Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

Matias Bøe Olsen

Designing a Value Robust Shuttle Tanker to Handle Environmental and Technical Uncertainty

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2020

NTNU
Norwegian University of
Science and Technology

Matias Bøe Olsen

Designing a Value Robust Shuttle Tanker to Handle Environmental and Technical Uncertainty

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
June 2020

Norwegian University of Science and Technology
Faculty of Engineering
Department of Marine Technology

NTNU
Norwegian University of
Science and Technology

Master Thesis in Marine Systems Design

Stud. techn. Matias Bøe Olsen

"Designing a Value Robust Shuttle Tanker to Handle Environmental and Technical Uncertainty"

Spring 2020

Background

In 2022 the opening of Johan Castberg field will begin a new era for the production of oil on the Norwegian Continental Shelf. A decision in late 2019 concluded that shuttle tankers would supply the Floating Production, Storage and Offloading (FPSO) unit in the Barents Sea. At the same time, new regulations will affect the conceptual ship design of the shuttle tanker supplying the offshore installations. Notably, the visions established by the International Maritime Organisation (IMO), of 40% and 70% reduction of GHG within 2030 and 2050 are relevant factors for developing a ship design concerning in shifting environments. The shipping industry has been modest in adopting technologies that have an economically demanding profile. However, the trend is clear, and the willingness to embrace new technologies are increasing globally along with the ratifying of regulations. It is difficult to predict the future outcomes of any regulations and the uncertainty related to these future outcomes. Which leads to the main objective.

Overall aim and focus

The overall aim of the master thesis is to establish a value robust shuttle tanker design solution for the Norwegian Continental shelf to meet regulations towards IMO 2030 and 2050 ambitions.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Provide an overview of technology possibilities and identify the most promising technologies as fuel providers for a shuttle tanker supplying Johan Castberg in a 2030 and 2050 perspective.*

2. *Present the relation between power, ship size and speed. Then investigate how it affects the infrastructure for new fuel providers.*

3. *Identify how traditional and modern ship design theory can be used to cope with uncertainty in future market environments. Then apply strategy methods to establish a market outlook for value creation related to a shuttle tanker operating in the North Sea.*

4. *Develop a 2050 shuttle tanker design solution for a case study for transporting crude oil from Johan Castberg, using the Responsive Systems Comparison Method (Epoch – Era methodology) addressing uncertainty and complexity aspects in conceptual ship design.*

5. *Discuss and conclude*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor.

The work shall follow the guidelines given by NTNU for the MSc Project work

Stein Ove Erikstad
Professor/Responsible Advisor

Summary

This master thesis investigates how marine system design can be used to create value robustness across changing context and future uncertainties for a shuttle tanker. Additionally, this thesis focus on how new environmental regulations affect ship design and how such methods can create value as new rules are implemented. These zero-emission regulations have the objective to reduce greenhouse gases (GHG) and local emissions (NO_x, SO_x). A shuttle tanker supplying the Johan Castberg oil field in the Barents sea is used as a case for evaluating value robustness across uncertain environments. The structure of this thesis is divided into three parts, technology, infrastructure and the responsive system comparison method (RSC).

The technological aspect of providing emission-reducing solutions is the foundation for any future designs operating in the Norwegian Continental Shelf. The technologies that will be sufficient in the future can be summed into two categories, 2030 compliant and 2050 compliant. Within 2030 the global GHG reduction is supposed to be at least 40 %, compared with 2008 levels. This goal can be achieved through any measures that provide a reduction. Nevertheless, shifting to LNG as fuel with one additional 10% reducing equipment (Flettner rotor, battery pack or engine optimisations) is seen as the best option. LNG reduces approximately 20 % GHG from reference levels. Thus, the reason for LNG only needs one extra equipment due to volatile organic compounds (VOC) reducing systems providing an approximate 10 % reduction already. ULSFO or similar diesel fuels can also provide feasible 2030 designs, but extensive usage of extra emission-reducing equipment is expected. In 2050 70 % reduction is visioned meaning that a zero-emission fuel has to be developed already within the next 10-15 years. The options concluded in this thesis as the most feasible are ammonia (NH_3) for deep-sea shipping and liquefied hydrogen (H_2) for short sea shipping.

