this step the uncertain environment is set up and used to model the base case under uncertainty, to see the effects of uncertainty on the lifetime system performance. This is done by using the distributions of the uncertain input parameters over time to calculate the distribution of the performance metric, typically through simulation. The point in this step is to see how the system performance differs from the deterministic base case model, due to Jensen's inequality, which will be the case for most systems.

Step 5: Flexibility Analysis

The focus in this step is to identify and explore different kinds of flexibilities, and to see how they affect the performance metric. This includes the opportunities to reduce downside and increase upside possibilities. By the recognition of intelligent management, system operators can make decisions such as adapt, reconfigure and postpone, depending on how the future resolves. This step involves a separation of "on" and "in" options analysis.

First the "on" options analysis is performed. This involves implementing traditional operational "on" options such as to temporarily lay-up a ship. After that, the "in" options analysis is performed. This involves classifying the system as described in Chapter 6.2, before identifying and valuing candidate design flexibilities.

The goal of this step is then to demonstrate that flexible strategies can lead to significant added value compared to the base case design. Focus should also be on formulating relevant decision rules, and investigating optimal triggering strategies. Analyses can also include aspects of game theory, the time value of money, economies of scale and learning effects.

Step 6: Sensitivity Analysis and Strategy Recommendations

In the final step, a sensitivity analysis can be performed to characterise the drivers of the value of flexibility and to serve as a test of value robustness. This step helps the decision makers understand how the different system characteristics in various future situations give value to flexibility. Based on synthesized material from the analysis, strategic recommendations can be given.

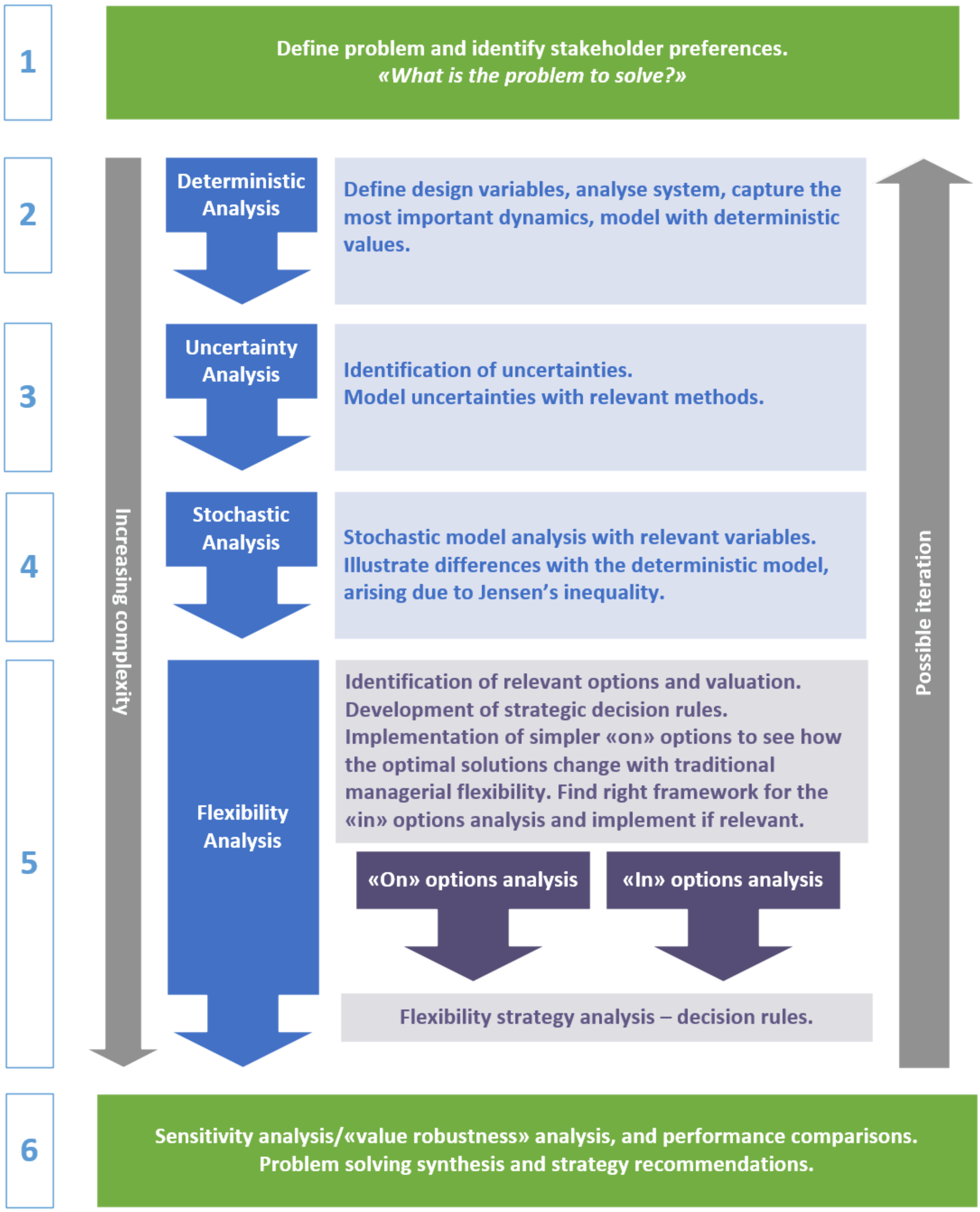


Figure 6.2: Flexibility analysis framework (adapted from Cardin et al. (2013)).

Chapter 7

Illustrative Case Study

The intention of this chapter is to demonstrate the applications of the flexibility analysis framework presented in this thesis on a case from the maritime industry. This is done with an illustrative example of decision support for the design of a large container ship, subject to uncertainties in the future operating context.

First, the case will be introduced, then container ships and the container market will be discussed. Technical aspects of the base case design and the system model is presented before the flexibility analysis is performed, following the procedure from Chapter 6.

7.1 Case Study Description

The management team in a liner company wants to expand their fleet by contracting a new ultra large container vessel (ULCV) for the Asia-Europe trade. They are mainly concerned about the capacity, energy efficiency and fuel consumption of the ship. They are interested in advice to help answer the questions: What is the most economically valuable design choice, and how do we design in the face of uncertainty?

Due to the economies of scale in the container ship segment, the management team is originally interested in building a ultra large ship with a capacity of 20 000 TEU, which would be larger than the largest container ship in the market as of 2015.

The task for the analysts is to provide help for the decision-making in the design process. The analysts use the proposed framework on the task, and plan to investigate flexible design opportunities.

7.2 Container ships and the container market

Container ships are cargo ships that carry their cargo in containers. Their capacity is usually measured in how many twenty-foot equivalent units (TEU) they can carry. The trend in the intercontinental container ship industry has been that bigger is better. As illustrated in Figure 7.1, where costs per unit transported drastically are reduced when the size increases, economies of scale play a major role in the industry.

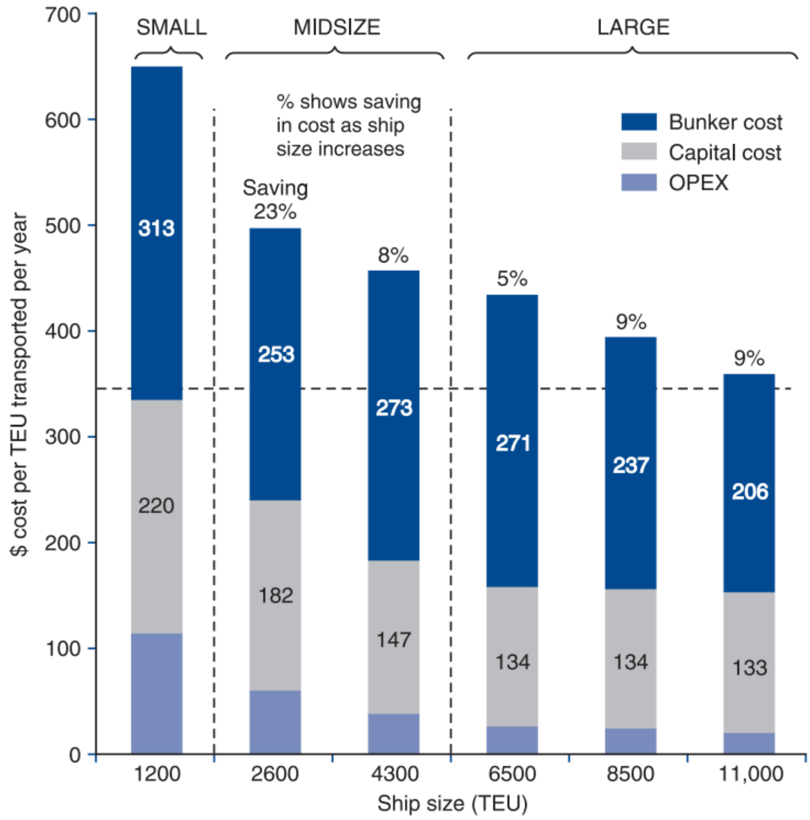


Figure 7.1: Economies of scale for container ships illustrated by cost per TEU transported (Stopford, 2009).

> *Container ship technology is in a process of rapid change. Over the past five years (2009-2014), vessels sizes and cargo capacity have increased dramatically while service speeds have dropped. At the same time, regulatory pressure to improve environmental performance has had a significant impact on the design, construction and operation of container ships.*
>
> DNV GL Brochure (2014)

As illustrated in Figure 7.2, the development of the largest container ships have increased heavily over the past decades, and is still increasing. This is in contrast with for example oil tankers, which also increased in size until the largest reached the ultra large crude carrier (ULCC) size of approximately 500 000 deadweight tonnes (dwt) built in the 1970s-1980s, and then decreased again to the largest ships stabilizing at the very large crude carrier (VLCC) size of approximately 300 000 dwt. The size of these ships are for example limited by sailing area, available ports and transportation demands.

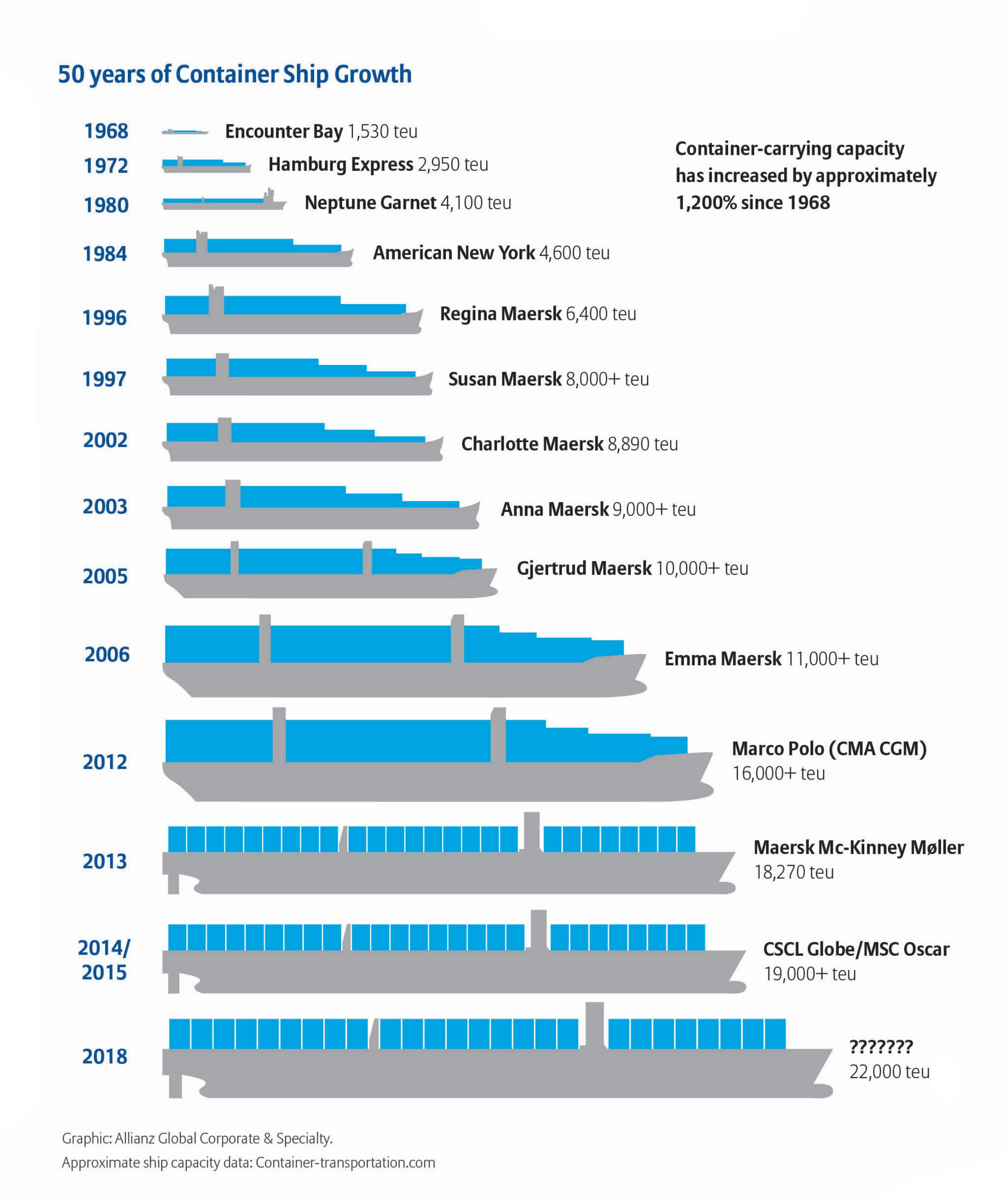


Figure 7.2: 50 years of container ship size growth. [1]

The container transportation demands have seen a steady increase the past decades, as illustrated in Figure 7.3. Container transport demands are typically related to the world economy,

[1] http://www.worldshipping.org/about-the-industry/liner-ships/container-ship-design, accessed August 11, 2015.

and one can see the consequences of the financial crisis of 2008 as a significant bump in the trend in the figure.

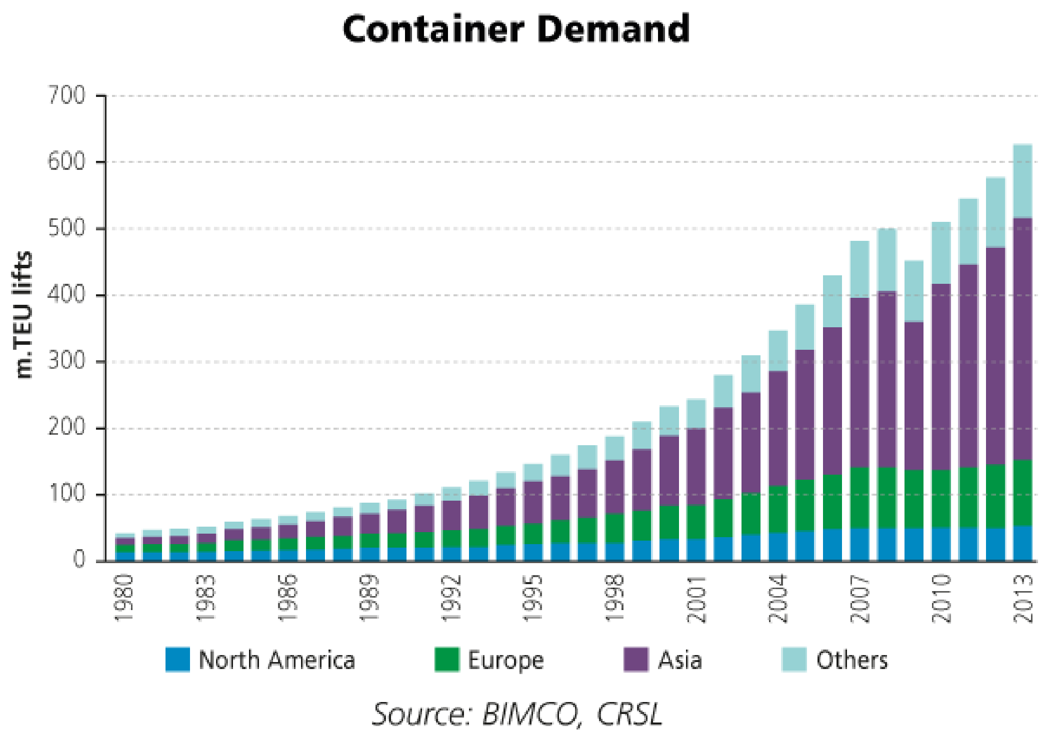


Figure 7.3: Container transportation demand since 1980s, measured in the number of global TEU lifts in ports. [2]

7.3 Technical Descriptions of the Base Case Design

In order to make this case study realistic in a simple way, we use the same case as Khor et al. (2013), who studied speed optimization for very large container ships. The ship is planned to have a capacity of 20 000 TEU and is intended for the Asia - Europe trade, with the following route pattern: Shanghai - Hong Kong - Singapore - Valencia - Rotterdam.

Figure 7.4 illustrates the layout of the proposed container ship design. The ship has a "twin island" design concept, separating the engine room from the accommodation area. This design solution provides a higher stacking of containers, without violating bridge vision requirements.

[2] `https://www.bimco.org/en/Reports/Market_Analysis/2012/1017_ContainerSMO02012-5.aspx`, accessed August 11, 2015.

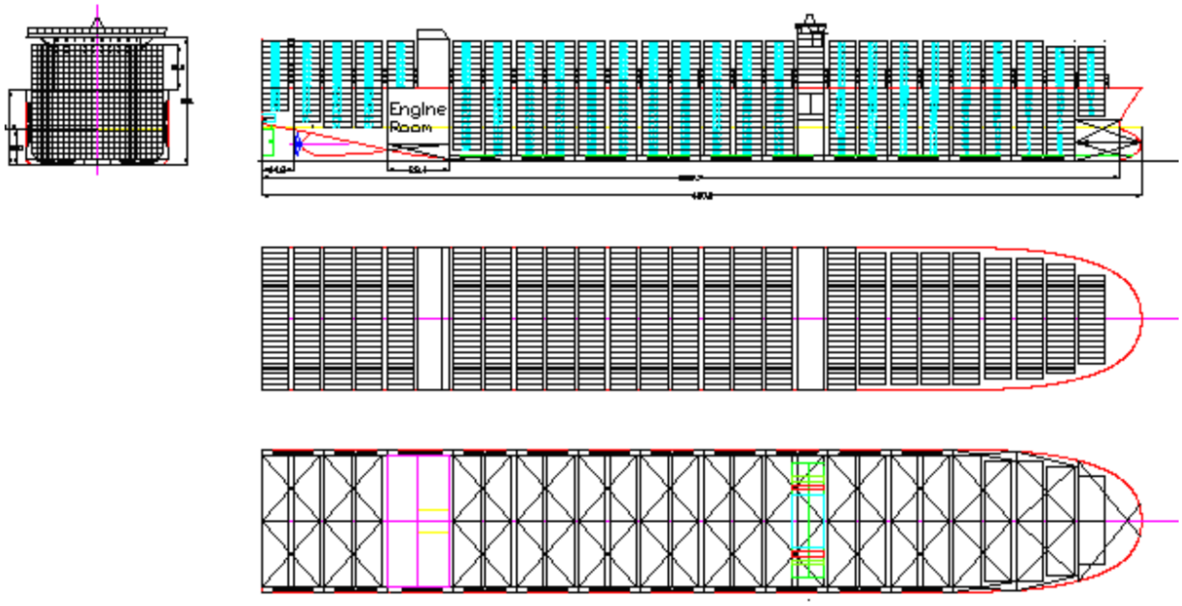


Figure 7.4: Base case container ship drawings (Khor et al., 2013).

The base case design parameters are given in Table 7.1. In the dynamic model introduced later, the capacity and speed variables are not fixed, and hence the break horsepower is a function of these parameters based on simple resistance models.

Table 7.1: Base case design parameters (adapted from Khor et al. (2013)).

Design parameter	Value
Capacity	20 028 TEU
LOA, LWL	400 m, 390 m
Beam	65 m
Draft, Depth	16 m, 34 m
Speed	20 knots
BHP	60 MW

Container Ship System Model

The container ship system model is a simplified version of the "propulsion and cash flow" model used by Khor et al. (2013) to assess optimal speed for large container ships.

The container ship system model consists of two main parts: a propulsion analysis and a cash flow analysis. The propulsion analysis involves hydrodynamics and machinery, and is a low-fidelity model describing the relationship between ship size, speed, resistance and engine power. The revenue and cost analysis involves calculating the yearly revenue based on the freight rate per TEU and the number of trips per year. The number of trips per year depends on the transit time and port time, and the transit time again depends on the speed of the ship. This short description illustrates the complexity of even such a simple model of a ship as a system. The details of the model is presented in Appendix B.1.

This model is a technical and financial model of the system. It does not include system environmental dynamics, describing how the ship interacts with external factors such as ports, canals, fuel rates, market rates. For example, it is reasonable to believe that ultra large ships cannot be accepted at all ports. Not to mention their effect on the port time, as it probably will take longer time to load and unload. In this simple study, we assume that there are no port or canal issues, and the market rates and fuel prices are later modelled as exogenous stochastic processes. We further assume that 100% of the newbuilding price of the ship is financed with a loan, and that there are no taxes to be paid.

Table 7.2: Container ship analysis parameters.

Analysis parameter	**Value**
Construction time	2 years.
Discount rate	10 %
Loan interest rate	8.5 %
Lifetime	25 years
Newbuilding cost	$200 million
OPEX (excl. fuel)	$10 000 /day
Fuel price (IFO380)	$500 /MT
Freight rate	$800 /TEU
Specific fuel consumption (SFC)	200 g/kWh

7.4 Flexibility Analysis of Container Ship

The case is analysed with the generic framework proposed in Chapter 6. The Matlab code for the case study is attached in Appendix D.

Step 1: Determine the goal of the analysis

The objective of the study is to provide design decision support in favour of maximizing the Net Present Value (NPV) of the project. Furthermore, given the first objective, it is of interest to have a low initial investment.

Step 2: Deterministic Analysis

A discounted cash flow analysis (DCF) is implemented in Matlab under the assumptions presented above, and the project net present's value (NPV) for the deterministic base case scenario is calculated. The NPV is found to be $85 million.

Step 3: Uncertainty Analysis

There are several uncertainties that may affect the future performance of the ship. A general assessment of relevant uncertainties for the case study is presented in Table 7.3.

Table 7.3: Uncertain parameters from discussion with field experts.

Area	Comment
Market rates	Market rates heavily affect the revenue generated by the ship, can be considered exogenous to the model and are highly volatile.
Fuel prices	Fuel prices affect the voyage costs, can be considered as exogenous to the model and are highly volatile.
Interest rates	Affect the regular capital expenditures.
Ports	The ability of the ports to expand and handle ultra large ships affect the lifecycle performance of ships, hence imposing restrictions for the ship.
Canals	Ship canals, such as the Panama canal, impose restrictions on the size of ships, and their future ability to handle large ships can be considered as an uncertain factor. Furthermore, canals may close due to political conflicts and wars.
ECAs	New emission control areas (ECAs) may restrict the allowed emissions of a ships.
Design speed	As a measure to adapt to changing market conditions, ships can regulate their speed. However, this often affects the efficiency, as a ship typically is optimized for a particular speed. Then as a consequence of changing market conditions, the future optimal design speed is subject to uncertainties.
Second hand market prices	As with other assets, supply and demand control values and due to relatively long time it takes to build a ship, second-hand markets typically experience large volatilities.
Scrap prices	The value of scrapping the ship is dependent on the scrapping prices, which again are dependent on supply and demand, and the steel price.

With respect to the particular system model that is developed in this case study to describe the performance of the ship, a sensitivity analysis can be used to see how sensitive the deterministic design is to variations in its input parameters. This is illustrated in Figure 7.5. Design capacity and design speed are design variables, and the other tested sensitivities are model parameters - exogenous to the model itself.

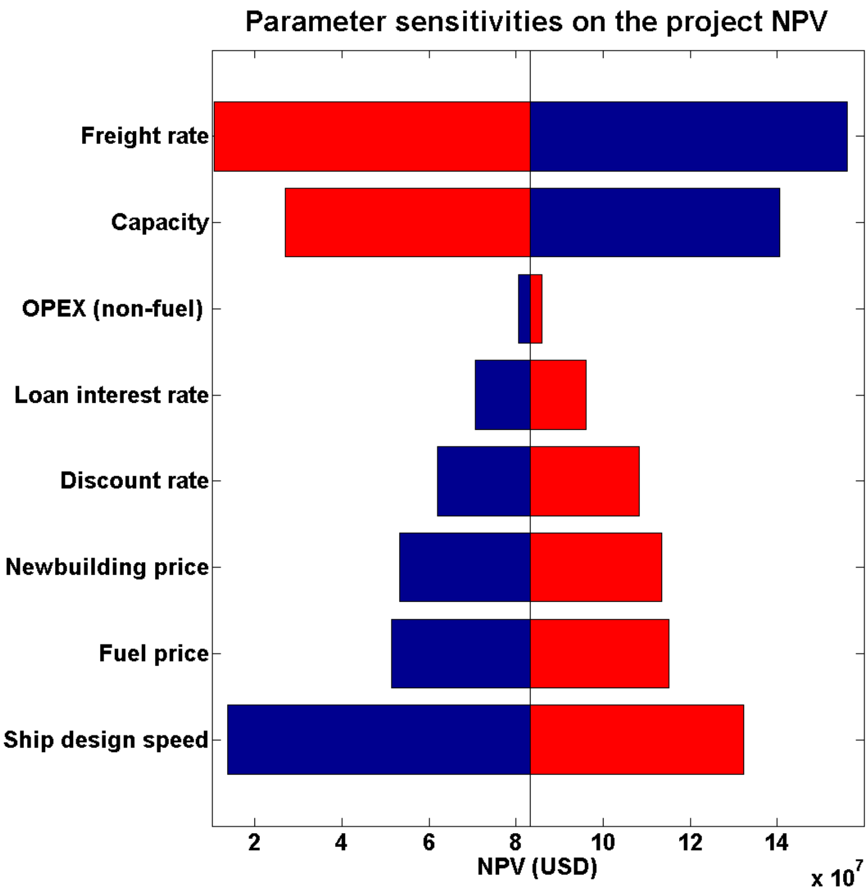


Figure 7.5: Tornado diagram for container ship model parameter sensitivity analysis. Blue colour for 10% increase and red for 10% decrease of parameter value. [3]

At the top of the tornado diagram, one can see that the freight rate and the design capacity have high impact on the deterministic system performance measured in NPV. Furthermore, these are the only tested sensitivities that have a positive derivative, that is by increasing their value the NPV increases.

The other model variables and parameters tested have a negative derivative value, which means that increasing their value decreases the NPV. In the bottom end of the tornado diagram, the fuel price and the ship design speed also have a relatively high impact the model. We also see that the newbuilding price of the ship, the interest on the loan and the discount rate have significant relevance for the model.

[3]The plot was generated in Matlab by a generic tornado plot code made by Richard McCulloch in 2013.

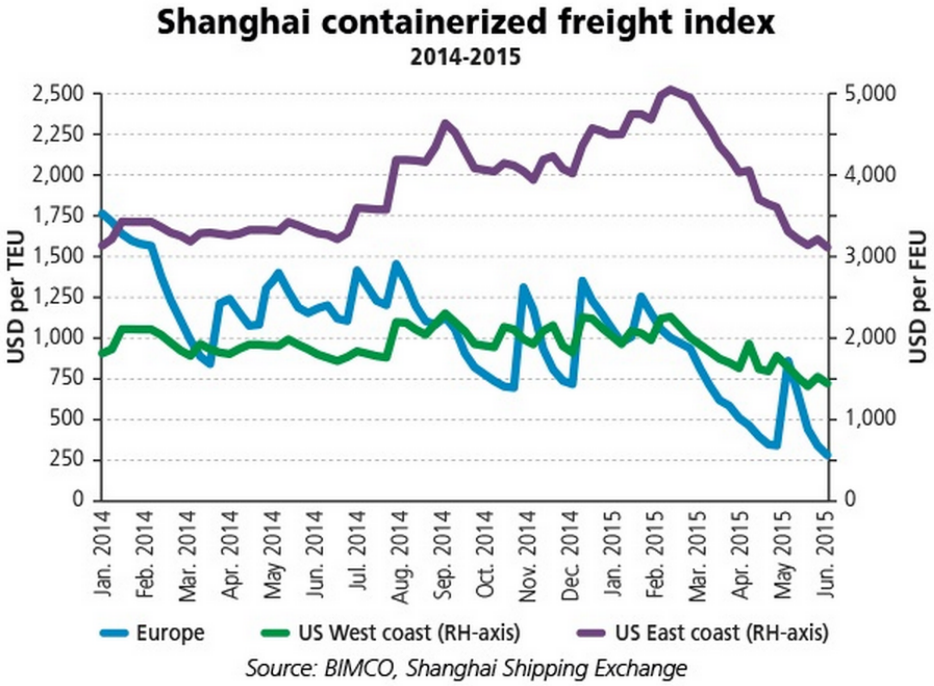


Figure 7.6: Container freight rates 2014-2015 [4].

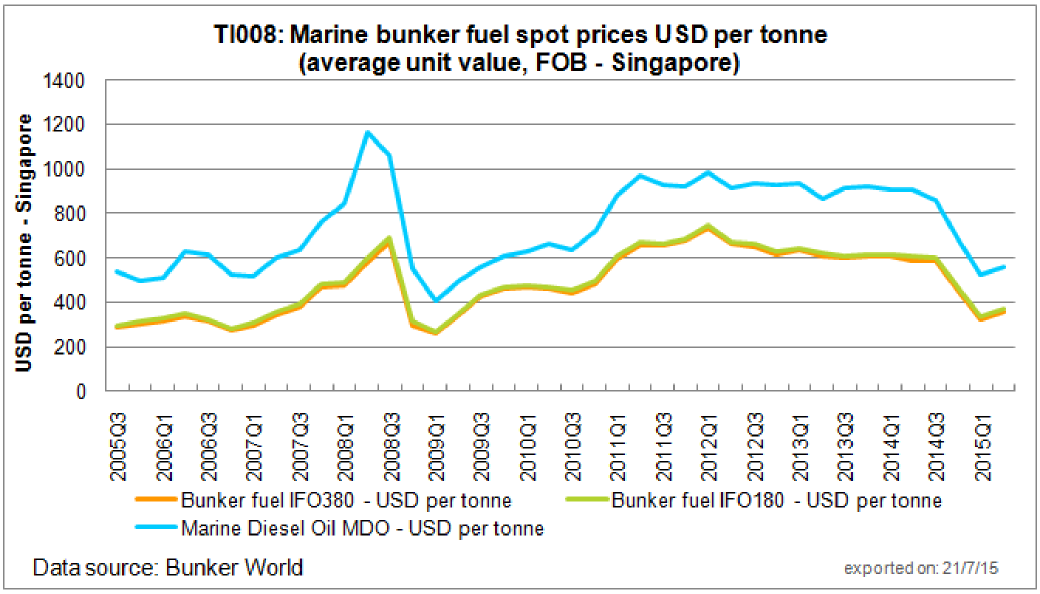


Figure 7.7: Historical bunker fuel data [5].

The freight rate and the fuel price are the most important exogenous parameters affecting the deterministic NPV model. As seen in Figure 7.6, the Shanghai-Europe freight rates are highly volatile. In fact, this rate has dropped from \$1750/TEU to \$250/TEU in the short period from June 2014 - June 2015. The fuel prices also show signs of high volatility. In Figure

[4] `http://maritime-connector.com/maritime-economy/container-shipping-spot-rates-in-a-sink-hole-while-charter-rates-for-smaller-containerships-soar/`, accessed August 21, 2015.

[5] `http://www.transport.govt.nz/ourwork/tmif/transportpriceindices/ti008/`, accessed August 19, 2015.

7.7, one can see that the IFO380 fuel price vary between $250 to $700 per metric tonne (MT) in the period between 2005 and 2015.

Step 4: Stochastic Analysis

Due to the high volatility of the two important exogenous factors, the market rate and fuel price, we model them as stochastic processes to demonstrate the different net present value results obtained. For simplicity, both values have been assumed to follow a geometrical Brownian motion. In this simple analysis, we assume that they are not correlated.

Table 7.4: Stochastic parameters for the fuel price and the market rate (MT = metric tonne).

GBM parameter	Fuel price	Market Rate
Start point (base case)	500 [$/MT]	800 [$/TEU]
Drift	0.01	- 0.01
Volatility (σ)	0.2	0.3

The assumed parameters for the stochastic models are presented in Table 7.4. A weak negative trend is given for the freight rate, due to the decreasing costs per unit transportation with more, larger ships in the market. A weak positive trend is given to the fuel price. These assumptions have great impact on the model results, and for a study that is not only for illustrative purposes, investigating these parameters properly is of great importance.

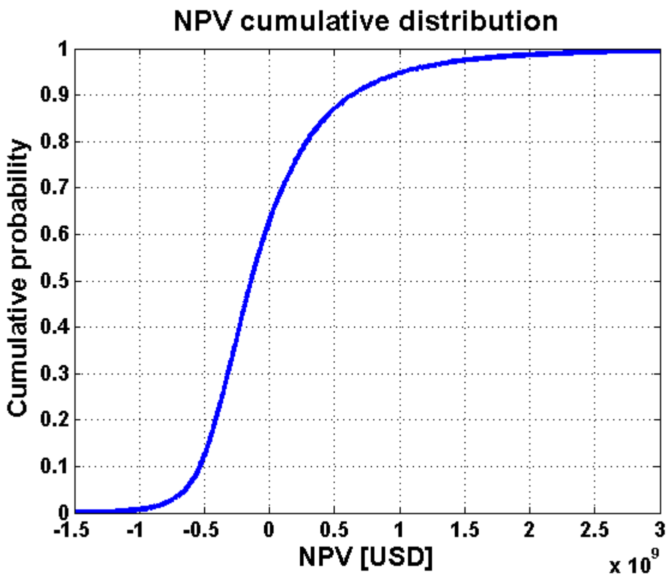


Figure 7.8: Cumulative distribution function from 2000 stochastic simulations.

This yields an expected net present value (ENPV) of - $ 11 million. A significant change from the deterministic analysis. The cumulative NPV distribution from 2000 simulations is illustrated in Figure 7.8, where one can see that in fact there is a 60% chance of a negative NPV.

Step 5: Flexibility Analysis

A) "On" options analysis

Standard "on" options as presented in Table 2.6 are considered. The most essential "on" option found is the option to temporarily lay up the ship, if it has unacceptable performance.

This "on" option is implemented in the cash flow analysis with the following decision rule: if the cash flows in a year falls below the yearly non-VOYEX related costs, that is the non-fuel OPEX and the interests on the loan, then the ship will be temporarily taken out of service the next year. This can for example be by anchoring up somewhere, waiting for better times. The yearly costs in this state is assumed as the non-fuel related OPEX of $3.7 million and the interests on the ship investment, at 8.5% interest rate. This threshold value for the 20 000 TEU ship is approximately $20 million. If the potential cash flow goes back up, the ship will be taken back in service.

With this strategy implemented in the analysis, the expected net present value (ENPV) is $37 million. That is, including this management flexibility in the analysis increases the ENPV by $48 million. As illustrated in Figure 7.9, this "on" option drastically reduces the potential downside of the NPV.

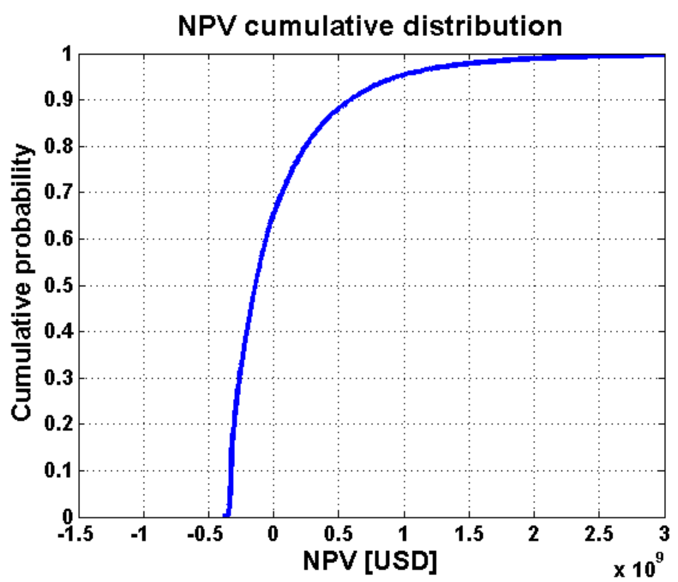


Figure 7.9: Cumulative distribution function from 2000 stochastic simulations with the lay-up "on" option included.

B) "In" options analysis

System characterization and method selection
Using the procedure for choosing which method to use for the identification and valuation of design flexibility in Chapter 6.1, we characterise the system as following:

Table 7.5: Characteristics of the container ship system.

Guidance criteria	Characteristic
Main area of flexibility	Physical
Frequency of exercise	Infrequent
Intended audience	Non-technical
Intensity of LCC	High
Nature of uncertainty	Progressive / drastic
Stakeholder preference	Monetary
System complexity	High

The idea is to match system characteristics in Table 7.5 with characteristics in Figure 6.1 to find the appropriate method(s) for identification and valuation of flexibility. However, as this is not a comprehensive framework, it serves only as a guidance tool.

For flexibility identification, it seems that the interview methods or screening methods are most appropriate. Because the intended audience mainly is of non-technical character, the MATE/EEA and information flow methods becomes less relevant. Since this is an illustrative study, we will not conduct interviews, but rather focus on the screening method.

For the valuation procedure, it seems that simulation is an appropriate method. Since the stakeholder preference mainly is monetary and the fact that the intended audience is non-technical, the VASC method is less appropriate. Additionally, the main sources of uncertainty are progressive (market rates and fuel prices) and we have an infrequent exercise pattern and a system of high complexity. Simulations therefore seems like a appropriate flexibility valuation method.

Identification of flexible design opportunities
An approach using screening methods to identify candidate flexibilities is performed in the following section. As presented in Chapter 4.3, there are several types of screening methods, both for developing screening models (bottom-up, simulator and top down) and for using them for flexibility identification (conceptual, optimization and patterned search).

For the container ship system, a simple bottom-up model is been developed. It works as a generalised model of the deterministic cash flow model for the case, mainly by also making the model dependent on the ship capacity. The length of the time step in the model is one year, which makes it relatively quick to run. Furthermore, due to the nature of the problem, conceptual approach and patterned search are probably suited methods for identifying flexible design options.

I argue that for the maritime industry, where players always have the lay-up option available, it is necessary to include this "on" option in the search for "in" options. Hence, this option is implemented in the stochastic screening model for effectively searching the design space for attractive designs and candidate design flexibilities.

By using a simplified system model, we are able relatively quickly to get a rough search of the design space. This way, we can screen for interesting design opportunities. Figure 7.10 illustrates this. Even though it may look like it has a high "resolution", the design space have a grid resolution of length of 1 knots and 1000 TEUs. By then only considering 20*10=200 designs on the illustrated intervals, the screening model can relatively fast check how the system performs under varying contextual realizations.

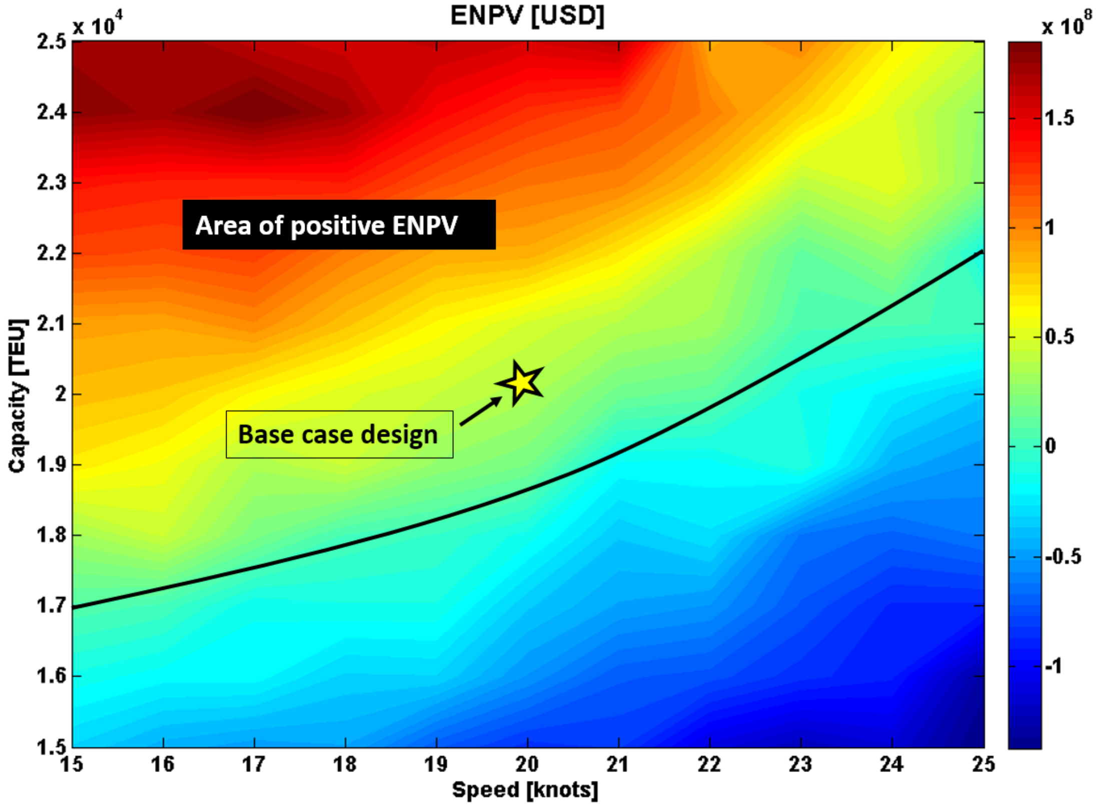
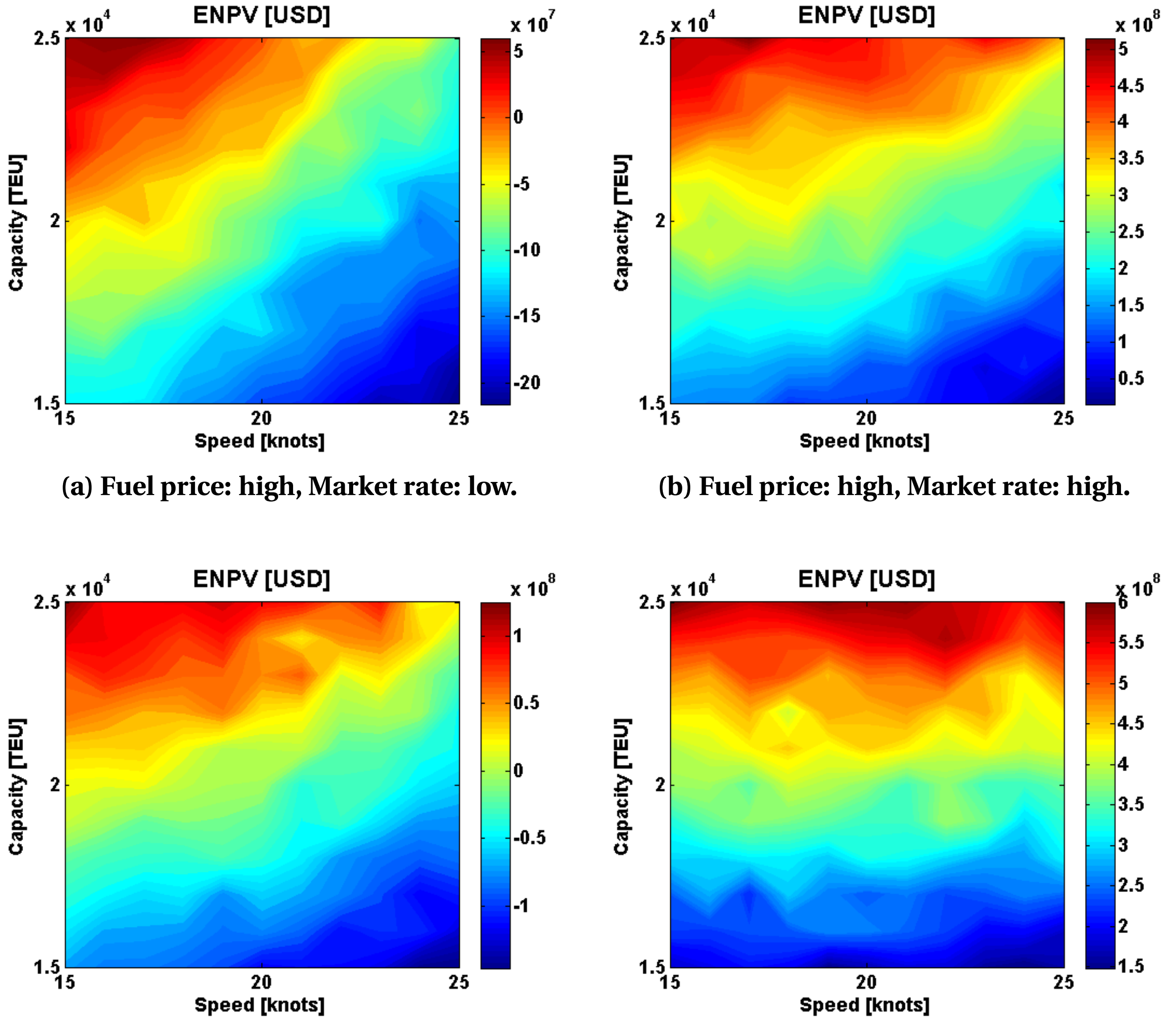


Figure 7.10: Screening of the design space, illustrating the expected net present value (ENPV) for different combinations of capacity and speed. Black line for ENPV=0.

More specifically, Figure 7.10 illustrates the stochastic ENPV of the project as a function of the capacity and design speed. As seen in the figure, for the parameters in the base case scenario, lower speeds and higher capacity is economically feasible. However, it is reasonable to believe that the performance of the ship for very low speeds is wrong due to aspects of market competition. That is, if the ship is too slow, it will lose container transport demand to competitors, unless taking a lower price. Both of these aspects will reduce the profit. If one assumes that the liner industry operates with low margins and competition, one can argue that over time ships will tend to be slightly to the left of the black line in the Figure 7.10, where ENPV=0. In this case example though, we do not explicitly consider aspects of market competition.

The point of the screening model is to provide a short list of candidate designs by rapidly analysing the performance of possible designs in varying contextual conditions. Therefore, the system ENPV is tested for combinations of capacity and speed are under varying fuel price and market rate developments.



(a) Fuel price: high, Market rate: low. (b) Fuel price: high, Market rate: high.

(c) Fuel price: low, Market rate: low. (d) Fuel price: low, Market rate: high.

Figure 7.11: ENPV for different combinations of design capacity and speed, under four cases for the development of the fuel price and the market rates. Note the different colour scales.

Figure 7.11 illustrates four screening cases for the development of the stochastic fuel price and the market rates, and the colour codes represent the expected performance for different combinations of design capacity and speed. The four cases are generated by changing the drift rate for the GBM characteristics. High drift rates are 0.03 and low drift rates are -0.03.

In Figure 7.11, one can see that the performance of the different designs is highly dependent on the contextual parameters. What that can be inferred is that both being able to change the design speed and the capacity are highly relevant areas of design flexibility. An interesting finding form this analysis is that in the case of low fuel prices and market rates (Figure 7.11d), only the capacity influencing the ENPV of the design, not the design speed. The main conclusion from this screening is that the capacity seems to be the most relevant factor to be able to increase. Being able to change the speed is also relevant.

For the base case ship design, with a capacity of 20 000 TEU and a speed of 20 knots, Figure 7.12 shows the impact of different initial values of the fuel price and the market rate for their stochastic processes. As one can see, the derivative of the lines with constant NPV is less than one, which means that the market rate has a higher impact on the NPV than the fuel prices. This is an indication of that designing flexible capacity may be more valuable than designing flexible fuel systems.

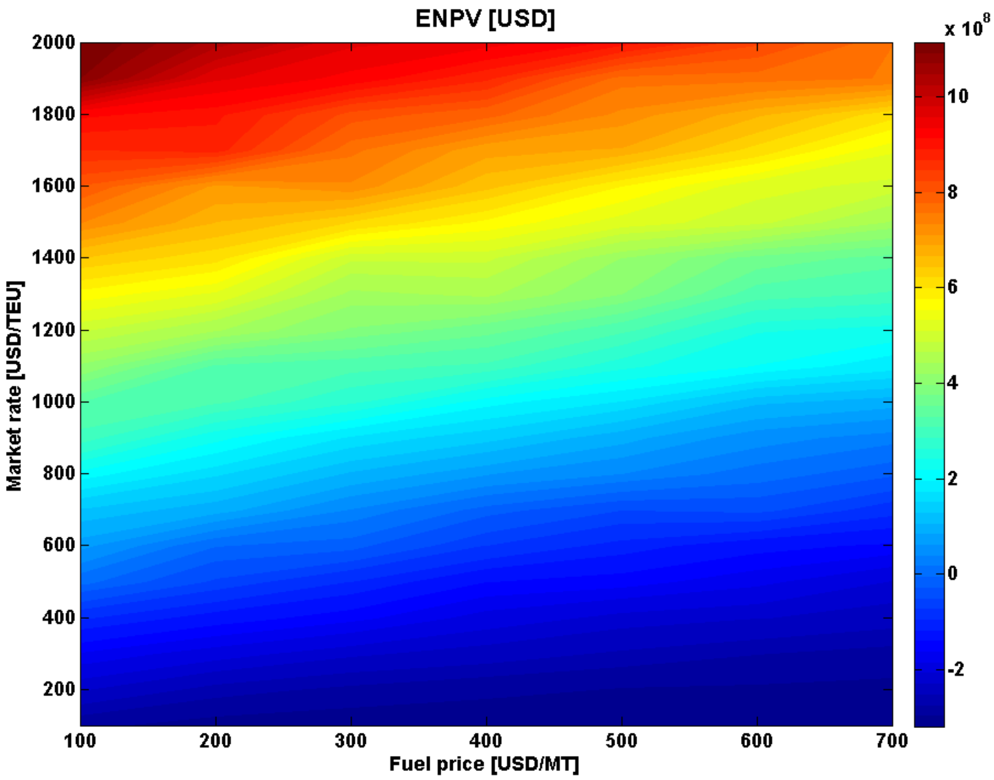


Figure 7.12: ENPV for different combinations of market rates and fuel prices.

The conceptual approach to identify candidate flexibilities with screening methods involves using the simple model to better understand how the complex system works. The method helps the designers see how one part of the design affects other parts and the overall performance of the system, hence helping them to think out of the box for flexible design solutions.

For the container ship model, important dynamics occur between the speed and the capacity. Higher speeds increase the number of trips per year, and therefore increase the revenue. Increased speed increases the resistance, and therefore the fuel costs rise. This function is highly nonlinear. Increased capacity of the ship, for a given speed, increases the fuel costs and the capital expenses, but also increases the revenue since it can transport more containers.

The option to be able to change the capacity of the initial design may be of high value. With regard to building very large ships, the number of ports and canals able to handle the ship quickly falls in number. For the container ship, one can increase capacity by for example increasing the length by one or two modules in the middle of the ship. This requires a reinforced ship hull, and that the hull is designed such that the increased length will not reduce the efficiency too much. Another way is by increasing the number of containers in the height. Numerous issues arise with this option. The bridge needs to be elevated to still to have enough vision, and problems may arise due to stability. Furthermore, increased height restricts the ship to enter several ports and canals.

To hedge against the fuel price, the container ship can possibly switch to other types of fuels. Switching between fuels are also relevant in terms of complying with emission control areas (ECAs), typically regulating the SOx emissions from ships (7.13). Standard heavy fuel oil (HFO) typically has a high sulphur content, which translates to high SOx emissions. This issue can be solved by switching to low sulphur fuels or cleaning the exhaust gas. In this case study, we investigate the option to switch from the HFO to LNG.

At this point, LNG is often seen to be significantly cheaper than HFO, but the price varies depending on bunkering location. Furthermore, the international availability of LNG is not very good, and the maximum quantities available at a bunkering station may not large enough certain ships. Additionally, the development of these factors is highly uncertain. In this case study, we assume no issues with LNG for use as fuel for the intended Asia-Europe trade.

Designing a ship that can change fuels involves using an engine that easily can be converted, or that can use both fuels, and a storage tank for the LNG. LNG is very cold and needs expensive cryogenic equipment, and it has a low density so it takes up more space than HFO. Therefore, for a volume restricted ship such as a container ship, volume that could have been used for containers will probably have to be replaced by LNG tanks.

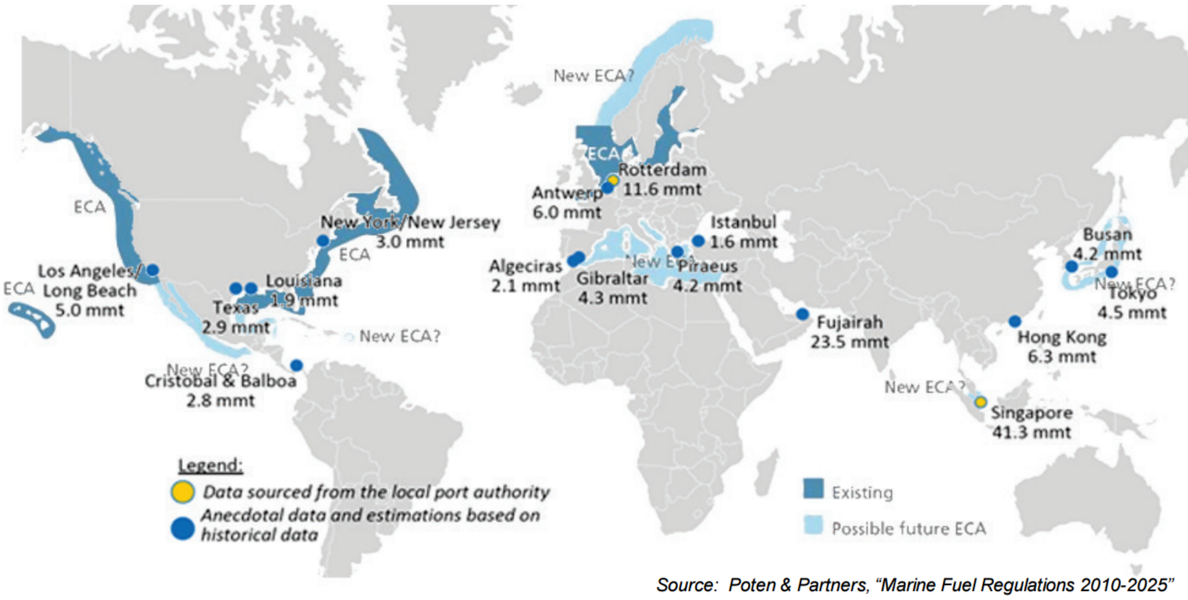


Figure 7.13: Existing and possible ECAs and LNG bunkering stations (Adamchak and Adede, 2013).

To make the ship more flexible, the option to change speed is of interest. As discussed with regard to the plots above (Figure 7.10 and 7.11), the speed of the container ship is highly relevant for the performance of the ship at a given capacity. Additionally, adjusting the speed may increase the competitiveness of the ship in dynamic open markets. Changing the speed of a ship is done by changing the engine power. However, a vessel's engine and propeller are typically optimized for a particular speed, and changing this will lead to decreased efficiency and increased fuel costs. One method to handle this is by derating. Derating of an engine is the concept of enabling an engine to run relatively efficiently on a lower output than what it is originally designed for. Derating an engine also involves doing measures to the propeller, which is of high importance to the efficiency of the propulsion system. Either, a more robust propeller design can be chosen to better deal with changing speeds, or one can change the propeller in the event of a change of engine power. Specific fuel oil consumption savings can be significant after a derating (Woodyard, 2009), and post design derating of propulsion systems can cost millions of dollars for large ships[6].

Table 7.6 sums up the relevant identified design flexibilities. In this illustrative case study, we will further analyse the capacity expansion option and the fuel-switching option. In the case of the capacity expansion option, the engine is assumed to be derated and able to maintain relevant speeds in the case of a capacity expansion.

[6] `http://primeserv.man.eu/docs/librariesprovider5/primeserv-documents/de-rating.pdf?sfvrsn=2`, accessed August 23, 2015.

Table 7.6: Relevant "in" options for the container ship for further valuation.

Relevant "in" option	Description
Expand capacity	To meet possible increasing demand and market rates in the future by in building in a length expansion option.
Switch fuel	To hedge against fuel prices one can switch between from the design fuel (HFO) to liquefied natural gas (LNG), and possibly back if profitable.
Change service speed	To meet customer demands, one can have an engine that is de-rated, introducing the possibility to increase or decrease engine power to ship at optimal speeds.

Valuation of flexible design opportunities

An appropriate methodology for valuing candidate design flexibilities is Monte Carlo simulation, with appropriate decision rules. Since the lay-up "on" option also can be exercised for the presented "in" option alternatives, this is included in the "in" option valuations. The valuation is done at the design speed of 20 knots. For simplicity, it is assumed that the expansion option and the fuel-switch option do not affect each other, so they can be priced individually. However, for a proper quantitative analysis, it is reasonable to assume that the fuel-switch option may become more valuable in the event of an expansion. This is because the ship will consume more energy, and have a higher fuel cost risk profile.

Expand capacity

There are several approaches one can take to find the optimal design expansion strategy and the appropriate decision rules for triggering the exercise of the real option. For simplicity, we will consider two cases: build 18 000 TEU with an expansion option to 20 000 TEU, or build 20 000 TEU with an expansion option to 22 000 TEU. When looking at Figure 7.11, the expansion option seems to be of interest in every contextual case, perhaps only less in the case with high fuel prices and the low market rates. The expansion option is assumed to be exercised if there is a three-year period with average net profit margins of above 30%. The profit margin is the net profit divided by the revenue. This measure can therefore both take in consideration aspects of the market rate and fuel prices. Multiple decision rules are not tested in this simple study.

Estimating the cost of this real option is not straightforward. A longer ship will have more resistance, and the engine must be able to increase the power output in order to make the ship maintain design speed. We assume that the engine initially is derated. The initial structural hull reinforcement is assumed to cost $1 million. The propeller may have to be replaced upon expansion and the physical expansion of the ship is assumed to cost 5% of the initial newbuilding price. We further assume that the efficiency of the propulsion system drops by 5% in the event of a length expansion from the date of expansion. The non-linear effects on the ENPV will be calculated in the model.

Table 7.7: Performance with the expansion option (numbers in millions).

Design Alternative	ENPV	10%-ile	90%-ile	Initial investment
18 kTEU no flex	$ 25	-$ 292	$ 516	$ 175
20 kTEU no flex	$ 37	-$ 324	$ 574	$ 200
Flex: 18 to 20 kTEU	$ 39	-$ 292	$ 581	$ 176
Flex: 20 to 22 kTEU	$ 70	-$ 325	$ 757	$ 201

As seen in Table 7.7, the ENPVs for the two flexible design options are higher than the inflexible. The value of the expansion flexibility is $14 million for the 18 kTEU design, and $33 million for the 20 kTEU design. From the simulation it was found that in approximately 40% of the cases the expand option was exercised. These calculations do not consider any external restrictions on the size of the ship. In reality, there are several restrictions to the size of the ships that will affect its revenue-generating factors, particularly form ports.

Switch fuel type

The real option to switch between different types of fuel will in this case be between HFO and LNG. This is a bit different from the more normal approach to fuel-switching, which is between HFO and MGO. In addition to directly being a measure to increase profits, the option is also relevant for sulphur reduction and ECA compliance. There are however several options for reducing sulphur emissions, such as installing scrubbers to clean the exhaust or switching to fuels that do not contain sulphur, which includes MGO or LNG.

When it comes to the LNG contracts for shipping fuel, in the maritime industry the LNG price is often seen to be linked to the HFO price somehow. In this analysis, the price that is paid is the free market price for LNG and not a linked price. However, the Mean Reverting Ornstein-Uhlenbeck stochastic process used to model the two prices has a mean reversion factor of 0.5 and the prices therefore tend to correlate.

As with the capacity expansion option, there are several approaches to finding the optimal fuel-switch strategy. In this illustrative example, it is assumed that a standard HFO ship is to be built initially. Two cases are examined, one with flexibility from the first year and one with an option to retrofit later. For the case with flexibility from year 1, the ship is built with an engine that can take both types of fuel, and with storage for both types, and the ship will then choose the cheapest fuel every year. This is however for a flexibility cost of $10 million upfront. For simplicity, the assumed price for installing or retrofitting the system propulsion system is $10 million. When the ship flexibility is installed, the LNG tanks are assumed to take up 5% of the capacity of the ship, and the total fuel efficiency is assumed to drop 2%.

For the case with an option to retrofit the ship at a later stage to be able to choose between the fuels, the decision rule implemented is such that if the relative difference between prices of fuels become more than 20% for a two-year consecutive period, the fuel-switch flexibility is installed and ready for the period after. This approach postpones the investment cost of the expensive equipment required for the flexibility to the year of installation. For simplicity, multiple decision rules are not tested in this case study.

Table 7.8: Performance with the fuel-switch option (numbers in millions).

Design Alternative	ENPV	10%-ile	90%-ile	Initial investment
No flex (base case)	$ 37	-$ 324	$ 574	$ 200
Flex from year 1	$ 56	-$ 340	$ 639	$ 210
Option to retrofit later	$ 69	-$ 359	$ 681	$ 201

As one can see from the Table 7.8, significant value is added to the design by the fuel-switching flexibility as the ENPVs for both of the examined cases are higher than for the initial design. What is found in the simplified analysis is that the most valuable option is to prepare the ship for a later retrofit. Additionally, this is an option with little initial costs. The value of the flexibility is $19 million for the flexible from year 1 design and $32 million for the design with the option to retrofit later. In the simulation, it was found that the fuel-switch option was exercised in 80% of the scenarios.

In general, this flexibility is essentially a bet on the availability and volatility of the relevant fuels. LNG is an emerging market and substantial uncertainties are connected to the availability and the price of the fuel. In this case study, it is assumed that sufficient LNG is available when needed.

Total value of "in" option flexibility

We assume that the two "in" options can be individually priced and added to obtain the total value of the "in" option flexibility. The expansion option flexibility is worth $33 million for the 20 kTEU design, and the flexibility for the option to retrofit later for fuel-switch is worth $32 million. Hence, the total added value of the "in" option related flexibility is estimated at $65 million. The base case design with the lay-up option included has an expected net present value (ENPV) of $37 million. Therefore, the combined "in" option flexibility represents an increase in the ENPV of 176%. The numbers may seem high. To get a better understanding of the value of flexibility, one should also compare it with the initial investment, which for the container ship is $200 million. The profitability index (PI), or the profit investment ratio (PIR), is the ratio of payoff to investment for a project, and for the container ship case this increases by 27%, from 1.19 for the base case design to 1.51 for the flexible case.

Step 6: Sensitivity Analysis and Strategy Recommendation

The analyses performed in the earlier steps already indicate how the different system alternatives will perform in light of uncertain parameters. However, the point of this last step is to further illustrate the increased value robustness of the flexible systems with a sensitivity analysis, which probably is a more recognized method to show robustness.

In Table 7.9 the "Base case" represents the stochastic analysis from step 4 without any implemented options. The "Lay-up" design introduces "on" option flexibility to lay up the ship if it performs unsatisfactory. The "Expansion" design represents the 20 to 22 kTEU expansion case, since this had the highest expected net present value identified in step 5. The "Fuel switch" design case represents the option to retrofit later, since this had the highest expected value, also identified in step 5. As mentioned earlier, even though it is obvious that the two "in" options affect each other, since for example the LNG tanks displace 5% of the capacity, their value in this case is assumed independent.

Table 7.9: Sensitivity analysis: ENPV for different designs under varying contextual parameters (numbers in millions) of fuel [$/MT] and market rates [$/TEU]), base case context parameters in bold.

(Fuel, Market)	Base case	Lay-up	Expansion	Fuel-switch
(400,700)	- $ 22	$ 22	$ 52	$ 28
(400,800)	$ 55	$ 67	$ 111	$ 103
(400,900)	$ 142	$ 141	$ 188	$ 184
(500,700)	- $ 93	- $ 34	$ 12	- $ 10
(500,800)	**- $ 11**	**$ 37**	**$ 70**	**$ 69**
(500,900)	$ 70	$ 104	$ 143	$ 139
(600,700)	- $ 166	- $ 68	- $ 28	- $ 63
(600,800)	- $ 78	$ 0	$ 29	$ 11
(600,900)	- $ 1	$ 70	$ 103	$ 63

The sensitivity analysis is in this illustrative case conducted by changing the initial values for the stochastic processes generating scenarios for the fuel prices and the market rates. It is obvious that other types of sensitivity analyses could have been done, such as also looking at price volatilities, but for this illustrative case study we keep it simple.

As one can see in Table 7.9, the flexible designs outperform the base case and the lay-up, for all tested scenarios. Now it should be also mentioned that the "in" option flexibility given from the expansion and the fuel-switch also has the "on" options to lay up. The concluding remarks from this flexibility analysis is therefore that the two analysed "in" options flexibilities are recommended. To clarify, the two recommended "in" options are: the option to expand capacity from 20 kTEU to 22 kTEU and the option to prepare the fuel systems for a later retrofit to change between HFO and LNG.

Since this is an illustrative case, we will not in detail present more sensitivity analyses and strategy recommendations. However, for a proper analysis using real data, this step is highly important to demonstrate for the decision-makers that the identified flexibilities may in fact be the smartest design choice.

Chapter 8

Discussion

In this chapter, we will discuss uncertainty and flexibility in marine systems, the presented methodologies and framework, and the illustrative case study.

8.1 Uncertainty and Flexibility in Marine Systems

The main topics discussed in this thesis are methods for identifying and valuing flexibility for marine systems in order to handle uncertainty and manage risk for marine systems facing contextual changes. However, one may ask, why is this desirable? In light of material presented in the thesis, further critical questions may be:

- Why focus on handling uncertainty in marine system design?
- Is flexibility the right way to handle uncertainty?
- Why is flexibility rarely found in the industry when most analyses say it is valuable?

Why Focus on Handling Uncertainty in Marine System Design?

The traditional capital-intensive maritime industry is known to be highly volatile, introducing the asset owners to high risks, both positive and negative. Hence, from a rational player's perspective, it is obvious that methods for handling uncertainty is highly relevant. If methods for handling uncertainty actually make the assets perform better, the industry players using them will then on average perform better than the competitors, other things equal. As with traditional evolution theory, this implies not necessarily that everybody will start using it, but those who do not will probably be phased out over time and value robust flexible designs will dominate eventually. This is of course given that future scenarios remain uncertain.

The maritime industry involve several segments, each subject to different types of uncertain factors. From the summer of 2014 to the summer of 2015, the Brent crude oil price plummeted from \$115/barrel to approximately \$50/barrel. This represents a reduction of more than 50%, highly affecting numerous maritime companies depending on this price. These companies are typically offshore related and may be owners of ships assisting drilling operations in the North Sea, or the drilling rig owners themselves. These companies have seen their market values plummet along with the oil price.

In relation to the methods presented in this thesis for handling uncertainty, one may ask: Is an established framework from the systems engineering domain just adapted to marine technology domain to follow the general engineering design trend, or is there a fundamental need for it in the maritime industry? I would argue that there is a fundamental need for it, particularly due to the high volatilities that dominate in this capital-intensive industry. What is seen in the industry today (2015) is that several offshore vessels are laid up, which in itself is a operational flexibility to reduce costs. However, never getting a contract generates no revenue and implies a low return on the investment for the asset owners. One has indeed seen examples in the media recently[1] of multi-purpose, and highly complex ships, are more expensive to operate and in fact in the collapsing offshore market of 2014/2015, can be considered as multi-useless[2]!

Is Flexibility the Right Way to Handle Uncertainty?

The main focus in this thesis has been on handling uncertainty by untraditional means, that is by explicitly considering it at the conceptual design phase, instead of operational post-design hedging with established market mechanisms such as financial derivatives. However, one may ask, why is this desirable? Why build flexible marine systems when several uncertainties may be hedged, for example by using fuel futures to hedge against the fuel price?

What is important to make clear is that the two approaches are not similar and should be used to complement each other in the overall design process. Designing better systems will involve taking the best from all of the available methods for handling uncertainty. What may be relevant for one system may not be relevant for another. An example from the shipping industry is that ships often operate in fleets, and often in diversified fleets, where the performance of the overall fleet is of main interest for the owner. Hence, handling uncertainty on a fleet level becomes more important, and not on the physical ship design level. An expansion option for the fleet may then be exercised by for example adding another ship to the fleet, instead of the physical aspects it would involve expanding the capacity of a single ship. By this way, the traditional "on" options approach to handling uncertainty can be of higher relevance, in contrast to focusing on single ships. Furthermore, additionally having physical

[1] Superskipet som ble et mareritt (The super ship that became a nightmare) `http://www.dn.no/nyheter/naringsliv/2015/06/14/2052/Oljeservice/superskipet-som-ble-et-mareritt`, accessed June 17. 2015.

[2] Notation adapted from Per Olaf Brett, Vice President at Ulstein International.

"in" options on single ships that operate in a fleet may introduce additional complexity, and reduce the value of this option.

I would further argue that "in" and "on" options in the maritime industry tend to focus on different aspects of uncertainty. When looking at large single installations, traditional strategic "on" options such as the lay-up and abandon options, are good candidates for protecting against the downside risk. Then in particular, "in" options become more relevant for better being able to take advantage of upside risks.

Why is Flexibility Not Used More When Research Suggest it is Valuable?

Generally, when reading the literature on designing flexible engineering systems the conclusions are almost always that substantial value can be added to the design through flexibility. However, despite the analytical conclusions, we relatively rarely see flexible installations in the industry. There are however some bridges and buildings that are sometimes mentioned in the literature (de Neufville and Scholtes, 2011). In the maritime industry however, there are not many flexible systems designed, that is with "in" option characteristics, such as the midship elongation options exercised on the cruise ship MV Balmoral in 2008. What is the reason for this?

Pettersen (2015) discusses flexible design of offshore construction vessels, and finds that flexible design solutions significantly improve expected values. That is, increasing the ENPV from approximately 500 million NOK to 4500 million NOK for a single ship, hence pricing flexibility to around 4000 million NOK. Considering that an offshore construction vessel typically cost around 400-600 million NOK, and flexible equipment such as a crane costs 20-40 million, the expected value flexibility is significant. This is perhaps particularly relevant when the current (2015) offshore shipping market is relatively unprofitable due to low oil prices and little offshore activity. When seeing such extreme improvements, and flexibility still is not implemented in the industry to a particular degree, one might ask why is this so?

For offshore ships Pettersen (2015) argues that perhaps yards, dry-docks and other facilities may be a restrictive factor for retrofitting offshore ships. This may be an interesting point, that when retrofit "in" options are relevant for exercise, perhaps they simply cannot be done because facilities are not available.

Other answers may be that the industry is too conservative and not mature enough to incorporate these more complex "in" options, or that there are doubts to the results obtained from the analyses. One critical aspect of the maritime industry is the relatively strict classification scheme that must be followed. These classification companies complicate the process of implementing "in" options, and are probably a major reason why the marine industry is rather conservative. I would therefore argue that changing the industry is partly their responsibility.

However, what is seen now (2015) is that the classification companies are starting to incorporate flexible class notations. These notations are not for any type of flexibility though, and is currently focusing switching to LNG as fuel. This is seen at DNV GL (GAS READY) and Lloyd's Register (Gas Fuelled Readiness (GR)) as discussed in Chapter 8.4.

In the development of the flexibility analysis framework, weight is put on developing an understanding of the drivers of flexibility and therefore help build acceptance among the decision-makers. This is particularly addressed by Cardin et al. (2015), who discuss that researchers understand the concept of flexibility, but for practical applications, the industry decision-makers have generally not accepted the concept. They exemplify a conversation between an analyst and a decision-maker:

> **Analyst:** *Although you have not done so before, we need to look at uncertainties. I have done so. My calculations show that you can expect much improved performance using a novel design.*
>
> **Decision-Maker:** *Our designs have worked well. Your uncertainties are full of assumptions. I do not understand how it is possible to increase expected value so dramatically. I cannot risk your proposed solution, especially if it costs more, and I may not use the flexibility in the end. [Please go away.]*
>
> Cardin et al. (2015)

As discussed in the approach in the introduction for the development of this thesis, it is of interest to have an analysis framework that can serve as a base of communication between key non-technical and technical stakeholders, designers and consultants. The intention of the proposed stepwise approach to analysing flexible systems is to serve as such a base.

Satsficing vs. optimizing

In his book on the sciences of the artificial, Herbert A. Simon discusses several theoretical and empirical methods that can be used in design (Simon, 1996). These include utility theory, optimization, dynamic programming, control theory, queuing theory and statistical decision theory. Despite all these available tools, he argues that actually finding an optimal design solution often is next to impossible for real life situations. For example, the simple travelling salesman problem (TSP) quickly becomes an extremely large problem, as the number of possible paths grows exponentially with the number of nodes. In such complex problems, we have to settle with good solutions that are probably not optimal. Simon labels these design methods as "satisficing". In operations research and related fields we have heuristics that can find satisficing solutions rather quickly for various difficult problems.

Since finding the optimal solution for something that is uncertain is rather contradictory, I think it is important to focus on “satisficing” methodologies in terms of handling uncertainty in preliminary design of marine systems. However, there are some methods that already try to take uncertainty into account. Stochastic optimization, for example, strives to find the optimum based on the expected value. The method can therefore settle on a solution that would be suboptimal given mean parameter values, but by taking different scenarios with corresponding probabilities into account, the solution space may look completely different. Another interesting point Simon touches upon, is searching for alternatives. Before one can build flexibility as real options into a design, one has to identify it. This can in itself be a cumbersome procedure, which is not straight out of the book. When designing to handle uncertainty one also has to find realistic scenarios, which can be hard. However, it is of significant importance for the evaluation of the different designs.

8.2 Methods and Framework for Flexibility Analysis

Methods for Analysis

With regard to the methods discussed for modelling the future and identifying and valuing flexibilities, it is of interest to assess the material in a critical way.

First, the approaches discussed for modelling the future do not capture the problem in the same way. Scenario thinking is about exploring the room of possibilities, structuring the thinking about the future and identifying the main drivers of uncertainty. Epoch-Era is by a moderate amount similar, but involves more explicitly generating realisations of the future along a time axis, and comprises a fundamental way to assess the future for the discussed tradespace methods. Using time series and stochastic processes are more relevant when it comes to modelling how specific parameters, such as the fuel price, evolve over time. Stochastic processes are typically used for pricing real options the traditional way. The reason why I included aspects of scenario thinking first is that this mind-set is central when it comes to handling uncertainty. "What will happen if this is a scenario, or this?" However, when it comes to actually making an analysis, using historical data and generating the right stochastic processes or epoch-variables is the important thing as uncertainty drives the value of flexibility.

Methods for identification of flexibility are less developed than for valuation. The reason for this is probably that traditional "on" options usually are quite clear and need no formal identification method. However, for more complex "in" options that typically are embedded into a design itself, option identification methods are of much higher relevance. The reason why I put much weight on screening methods for flexibility identification is that I argue that it is of particular relevance for marine systems. As mentioned in the introduction chapter, the approach of this thesis has been inspired by thinking about how maritime consultants at DNV GL Maritime Advisory can analyse flexibility for their customers. Since they already have divisions specializing on particular areas of marine engineering, they can more easily use these to build screening models from the material and expertise they already have. Hence, they do not have to create completely new models, such as needed when using the information flow methods or the discussed tradespace methods.

When it comes to the valuation methods, I argue that all of them are relevant for flexibility valuation in design of marine systems. Methods include analytical, tree-methods, simulations and the valuation approach for strategic changeability (VASC). Analytical- and tree methods are good at pricing traditional options, because they are fast and the values obtained are for optimal exercise of the options evaluated. These methods are however more difficult for implementation with "in" options, which is why simulations and VASC deserve much attention. For flexibility analysis support from marine consultants in general, I would argue that simulations is a very good approach to analysing flexibility. The reason why I think simulations prove well is that it is generic, and more easily can handle all types of complex dynamics. However, it is more difficult to design the valuation simulation to maximise the expected value of the decision-making strategy. This can be done by for example introducing triggers that exercise the option, and find the trigger value that maximises the expected value. However, as Simon (1996) discusses, perhaps satisficing and not optimizing, is good enough.

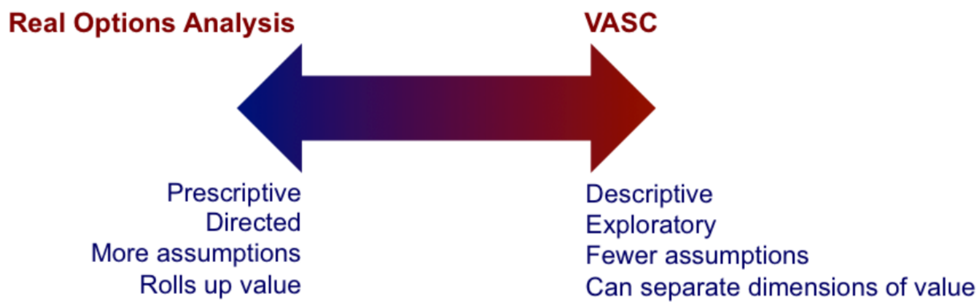


Figure 8.1: Notional "analysis spectrum" from ROA to VASC (Fitzgerald, 2012).

The main reason tradespace evaluation methods (VASC) is included is to provide a completely different way of quantifying flexibility. As Fitzgerald (2012) discusses, real options analysis (ROA) and VASC operate on a sort of "analysis spectrum", which is illustrated in Figure 8.1. He argues that ROA is designed to provide focused, prescriptive judgements such as "This option is *worth it*, since the expected income is higher than costs.". Therefore, one of the benefits of ROA is that it is simple to understand and communicate to non-technical stakeholders. VASC, on the other hand, is designed in a more exploratory manner, where the design space is searched and large amounts of descriptive data about changeability and its value is provided.

Which methods that are most appropriate may also depend on what types of data that is available. In general, the ROA methods are more dependent on detailed data than VASC, as VASC is more of an exploration tool. However, ROA methods can also be used to explore decision domains, that is determining for which sets of parametric values different decision strategies are most valuable, and therefore be less dependent on data.

Framework

Initially, it was of interest to design a particular flexible system in the master thesis, such as a ship. However, it was unclear how to proceed in the flexible analysis part, and hence the thesis took a direction of classifying and analysing different methods, and illustrating which method that could be used when. There was already a framework for analysing flexibility discussed by Cardin and de Neufville (2008), but this was not directed against methods for marine systems in particular, and did not include more novel tradespace exploration and evaluation approaches that are seen more and more in the literature today.

In this thesis, I have added the tradespace exploration and valuation methods to the framework presented by Cardin and de Neufville (2008). There may be multiple reasons why they did not include them in their working paper, a good reason may be that the methods discussed here such as Epoch-Era Analysis and the Responsive System Comparison (RSC) method are relatively new methods, and were probably under development at the time their paper was written. However, I argue that these methods are so relevant for design of marine systems that they should be included in the framework. The main reason is that these methods provide interesting approaches to solve problems including "in" options. In order to better characterise systems for flexibility analysis, I also added two classification criteria to the selection process proposed by Cardin and de Neufville (2008): stakeholder preference and system complexity.

Tradespace methods for marine system design are of particular relevance due to the benefits from in a good way capturing different aspects of changing contextual parameters with the Epoch-Era framework, and that the stakeholders' preferences are in focus. However, I do not argue that there is a particular need for a strong separation between the methods. Probably there are several synergy effects in combining them. In fact, in his thesis Pettersen (2015) combines aspects of Epoch-Era and stochastic processes to generate scenarios for ships. I would argue that he takes the best from both areas, with the narrative approach for era-construction together with the relevant stakeholders, and the stochastic processes combined with a Monte Carlo simulation method to value the flexibility with real options. This can be of particular relevance in the maritime industry when it comes to combining drastic and progressive uncertainties, for example as drastic shifts in the emission regulations in addition to prices of different types of high and low sulphur fuels change on a day-to-day basis.

8.3 Case Study Discussions

The container ship serves as an interesting case to study when it comes to analysing flexibility in design. As the case is meant as an illustration of the proposed framework, multiple simplifications and assumptions were made and therefore the model has several shortcomings compared to what it would have had in a proper analysis.

A particular shortcoming of the flexibility valuations is that only one predetermined trigger rule value was tested for each option. In order to properly maximise the value of flexibility, and explore the best management strategies, it would be of great importance to find the optimal trigger values. Furthermore, only two "in" options were evaluated. To make the analysis more realistic it would be interesting to include a handful of alternatives. Then it would also be more relevant to consider how these options influence each other, which would make the valuation procedure more complex.

When it comes to the numerical results of the analysis, the "in" option flexibility increased the expected net present value (ENPV) of the project by 176%. It probably makes more sense to illustrate this relative to the ship investment, which then results in a 27% increase in the profitability index (PI). However, it is reasonable to assume that these estimates are too high, since the "in" options should be valued combined, and that we simplify and do not restrict the upper size of the ship. This can be further assessed with models that include the relevant factors in the environment of the ship, for example also describing the port and canal restrictions and uncertainties related to these, and the dynamics of the fuel price, container demand and freight rates. That is, a proper model, comprising technical, financial and environment sub-models would be of interest for a detailed analysis of this case. Perhaps also more innovative design flexibilities then could be identified, like the case with oil platform design discussed by Lin et al. (2013), where the subsea tiebacks were found to be highly relevant for the overall platform design.

When it comes to the models used, I would argue that the combination of screening for identification and simulation for pricing seems like a good combination for flexibility analysis in design of large commercial cargo ships. However, it would be interesting to see how other methods for identification and valuation compare when used on the same case. Perhaps it would be of particular interest to investigate how tradespace exploration methods potentially could be used also for these types of problems, because these novel methods remain relatively unexplored for use in design of marine systems.

What was further explored throughout the case study was that it probably makes sense to include the most obvious "on" options protecting from downside, such as lay-up, before identifying "in" options. This is because these "on" options are more fundamental to the managers, and will always be of relevance for commercial marine systems.

8.4 Framework Applications in the Marine Industry

There are multiple potential users of the proposed flexibility analysis framework presented in this thesis. The group that probably are of most interest involve owners, designers, yards and classification companies. Since the classification companies have a central role in restricting and directing the international maritime industry with their mandatory classification notations, I will in the following discuss them further, and how the intended framework can be used by them. As mentioned earlier, this was also one of the driving factors of the development of this thesis.

Classification companies such as DNV GL and Lloyd's Register establish and maintain rules and standards for the construction and operation of ships and other structures in the marine industry. In addition to their major role as classification companies, they often also represent other bodies mainly providing technical advisory in the maritime, oil and gas and energy industries. At DNV GL Maritime Advisory, they have groups that specialise in subjects such as hydrodynamics, machinery, structure and conceptual design. Their vast interdisciplinary knowledge in the field is of particular relevance when it comes to the methods for identifying and valuing candidate flexibilities, as it would be of interest for them to be able to use models they already have. For example for the case of using screening methods for identification of flexibility, they already have models describing subsystems of ships that can be used to build bottom-up screening models.

DNV GL and Lloyd's Register have recently developed flexible class notations, with GAS READY and Gas Fuelled Readyness (GR) respectively. DNV GL's GAS READY class notation is aimed at ship owners who are interested in LNG as fuel, but don't want to have LNG as fuel from delivery. With the flexible notation, the ship has been prepared for LNG fuel during the newbuilding stage (DNV GL, 2015). With the flexible class notations, the shipowner has more flexibility and less trouble with the classification society upon retrofit. This flexible notation also to a greater extent help DNV GL assist owners in the design process, additionally it helps to build a framework for the overall project with parties including owner, designer, approval engineers and surveyors. The GAS READY classification notation has several levels and requirements. The two minimum levels include dual fuel convertible main engines and verification of compliance with GAS FUELLED rules for future LNG fuel operations. Dual fuel engines are typically capable of using regular diesel or natural gas as fuel. Since GAS

READY involves making the ship ready for a later retrofit to become flexible, it can essentially be characterised as a compound option.

Barzan (2015), an 18 800 TEU container ship owned by the Unites Arab Shipping Company (UASC) was the first ship to receive the GAS READY notation by DNV GL. There are 16 sister ships that will get the same class notation. The CEO and president of UASC, Jørn Hinge said:

"We are expanding our fleet by building larger, greener vessels, which support our global ambitions to fulfil or even exceed our customers' environmental requirements. We have worked closely with DNV GL to deliver the industry's greenest container vessel to date, the Barzan. We believe that this vessel, as well as the rest of the vessels in our new building program, demonstrates our commitment to technical innovation and eco-effectiveness". [3]

[3] https://www.dnvgl.com/news/naming-of-uasc-containership-barzan-sees-first-vessel-with-dnv-gl-s-new-gas-ready-class-notation-hit-the-water-23922, accessed August 11, 2015.

Chapter 9

Conclusion

9.1 Concluding Remarks

In this thesis, we have evaluated a number of alternative approaches for identifying and valuing flexibility for applications in marine systems design, in addition to presenting a generic approach for flexibility analysis. The methods investigated originate from two main areas: the financial domain with real options, and the systems engineering domain with more novel techniques. From an established real options valuation side it is obvious that strategic flexibility has value. However, for non-standard applications, it is more ambiguous how to proceed with the analysis. To better structure options for marine systems design, we have demonstrated that a classification of "on" and "in" options serves as a good way of characterizing options and directing the analysts towards their use and potential value. The discussed methods have different strengths and drawbacks, and we can therefore conclude that there is no universal approach that is best. However, through an illustrative case study, screening methods for identification and Monte Carlo simulation methods for valuation have been demonstrated to be of high relevance for applications to design of flexible commercial marine engineering systems. This is particularly because screening methods can build on already developed models describing the components of a system, and that Monte Carlo simulations methods opens up for easier modelling of more complex "in" options.

A generic framework for flexibility analysis is presented, with the purpose of serving as both a proper approach for quantifying flexibility, and as a demonstration of the drivers of the value of flexibility through a stepwise procedure. Hence, the framework also serves as a means of communication between analysts and decision-makers, both technical and non-technical. Since the maritime industry comprises several players such as owners, yards, designers and classification companies, a mutual understanding of the concept of flexibility is central for the concept to take root in the industry. To make this happen, we argue that it is of importance that key players, such as the classification companies, act as catalysts for introducing flexibility, for example by introducing more flexible class notations.

What can be further concluded from this thesis is that due to the high volatilities and wide range of uncertainties facing the maritime industries, such as from markets, regulations, technologies and operating conditions, focusing on methods for better handling these uncertainties at the early design phase is more relevant than ever. Even though it exists multiple methods to draw upon, for both identification and valuation of flexibility, effort should be made at better adapting them for marine applications. Additionally, we argue that it is of importance not only to focus on the theoretical procedures, but also on understanding how the key players in the industry have to collaborate to go from theory to practice.

9.2 Recommendations for Further Work

Even though the value of flexibility in design is recognised and accepted by analysts, further effort should be made at understanding the design decisions of the key stakeholders. The proposed flexibility analysis model is intended to work as a platform for communication between analysts and decision-makers, through developing mutual understanding of the drivers of flexibility and the analysis procedure. However, there is still much left to be done in order to go from academic aspects only, to actual implementations in the industry.

When it comes to the methods discussed, further work should be on better combining the methods from the financial and systems engineering domains. This includes stochastic processes and Epoch-Era methods for assessing scenarios, and real options and tradespace evaluation methods for value quantification. Further, it would be of interest to explore practical aspects of how and when different types of "on" and "in" options are exercised in the industry, to build more realistic models. It may also be of interest to further build on the discussed option classification scheme, and for example, more formally differentiate between options that exploit upside uncertainties and options that mitigate downside risks. Perhaps in this way one could better demonstrate the value of the different options, which for example could help the flexibility analysis framework to better demonstrate the individual options' contributions to the added value of flexibility.

For the case study, it would be relevant to extend the analysis to focus more on using realistic data, and to include an assessment of optimal triggering rules for the valuation. Further, it would be relevant to extend the model describing the container ship with a "ship-environmental" model, including ports and the dynamics of the market rates. Additionally, one can include aspects of the strategies of competitors through game theory. In a more general marine engineering perspective, it would be of relevance to apply the presented methods and framework on current issues, such as compliance with emission control areas (ECAs) or ballast water treatment rules.

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Appendix A

Acronyms

AR Auto Regressive

BOPM Binomial Option Pricing Model

CDF Cumulative Distribution Function

CPA Change Propagation Analysis

DSM Design Structure Matrix

ECA Emission Control Area

EEA Epoch-Era Analysis

ENPV Expected Net Present Value

ESM Engineering System Matrix

FDO Flexible Design Opportunities

FOD Filtered Outdegree

GBM Geometrical Brownian Motion

MATE Multi-Attribute Tradespace Exploration

MCS Monte Carlo Simulation

NPV Net Present Value

ROA/ROV Real Option Analysis/Real Options Valuation

VASC Valuation Approach for Strategic Changeability

Appendix B

Case Study Material

B.1 Container Ship System Model Description

The container ship system model is based on the "propulsion-cash flow" model developed for optimal speed analysis for large container ships, by Khor et al. (2013). The model used for the illustrative example uses their results directly, but generalises their results to some degree in order to build a dynamical model taking the ship capacity into account. For a more detailed presentation of the model, please see their paper.

Resistance and Powering Models

Khor et al. (2013) estimate the total hydrodynamic resistance of the ship with simple software based on the Holtrop-Mennen method. The resistance, as a function of ship speed, is presented in Figure B.1.

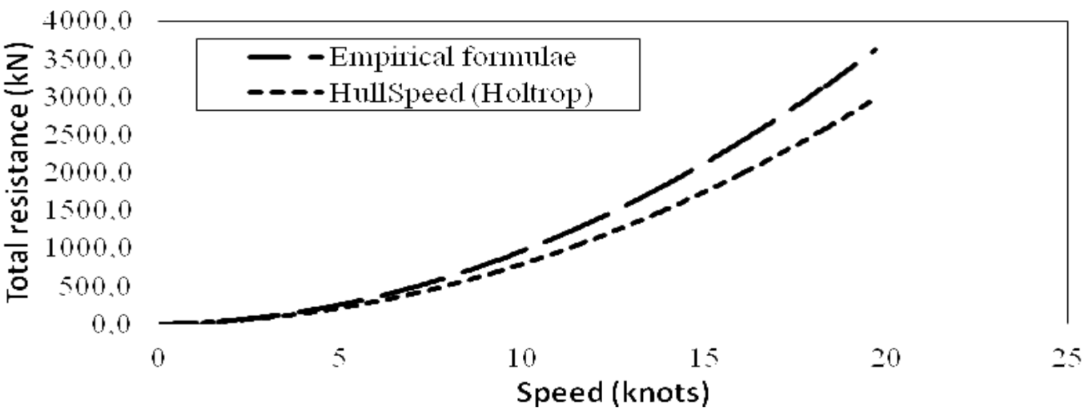

Figure B.1: Case study resistance prediction analysis results, from Khor et al. (2013).

Using power regression, this function is simplified to the following relation, assumed to work for relatively small deviations (± 20 %) form the design speed of 20 knots:

$$R_{tot} = 6.05 \cdot (V_{ship})^{2.09} [kN] \quad \text{(B.1)}$$

Where V_s is the ship speed in knots. The required engine break power (P_b) is then found from the following relation:

$$P_b = P_b(v_{ship}) = \frac{P_e}{\eta_{tot}} = \frac{R_{tot}(V_{ship}) \cdot V_{ship}}{\eta_{tot}} \tag{B.2}$$

Where P_e is effective power R_{tot} is the total resistance and η_{tot} is the total efficiency. The total efficiency is given by $\eta_{tot} = \eta_{prop} \cdot \eta_{mech}$, where η_{prop} is the propulsion efficiency and η_{mech} is the mechanical efficiency. For simplicity in this study, the total efficiency is assumed constant and equal 0.6.

For the flexibility analysis, we assume a simple model for required break power as a function of both the ship speed and the capacity (TEU):

$$P_b(CAP, V_{ship}) = P_b(V_{ship}) \cdot \left(\frac{CAP}{CAP_{basecase}}\right)^{\gamma} \tag{B.3}$$

This is assumed to work for relatively small changes in the capacity (± 20%). One can use regression analysis on empirical data, or data given from high-fidelity simulation methods to find good γ parameter values. In this illustrative study γ is assumed the value of 0.5. This is because we assume that the small deviations from the design capacity mainly will affect the friction resistance, and not the wave-making resistance, since the Froude number is approx. the same.

We further assume a specific fuel consumption (SFC) of 200 g/kWh ($2 \cdot 10^{-4}$ MT/kWh). For a given fuel price FC [$/MT], and a transport time factor (TTF) of 0.9 [-] (time in laden/(time in laden and port)), we get the following yearly fuel costs (FC) [$/$year$]:

$$FC(FP, V_{ship}, CAP) = FP \cdot SFC \cdot 8760 \cdot TTF \cdot P_b(CAP, V_{ship}) \tag{B.4}$$

Revenue and Cost Models

Revenue model

The yearly revenue from the container ship is evaluated based on the freight rate per TEU and the number of round trips which can be completed in a year. However, the number of round trips depends on voyage and port times, and the voyage time again depend on the ship speed. The mapping between revenue and propulsion can therefore be said to be rather complex.

$$\text{Round trip time} = \text{Journey time} + \text{Port time} \tag{B.5}$$

A relevant parameter for the revenue is the load factor (L_f), which represents cargo utilization. We assume that the load factor is 50% (see Khor et al. (2013) for more details). The yearly revenue (Rev) can then be given by:

$$Rev = L_f \cdot CAP_{tot} \cdot FR \cdot W \tag{B.6}$$

Where CAP_{tot} is the total capacity in TEUs, *FR* is the freight rate in $ per TEU transported, and W is the number of trips yearly.

Based on this approach Khor et al. (2013) find the following relationship between revenue and design speed (with a 0.5 knot step size in the speed) for a base case freight rate ($FR_{basecase}$) of $1 200 per TEU.

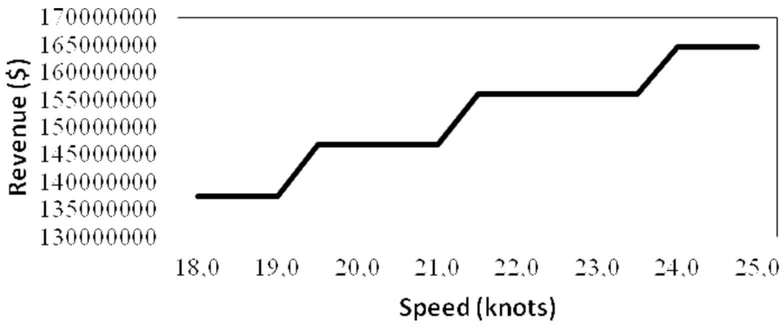

Figure B.2: Case study revenue curve, from Khor et al. (2013).

For simplicity, this function is linearised to the following relation:

$$Rev(V_{ship}) = 3.93 \cdot V_{ship} + 66.8 \ [\$ million] \tag{B.7}$$

Where *Rev* is the yearly revenue in $ million, and speed (V_{ship}) is in knots. The relation is assumed to work for relatively small deviations from the design speed of 20 knots.

For the flexibility analysis, a generalisation of this function is made, so the revenue function also is a function of the ship capacity (in total TEUs) and the freight rate (FR).

$$Rev(CAP, V_{ship}, FR) = Rev(V_{ship}) \cdot \left(\frac{CAP}{CAP_{basecase}}\right)^{\lambda} \cdot \left(\frac{FR}{FR_{basecase}}\right) \tag{B.8}$$

Again, this is assumed to work for relatively small changes in the capacity (± 20%). One can use regression analysis on empirical data or data from with high-fidelity models to find good fits for the λ parameter. For this case, we assume $\lambda = 1$.

Khor et al. (2013) discuss aspects of waste heat recovery and auxiliary power in their model. For simplicity, these are not explicitly included her.

Cost analysis

The total costs (TC) structure is structured the following way:

$$\mathrm{TC} = \mathrm{OPEX} + \mathrm{VOYEX} + \mathrm{CAPEX} \tag{B.9}$$

OPEX are the operating costs, assumed constant and equal to 10 000 $ per day. VOYEX are the voyage costs, where the fuel costs are significant. The fuel consumption is calculated with the propulsion model presented earlier. Another relevant part of the voyage costs are the port and cargo handling costs and not considered in this model. CAPEX are the capital costs, which includes the $200 million initial investment, assumed to be paid with an even distribution from the contract is signed to the ship is delivered over a period of two years. CAPEX also includes the interests on the loans, which for simplicity is assumed to be paid over the whole ship's lifetime, even though this probably not is very realistic. The loan interest rate is 8.5%. The value of the ship in the end of its lifetime is assumed to based on the scrap price 400 $ /LTD, where the ships has a light displacement (LTD) of 80 000 tonnes. Khor et al. (2013) also discuss inventory costs and safe stock costs, which are not included here.

For the flexibility analysis, it is of interest to briefly estimate the price of a container ship as function of the capacity. To make a dynamic model with the ship newbulding price as a function of the capacity, a regression analysis is performed of different designs and their cost prices. The following ships sizes and costs were used for the curve fitting:

Table B.1: Assumed ship price - capacity relations for regression analysis.

Capacity (TEU)	Price (mUSD)
2 500	18
3 500	25
6 500	70
12 000	105
20 000	200

Using power regression Matlab we get the following relationship for the newbuilding price (*NB*) as a function of the capacity *CAP* (TEU):

$$NB(CAP) = 3854 \cdot CAP^{1.095} \; [USD] \tag{B.10}$$

Test: NB(20 000) = 197 million USD, which is approximately 200 million USD and near enough for our analysis.

Profit calculation

The yearly profit (P) is calculated as follows:

$$P = R - TC \tag{B.11}$$

B.2 Mean reverting process for the HFO/LNG prices

For the "in" options to switch between LNG and HFO, it is of interest to the two fuel prices. A simple stochastic model for the development of the HFO and the LNBG prices is used.

The assumed initial price for HFO per metric tonnes is 500 USD. To make the correlated stochastic process simple, the initial price of LNG is assumed 700 USD per energy equivalent of 1 metric tonnes of HFO. Hence, it is only necessary to model the development between these two numbers, and not consider further technicalities.

The HFO price follows a geometric Brownian motion, as used in the general stochastic case. The price of LNG (P_{LNG}) is assumed to move towards the HFO price (p_{HFO}), with a random element, according to the following relation:

$$\frac{dP_{LNG}}{P_{LNG}} = (P_{HFO} - P_{LNG})\kappa + \sigma dB \tag{B.12}$$

where $\kappa = 0.5$ is the mean reverting parameter, σ is the volatility of the process, assumed the same as for HFO, and dB is a white noise.

Appendix C

Additional information

C.1 Illustrations

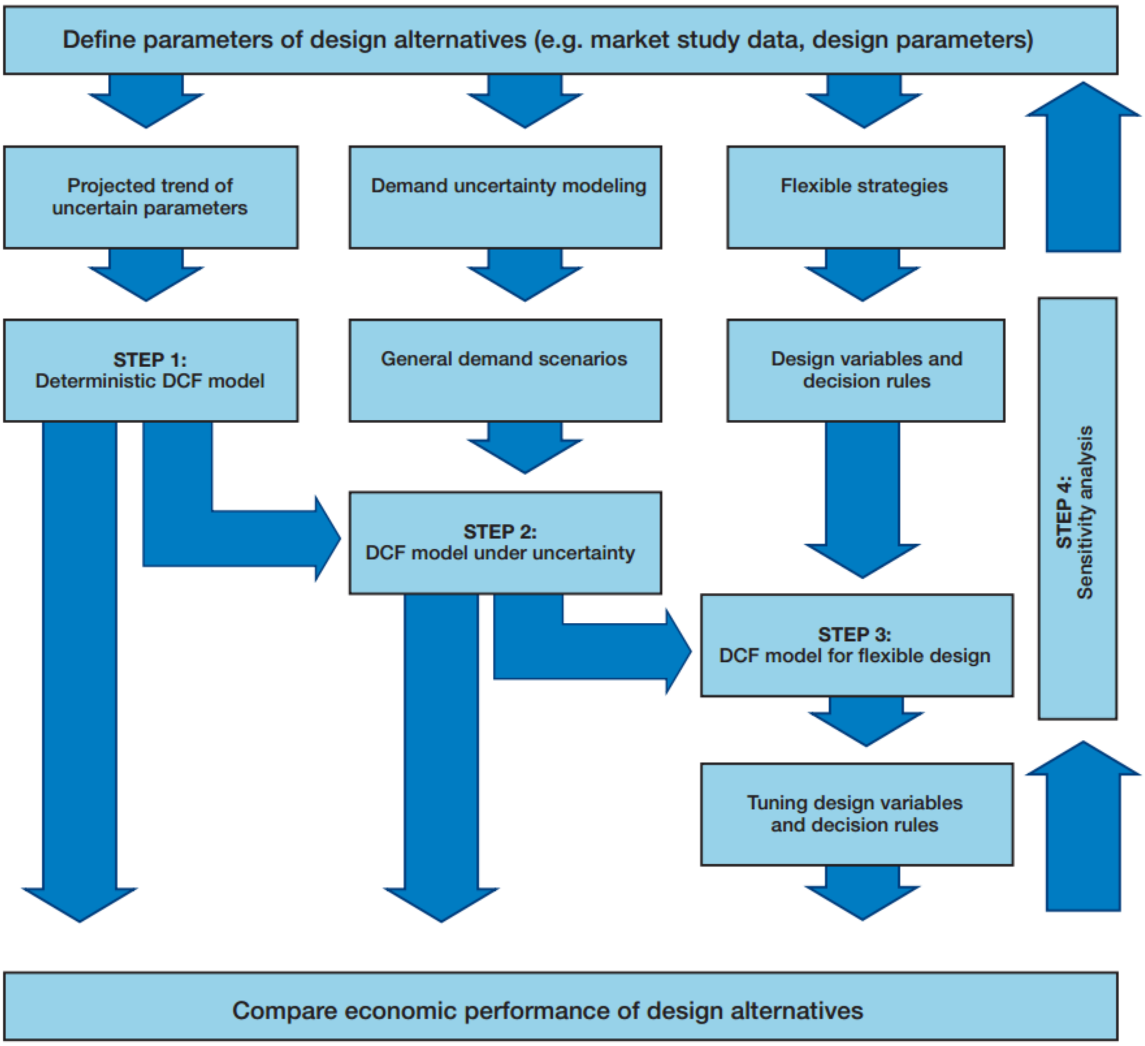

Figure C.1: A methodology to evaluate and compare flexible system designs, a four-step process, by Cardin et al. (2013).

Appendix D

Matlab Codes

The Matlab codes are also uploaded online at the NTNU DiVA Portal, where also a "readme.txt" file is included.

D.1 Input Parameters

Continuous parameters

```
function [dr, ir, CAP,...
    V_ship_design, lambda, gamma, Market_rate, OPEX_nonfuel_yearly,...
    HFO_price] = parameters_conainer_case_continuous()

% Interest rates and time parameters
dr=0.1;      % discount rate
ir=0.085;    % interest rate on loan, for an assumed ship lifetime loan

% Design parameters
CAP=20000;            % TEU
V_ship_design=20;    % knots

% Scaling factors
lambda=1;    % for thre revenue generation with respect to capacity
gamma=0.5;   % for the required power with respect to the capacity

% Rates and market prices
Market_rate=800;        % Base case market rate USD / TEU
OPEX_nonfuel_yearly=10000*365;   % USD/year
HFO_price=500;          % USD/mt

end
```

Discrete parameters

```
function [T_build, T_life]=parameters_container_case_discrete()

T_build=2; % Building time in years
T_life=25; % Operating life time in years

end
```

Parameters for the stochastic processes

```
function [drift_market,sigma_market,drift_fuel,sigma_fuel,Δt]=parameters_stochastic()

% Market rate:
drift_market=-0.01;
sigma_market=0.3;

% Fuel price
drift_fuel=0.01;
sigma_fuel=0.2;

Δt=1; % one year time period

end
```

D.2 Propulsion and Resistance Models

Resistance function

```
function rtot=R_tot(V_ship)
% Gives the resistance as a function of the speed

% V_ship in knots
% R_tot in kN

    rtot=6.05*(V_ship)^2.09;

end
```

Engine power function

```
function pb=P_b(V_ship,CAP,gamma)
% Calculates the brake engine power [kW]

% V_ship in knots
% CAP in TEUs
% gamma [-]

V_ship_ms = V_ship*0.514444; % Calculates speed in meters per second
CAP_basecase=20000; % TEU base case
eta_tot=0.6; % Total engine efficiency

    pb = (1/eta_tot) * R_tot(V_ship) * V_ship_ms* (CAP/CAP_basecase)^gamma;


end
```

D.3 Cash Flow Models

Newbuilding price function

```
function np=newbuild_price_function(CAP)
% Calculates the newbuilding price as a funciton of the capacity

% CAP in TEU
% np in USD

np=3854*CAP^(1.095);

end
```

Yearly revenue function

```
function Rev=yearly_revenue(FR,V_ship,CAP, lambda)
% This function gives the yearly revenue in USD.
% FR is fregit rate in USD/TEu, V_hip is in knots, CAP is TEUs lambda is
% dimentionless scaling factor

CAP_basecase=20000; % Base case design reference is 20 000 TEUs
FR_basecase=1200;   % Base case freight rate is 1200 USD/TEU, which is
                    % obtained from the reference case Khor et al. (2013)

    Rev = 10^6 * (3.93*V_ship + 66.8) * (CAP/CAP_basecase)^lambda * ...
        (FR/FR_basecase);

end
```

Yearly fuel costs function

```
function fcy = fuel_costs_yearly(FP, V_ship, CAP, gamma)
% Function gives yearly fuel costs as a funciton of fuel price, speed,
% capacity and scaling factor gamma.

% SFC in [MT/kWh]
% V_ship in Knots
% CAP in TEU
% Fuel price (FP) in usd/MT
% 8760 hours/year
% trandport time factor (TTF) = 0.9
% gamma is the scaling factor

TTF=0.9;        % Transport-time factor
SFC=2*10^-4;    % Specific fuel consumption

    fcy = FP * SFC * 8760 * TTF * P_b(V_ship,CAP,gamma);

end
```

Cash flow vector function

```
function cashflowvalues=CF(T_life, T_build, FR, FP, V_ship, CAP, lambda, gamma, newbuild_price, interest_rate, OPEX_nonfuel_yearly)
% This function generateas the deterministic cash flow for the base case ship design

%% Assumptions
T_interests=T_life; % Interests are paid over the lifetime

```

```
LTD=80000;          % Light dispalcement
scrap_price=400;    % Scrap price per light ship displacement


%% Logging vectors
revenue=zeros(1,T_life+T_build);
CAPEX=zeros(1,T_life+T_build);
OPEX_nonfuel=zeros(1,T_life+T_build);
VOYEX=zeros(1,T_life+T_build);
cash_flows=zeros(1,T_life+T_build);


%% Deterministic cash flow calculation
for i=1:T_life+T_build

    % Revenue yearly
    if i>T_build && i<T_life+T_build
        revenue(i)=yearly_revenue(FR(i),V_ship(i),CAP, lambda);
    elseif i == T_life+T_build
        revenue(i)=yearly_revenue(FR(i),V_ship(i),CAP, lambda) + scrap_price*LTD;
    end


    % CAPEX building costs - assume linearly spread over building time
    % CAPEX also includes interests
    if i≤T_build
        CAPEX(i)=(newbuild_price/T_build);
    elseif i≤T_build+T_interests
        CAPEX(i)=newbuild_price*interest_rate;
    end


    % OPEX nonfuel
    if i>T_build && i<T_life+T_build
        OPEX_nonfuel(i)=OPEX_nonfuel_yearly;
    else
        OPEX_nonfuel(i)=0;
    end


    % VOYEX fuel
    if i>T_build && i<T_life+T_build
        VOYEX(i)=fuel_costs_yearly(FP(i), V_ship(i), CAP, gamma);
    else
        VOYEX(i)=0;
    end

    %Cash flow calculation
    cash_flows(i)=revenue(i)-CAPEX(i)-OPEX_nonfuel(i)-VOYEX(i);
end

cashflowvalues=cash_flows;

end
```

Profit margin function

```
function pm=profit_margin(T_life, T_build, FR, FP, V_ship, CAP, lambda, gamma, newbuild_price, interest_rate, OPEX_nonfuel_yearly)
% Calculates the profit margin, same function as the cash flow function
% essentially
% this funciton is used for the findinf the threshold for option exercise

T_interests=T_life;
LTD=80000;
scrap_price=400;

%% Logging files
revenue=zeros(1,T_life+T_build);
CAPEX=zeros(1,T_life+T_build);
OPEX_nonfuel=zeros(1,T_life+T_build);
VOYEX=zeros(1,T_life+T_build);
cost_vector=zeros(1,T_life+T_build);
cash_flows=zeros(1,T_life+T_build);
profit_margin=zeros(1,T_life+T_build);

%% Deterministic cash flow calculation
for i=1:T_life+T_build
```

```

    % Revenue yearly
    if i>T_build && i<T_life+T_build
        revenue(i)=yearly_revenue(FR(i),V_ship(i),CAP, lambda);
    elseif i == T_life+T_build
        revenue(i)=yearly_revenue(FR(i),V_ship(i),CAP, lambda) + scrap_price*LTD;
    end

    % CAPEX building costs - assume linearly spread over building time
    % CAPEX also includes interests
    if i<=T_build
        CAPEX(i)=(newbuild_price/T_build);
    elseif i<=T_build+T_interests
        CAPEX(i)=newbuild_price*interest_rate;
    end

    % OPEX nonfuel
    if i>T_build && i<T_life+T_build
        OPEX_nonfuel(i)=OPEX_nonfuel_yearly;
    else
        OPEX_nonfuel(i)=0;
    end

    % VOYEX fuel
    if i>T_build && i<T_life+T_build
        VOYEX(i)=fuel_costs_yearly(FP(i), V_ship(i), CAP, gamma);
    else
        VOYEX(i)=0;
    end

    %Cash flow calculation
    cost_vector(i)=+CAPEX(i)+OPEX_nonfuel(i)+VOYEX(i);
    cash_flows(i)=revenue(i)-CAPEX(i)-OPEX_nonfuel(i)-VOYEX(i);

    profit_margin=cash_flows./cost_vector;
end

pm=profit_margin;

end
```

Net present value (NPV) function

```
function value=NPV(CF,r,t)
% calculates the NPV for a given cash flow vector, interst rate and the
% number of time periods as inputs.

DCF=zeros(1,t);

    for i=1:t
    DCF(i)=CF(i)*(1+r)^(-i);
    end

 value=sum(DCF);

end
```

D.4 Base Case Deterministic NPV Analysis

Base Case deterministic NPV script

```
%% Base Case deterministic NPV calculation
clear all
clc

%% Input data
% Collecting parameters
[dr, ir, CAP,...
    V_ship_design, lambda, gamma, Market_rate, OPEX_nonfuel_yearly,...
    HFO_price] = parameters_conainer_case_continuous();

[T_build, T_life]=parameters_container_case_discrete();
newbuild_price=newbuild_price_function(CAP);

%% Run deterministic NPV calculation

NPV_det(dr, ir, CAP,...
    V_ship_design, lambda, gamma, Market_rate, OPEX_nonfuel_yearly,...
    HFO_price)
```

D.5 Generation of Stochastic Processes

Market rate

```
function b=GBM_market(market_start,drift,sigma,total_time)
% Generates a GBM scenario for the market rates

nPeriods=total_time;
market_scenario=zeros(1,nPeriods);
Δt=1;

dB = randn(1,nPeriods);
market_scenario(1)=market_start;

    for i=2:nPeriods
        dFt = market_scenario(i-1)*(drift*Δt + sigma*dB(i));
        market_scenario(i) = market_scenario(i-1)+dFt;
    end

b=market_scenario;

end
```

Fuel price

```
function a=GBM_fuel(fuel_start,drift,sigma,total_time)
% Generates a GBM scenario for the fuel prices rates

nPeriods=total_time;
fuel_scenario=zeros(1,nPeriods);
Δt=1;

dB = randn(1,nPeriods);
fuel_scenario(1)=fuel_start;

    for i=2:nPeriods
        dFt = fuel_scenario(i-1)*(drift*Δt + sigma*dB(i));
        fuel_scenario(i) = fuel_scenario(i-1)+dFt;
    end

a=fuel_scenario;

end
```

Mean reverting fuel prices - for the fuel "in" option case

```
function [a,b]=stochastic_fuels(fuel_start_HFO, fuel_start_LNG, drift, kappa, sigma, total_time)
% Generates a scenario for the mean reverting HFO and LNG prices

nPeriods=total_time;    % scenario length in years

%% Vectors for storing the scenarios
fuel_scenario_HFO=zeros(1,nPeriods);
fuel_scenario_LNG=zeros(1,nPeriods);

Δt=1;   % time increment in years

dB = randn(2,nPeriods);
fuel_scenario_HFO(1)=fuel_start_HFO;
fuel_scenario_LNG(1)=fuel_start_LNG;

%% Generating the scenarios
    % HFO
    for i=2:nPeriods
        dFt1 = fuel_scenario_HFO(i-1)*(drift*Δt + sigma*dB(1,i));
```

```
        fuel_scenario_HFO(i) = fuel_scenario_HFO(i-1)+dFt1;
    end

    % LNG

    for i=2:nPeriods
        dFt2 = kappa*(fuel_scenario_HFO(i-1) - fuel_scenario_LNG(i-1)) + fuel_scenario_LNG(i-1)*sigma*dB(2,i);
        fuel_scenario_LNG(i) = fuel_scenario_LNG(i-1)+dFt2;
    end


a=fuel_scenario_HFO;
b=fuel_scenario_LNG;

end
```

D.6 Stochastic Base Case Analysis

Stochastic base case script

```
%% Stochastic base case analysis
clear all
clc

%% Input data
% Collecting parameters
[dr, ir, CAP,...
    V_ship_design, lambda, gamma, Market_rate, OPEX_nonfuel_yearly,...
    HFO_price] = parameters_conainer_case_continuous();

[T_build, T_life]=parameters_container_case_discrete();
total_time = T_build+ T_life;
newbuild_price=newbuild_price_function(CAP);

%% Stochastic simulation input
nSim=20000;     % Number of simulations

% Stochastic processes inputs
[drift_market,sigma_market,drift_fuel,sigma_fuel,Δt]=parameters_stochastic();
start_market=Market_rate;
start_fuel=HFO_price;

% Logging files
NPV_log=zeros(1,nSim);

%% Monte Carlo Simulation
for j=1:nSim

market_scenario=GBM_market(start_market,drift_market,sigma_market,total_time);
fuel_scenario=GBM_fuel(start_fuel,drift_fuel,sigma_fuel,total_time);
%speed_scenario=GBM_fuel(start_speed,drift_speed,sigma_speed,total_time);
speed_scenario=V_ship_design.*ones(1,total_time);

% CF_stochastic=CF(market_scenario,fuel_scenario);
CF_stochastic=CF(T_life, T_build, market_scenario, fuel_scenario, speed_scenario, CAP, lambda, gamma, newbuild_price, ir, ...
        OPEX_nonfuel_yearly);
NPV_log(j)=NPV(CF_stochastic,dr,total_time);

end

%% Plots and output data
figure(3);
cdfplot(NPV_log);
xlim([-2*10^9 3*10^9]);
NPV_mean=mean(NPV_log)
```

D.7 Lay-Up "On" Options Analysis

Lay-up "on" option cash flow function

```
function cf2=CF_on_option(CF_stochastic1, T_build, total_time,threshold)
% This function cuts the changes the cash flow as if it was generated by a
% ship that has the lay-up "on" option.

CF_stochastic2=CF_stochastic1;

    for i=(T_build+1):total_time
        if CF_stochastic1(i-1)<-threshold
            CF_stochastic2(i)=-threshold;
        end
    end

cf2=CF_stochastic2;

end
```

Lay-up "on" option analysis script

```
%% "On" options analysis, lay-up
clear all
clc

%% Collecting parameters
[dr, ir, CAP,...
    V_ship_design, lambda, gamma, Market_rate, OPEX_nonfuel_yearly,...
    HFO_price] = parameters_conainer_case_continuous();

[T_build, T_life]=parameters_container_case_discrete();
total_time = T_build+ T_life;
newbuild_price=newbuild_price_function(CAP);

%% Stochastic simulation input
nSim=20000;     % Number of simulations

% Stochastic processes inputs
[drift_market,sigma_market,drift_fuel,sigma_fuel,Δt]=parameters_stochastic();
start_market=Market_rate;
start_fuel=HFO_price;

%% VVectors for writing NPVs
NPV_log=zeros(1,nSim);

%% Monte Carlo Simulation
for j=1:nSim

    % Generating scenarios
    market_scenario=GBM_market(start_market,drift_market,sigma_market,total_time);
    fuel_scenario=GBM_fuel(start_fuel,drift_fuel,sigma_fuel,total_time);
    speed_scenario=V_ship_design.*ones(1,total_time); % constant

    % Generating cash flows from the scenarios
    CF_stochastic1=CF(T_life, T_build, market_scenario, fuel_scenario, speed_scenario, CAP, lambda, gamma, newbuild_price, ir, ...
            OPEX_nonfuel_yearly);

    %% "On" option valuation cash flow
    threshold=OPEX_nonfuel_yearly+newbuild_price*ir; % calculating the threshold
    CF_on=CF_on_option(CF_stochastic1, T_build, total_time,threshold); % calculating the post lay-up cash flows

    %% NPV calculations
    NPV_log(j)=NPV(CF_on,dr,total_time);

end

%% Output data
figure(4);
cdfplot(NPV_log);
xlim([-2*10^9 3*10^9]);

```

```
NPV_mean_on_option=mean(NPV_log)
ten_percentile = prctile(NPV_log,10)
ninety_percentile=prctile(NPV_log,90)
```

D.8 Screening Model

Screening script

```
%% Screening model
clear all
clc

%% Input data
% Collecting parameters
[dr, ir, CAP,...
    V_ship_design, lambda, gamma, Market_rate, OPEX_nonfuel_yearly,...
    HFO_price] = parameters_conainer_case_continuous();

[T_build, T_life]=parameters_container_case_discrete();
total_time = T_build+ T_life;

%% Stochastic simulation input
nSim=2000;     % Number of simulations

% Stochastic processes inputs
[drift_market,sigma_market,drift_fuel,sigma_fuel,Δt]=parameters_stochastic();
start_market=Market_rate;
start_fuel=HFO_price;

% Testvectors for screening
capacity_testvector=15000:1000:25000;
speed_testvector=15:1:25;

%% Vectors for writing NPVs
NPV_log=zeros(length(capacity_testvector),length(speed_testvector));

a=1;
for c=15000:1000:25000          % capacity
    b=1;
    for s=15:1:25               % speed

        %% Monte Carlo Simulation
        NPV_dist_log=zeros(1,nSim);

        for j=1:nSim

            market_scenario=GBM_market(start_market,drift_market,sigma_market,total_time);
            fuel_scenario=GBM_fuel(start_fuel,drift_fuel,sigma_fuel,total_time);
            speed_scenario=s.*ones(1,total_time);

            newbuild_price=newbuild_price_function(CAP);
            threshold=OPEX_nonfuel_yearly+newbuild_price*ir;

            % CF_stochastic=CF(market_scenario,fuel_scenario);
            CF_stochastic1=CF(T_life, T_build, market_scenario, fuel_scenario, speed_scenario, c,...
                lambda, gamma, newbuild_price, ir, OPEX_nonfuel_yearly);


            %% "On" option valuation cash flow
            CF_on=CF_on_option(CF_stochastic1, T_build, total_time,threshold);


            %% NPV calculations
            NPV_dist_log(j)=NPV(CF_on,dr,total_time);

        end
        % Storing the calculated ENPV calue
        NPV_log(a,b)=mean(NPV_dist_log);

        b=b+1;
    end
    a=a+1;
end


%% Plots
% post processing of data here
createfigure_screening(speed_testvector, capacity_testvector, NPV_log);
```

D.9 Cash Flow For "In" Options Models

Cash flow for "in" option function

```
function cashflows = CF_in_options(price_factor, T_life, T_build, FR, FP, V_ship, CAP, lambda, gamma, newbuild_price, ...
    interest_rate, OPEX_nonfuel_yearly, fuel_consumption_factor)
% Calculates the cash flow for the "in" options analyses

% Cap is vector
% fuel price is vector

%% Time parameters
T_interests=T_life;

LTD=80000;
scrap_price=400;

%% Logging files
revenue=zeros(1,T_life+T_build);
CAPEX=zeros(1,T_life+T_build);
OPEX_nonfuel=zeros(1,T_life+T_build);
VOYEX=zeros(1,T_life+T_build);
cash_flows=zeros(1,T_life+T_build);

%% Deterministic cash flow calculation
for i=1:T_life+T_build

    % Revenue yearly
    if i>T_build && i<T_life+T_build
        revenue(i)=yearly_revenue(FR(i),V_ship(i),CAP(i), lambda);
    elseif i == T_life+T_build
        revenue(i)=yearly_revenue(FR(i),V_ship(i),CAP(i), lambda) + scrap_price*LTD;
    end


    % CAPEX building costs - assume linearly spread over building time
    % CAPEX also includes interests
    if i≤T_build
        CAPEX(i)=(newbuild_price/T_build);
    elseif i≤T_build+T_interests
        CAPEX(i)=newbuild_price*interest_rate;
    end

    % CAPEX also includes expansion option price
    if i>T_build+2
        if CAP(i)-CAP(i-1)==2000
            CAPEX(i)=CAPEX(i)+newbuild_price*price_factor;
        end
    end

    % OPEX nonfuel
    if i>T_build && i<T_life+T_build
        OPEX_nonfuel(i)=OPEX_nonfuel_yearly;
    else
        OPEX_nonfuel(i)=0;
    end


    % VOYEX fuel
    if i>T_build && i<T_life+T_build
        VOYEX(i)=fuel_costs_yearly(FP(i), V_ship(i), CAP(i), gamma)*fuel_consumption_factor(i);
    else
        VOYEX(i)=0;
    end

    %Cash flow calculation
    cash_flows(i)=revenue(i)-CAPEX(i)-OPEX_nonfuel(i)-VOYEX(i);
end

cashflows=cash_flows;

end
```

D.10 Expansion "In" Option Analysis

Exercise year function

```
function expansion_year=expansion_option_year(profit_margin1, T_build, total_time,profit_factor)
% Calculating the year of the exercise of the expansion option

    expansion_year=0; % 0 indicates no expansion
    exercise=false;   % binary variable

    for i=(T_build+3):total_time

        profit_margin_2yr_mean=(profit_margin1(i-2)+profit_margin1(i-1))/2;

        if exercise==false && profit_margin_2yr_mean>profit_factor

            exercise=true;
            expansion_year=i;
        end

    end

end
```

Expansion option analysis script

```
%% expansion option valuation
clear all
clc

%% Collecting parameters
[dr, ir, CAP,...
    V_ship_design, lambda, gamma, Market_rate, OPEX_nonfuel_yearly,...
    HFO_price] = parameters_conainer_case_continuous();

[T_build, T_life]=parameters_container_case_discrete();
total_time = T_build+ T_life;
newbuild_price=newbuild_price_function(CAP);

%% Stochastic simulation input
nSim=2000;     % Number of simulations

% Stochastic processes inputs
[drift_market,sigma_market,drift_fuel,sigma_fuel,Δt]=parameters_stochastic();
start_market=Market_rate;
start_fuel=HFO_price;

%% VVectors for writing NPVs
NPV_log=zeros(1,nSim);
count_expansion=0;
threshold=OPEX_nonfuel_yearly+newbuild_price*ir;

%% Monte Carlo Simulation
for j=1:nSim

    %% on option
        market_scenario=GBM_market(start_market,drift_market,sigma_market,total_time);
        fuel_scenario=GBM_fuel(start_fuel,drift_fuel,sigma_fuel,total_time);
        speed_scenario=V_ship_design.*ones(1,total_time);

        CF_stochastic1=CF(T_life, T_build, market_scenario, fuel_scenario, speed_scenario, CAP, lambda, gamma, newbuild_price, ir, ...
            OPEX_nonfuel_yearly);
        profit_margin1=profit_margin(T_life, T_build, market_scenario, fuel_scenario, speed_scenario, CAP, lambda, gamma, ...
            newbuild_price, ir, OPEX_nonfuel_yearly);


    %% "On" option valuation cash flow
        CF_on=CF_on_option(CF_stochastic1, T_build, total_time,threshold);


    %% Expansion option

```

```
        profit_margin_expansion_factor=1.3;
        fuel_increase=0.05;
        price_fraction=0.05;

        expansion_year=expansion_option_year(profit_margin1, T_build, total_time,profit_margin_expansion_factor);
        expansion_vector=zeros(1,total_time);
        CAP_vector=CAP.*ones(1,total_time);

        cash_flow_in_expansion=CF_on;

        %% If expansion
        if expansion_year>0
            count_expansion=count_expansion+1;
                for m=expansion_year:total_time
                    expansion_vector(m)=1;
                end

            fuel_consumption_factor=ones(1,total_time)+(fuel_increase)*expansion_vector;
            CAP_new=CAP_vector+2000*expansion_vector;

            cash_flow_in_expansion=CF_in_options(price_fraction,T_life, T_build, market_scenario, fuel_scenario, speed_scenario, ...
                CAP_new, lambda, gamma, newbuild_price, ir, OPEX_nonfuel_yearly,fuel_consumption_factor);
        end

        %% If expansion finished
        CF_in_tot=CF_on_option_after_in(expansion_year,cash_flow_in_expansion, T_build, total_time,threshold);

    %% NPV calculations
        NPV_log(j)=NPV(CF_in_tot,dr,total_time);

end

%% Performance calculations
NPV_mean_in_option=mean(NPV_log)
exspansion_fraction=count_expansion/nSim
ten_percentile = prctile(NPV_log,10)
ninety_percentile=prctile(NPV_log,90)
```

Post exercise "on" option cash flow correction

```
function cf1=CF_on_option_after_in(expansion_year,CF_stochastic1, T_build, total_time,threshold)
% Lay-up "on" option valuation, after the expansion  option is exercised

CF_stochastic2=CF_stochastic1;

    for i=T_build+1:total_time

        if CF_stochastic1(i-1)<-threshold && i>expansion_year
            CF_stochastic2(i)=-threshold;
        end
    end

cf1=CF_stochastic2;

end
```

D.11 Fuel-Switch "In" Option Analysis

Retrofit year function

```
function retrofit_year=retrofit_option_year(fuel_difference, T_build, total_time,fuel_diff_factor)
% Finds the year of retrofit

    retrofit_year=0; % indicates no expansion
    exercise=false;  % binary variable

    for i=(T_build+1):total_time

        if exercise==false && fuel_difference(i-2)>fuel_diff_factor && fuel_difference(i-1)>fuel_diff_factor
            exercise=true;
            retrofit_year=i;
        end

    end

end
```

Fuel-switch option analysis script

```
%% "In" option analysis for fuel switch option valuation
clear all
clc

%% Collecting parameters
[dr, ir, CAP,...
    V_ship_design, lambda, gamma, Market_rate, OPEX_nonfuel_yearly,...
    HFO_price] = parameters_conainer_case_continuous();

[T_build, T_life]=parameters_container_case_discrete();
total_time = T_build+ T_life;

instalaltion_price=10^7; % fuel switch installation cost
newbuild_price1=newbuild_price_function(CAP)+instalaltion_price;
newbuild_price2=newbuild_price_function(CAP);

%% Stochastic simulation input
nSim=2000;     % Number of simulations

LNG_price_start=700; % Price of LNG per HFO metric tonne equivalent.
HFO_price_start=500; % Price of HFO per metric tonnes

% Stochastic processes inputs
[drift_market,sigma_market,drift_fuel,sigma_fuel,Δt]=parameters_stochastic();
start_market=Market_rate;
start_fuel1=HFO_price;
start_fuel2=LNG_price_start;

kappa=0.5; % Mean reversion factor


%% Vectors for writing NPVs
NPV_log1=zeros(2,nSim);

threshold1=OPEX_nonfuel_yearly+newbuild_price1*ir;
threshold2=OPEX_nonfuel_yearly+newbuild_price2*ir;

count_retrofit=0;

%% Monte Carlo Simulation
for j=1:nSim

        % Generating market, fuel and speed scenarios
        market_scenario=GBM_market(start_market,drift_market,sigma_market,total_time);
        [fuel_scenario1,fuel_scenario2]=stochastic_fuels(start_fuel1, start_fuel2, drift_fuel, kappa, sigma_fuel, total_time);
        speed_scenario=V_ship_design.*ones(1,total_time);

        fuel_scenario_min=zeros(1,total_time); % matrix for storing values

```

```
        fuel_increase=0.02;     % assuming a 2% increase in fuel consumption if the option is exercised
        contanier_tank_displ=0.05; % assuming that the LNG tanks take up 5% of the container space

        % choosing the cheapest fuel
        for i=1:total_time
            fuel_scenario_min(i)=min(fuel_scenario1(i),fuel_scenario2(i));
        end



%% HFO - LNG switch from day 1 (notation "1")

        fuel_consumption_factor=ones(1,total_time)+(fuel_increase)*ones(1,total_time);
        CAP_new=CAP.*ones(1,total_time)-(contanier_tank_displ.*ones(1,total_time));

        cash_flow_in_switch1=CF_in_options(0,T_life, T_build, market_scenario, fuel_scenario_min, speed_scenario, CAP_new, lambda, ...
              gamma, newbuild_price1, ir, OPEX_nonfuel_yearly,fuel_consumption_factor);

        % "on" options analysis is performed first
        install_year=2;
        CF_in_tot1=CF_on_option_after_in(install_year,cash_flow_in_switch1, T_build, total_time,threshold1);

        %NPV calculations
        NPV_log1(1,j)=NPV(CF_in_tot1,dr,total_time);



%% HFO - LNG option to switch later by retrofit (notation "2")

        fuel_scenario_HFO=fuel_scenario1; % matrix for storing values

        % First "On" option valuation cash flow
        CF_stochastic1=CF(T_life, T_build, market_scenario, fuel_scenario_HFO, speed_scenario, CAP, lambda, gamma, newbuild_price1, ...
              ir, OPEX_nonfuel_yearly);
        CF_on=CF_on_option(CF_stochastic1, T_build, total_time,threshold2);


        % First "On" option valuation cash flow
        fuel_diff_factor_switch=0.20;     % switch when the  (HFO-LNG)/HFO > is this
        price_fraction=0.05;     % price of the retrofit

        switch_vector=zeros(1,total_time);
        CAP_vector=CAP.*ones(1,total_time);

        fuel_difference=(fuel_scenario1-fuel_scenario2)./fuel_scenario1; % relative difference (HFO - LNG)
        retrofit_year=retrofit_option_year(fuel_difference, T_build, total_time,fuel_diff_factor_switch);

        cash_flow_in_switch2=CF_on;
        fuel_switch_vector=zeros(1,total_time);

        %% if switch
        if retrofit_year>0
            count_retrofit=count_retrofit+1;
                for m=retrofit_year:total_time
                    fuel_switch_vector(m)=1;
                end

            fuel_scenario_after_switch=fuel_scenario_HFO;
            for i=retrofit_year:total_time
            fuel_scenario_after_switch(i)=min(fuel_scenario1(i),fuel_scenario2(i));
            end

            fuel_consumption_factor_retrofit=ones(1,total_time)+(fuel_increase)*fuel_switch_vector;
            CAP_new_retrofit=CAP_vector-contanier_tank_displ.*fuel_switch_vector;

            cash_flow_in_switch2=CF_in_options(price_fraction,T_life, T_build, market_scenario, fuel_scenario_after_switch, ...
                  speed_scenario, CAP_new_retrofit, lambda, gamma, newbuild_price2, ir, ...
                  OPEX_nonfuel_yearly,fuel_consumption_factor_retrofit);
        end
        %% if switch finished

        CF_in_tot2=CF_on_option_after_in(retrofit_year,cash_flow_in_switch2, T_build, total_time,threshold2);

        % NPV calculations
        NPV_log1(2,j)=NPV(CF_in_tot2,dr,total_time);


end

%% Performance calculations

% Flexibility from year 1
NPV_mean_in_option1=mean(NPV_log1(1,:))
```

```
ten_percentile1 = prctile(NPV_log1(1,:),10)
ninety_percentile1=prctile(NPV_log1(1,:),90)

% Option to retrofit later
NPV_mean_in_option2=mean(NPV_log1(2,:))
exspansion_fraction2=count_retrofit/nSim
ten_percentile2 = prctile(NPV_log1(2,:),10)
ninety_percentile2=prctile(NPV_log1(2,:),90)
```