Introducing hydrogen-based fuels results in one main barrier that has to be solved; infrastructure. The extensive infrastructure needed to supply shuttle tankers and other segments in the maritime sector is challenging. This paper purposes a methodology to optimise the path for vessels travelling along the Norwegian coastline, with a primary focus on locations that could benefit the shuttle tanker market. Furthermore, the relations between ship size and speed is essential for understanding the amount of hydrogen-based fuel that is needed for sailing any distance. This analysis indicates the difference between ammonia and hydrogen, where range challenges with the latter are pointed out.

The central part of this thesis is the methodology used for developing a value robust design for supplying Johan Castberg. The RSC method is originally consisting of seven steps, but is in this paper simplified into three phases; Phase 1 - Case Description & Market Analysis, Phase 2 - Epoch - Era and Phase 3 - Results & Post Processing. The phases are meant to adapt the RSC to a typical structure of theory, method, results.

Phase 1 uses the background theory to understand stakeholders preferences and dynamics in the shuttle tanker market. The theory research establishes some essential knowledge. Firstly it shows how to understand uncertainty and that ”uncertainty causes risk/opportunities handled by mitigation/exploitation resulting in outcomes”. Furthermore, shipping markets is seen as cyclical, and that value has to be created across a shifting environment. Additionally, what value is and how different design methods can be used to satisfy stakeholders needs are examined. RSC is used as an example of a set-based design methodology, which means that a large tradespace is evaluated.

A tradespace consists of a large number of designs where the goal is to find one or a few exceptionally high performing designs. The evaluated tradespace is created through the Epoch-Era methodology (phase 2). An epoch is a specific context where variables are constant over some time, while an era consists of several epochs creating a shifting environment. The tradespace is evaluated by combining a design space (endogenous variables) and an epoch space (exogenous variables).

Phase 3 is providing the results and the post-processing of the findings. Multi-Attribute Utility (MAU) is used to capture what is perceived as value for stakeholders across eras. At the same time, the break-even freight rates and cost of investment is the primary measure of outcome. For bringing together MAU and cost, results are presented through the Pareto front. Designs that are aligned to the Pareto front provides the best value for the lowest cost, and such analysis can be given for each epoch. Thus, the preferred designs will hopefully be found in Pareto fronts across changing contexts (epochs).

The results found in phase 3 indicates that small vessel designs of approximately 625 000 bbl are the most valued in the case of supplying Johan Castberg from 2022. Ammonia or LNG machinery systems is favourable, but the difference between them is marginal. LNG is preferred when more conservative decision criteria analysis is conducted. At the same time, ammonia is seen as more opportunistic and providing a higher risk profile. Furthermore, the results also reveal the possibilities of having a larger vessel (980 000 bbl). In that case, LNG performs significantly better than the other options, mainly due to the risk of increasing fuel prices. Nevertheless, a larger vessel, in that case, will reduce total utility compared to the smaller vessels.

Separately from the case study of Johan Castberg, a single era analysis is also conducted for a perspective of 2050. It was resulting in ammonia becoming the best alternative. However, in this scenario, the vessel size was suggested to be around 800 000 bbl, due to higher constant production levels in the Barents Sea.

This thesis concludes that ammonia already from 2030 can become the preferred machinery system. The sooner zero-emission solutions, the better it is for the global community. Likewise, finding ammonia as both financial and environmental feasible solution is essential information for shipowners desiring to be at the forefront of reducing emissions and establishing corporate responsibility. For more risk-averse decision-makers LNG is the option that can provide the most value robustness in the nearest future. Nonetheless, LNG will not be sufficient in a 2050 regulation perspective.

Sammendrag

Denne master oppgaven undersøker hvordan marin prosjektering kan bli brukt for å skape verdi-robusthet gjennom endring i fremtidig usikkerhet for en bøyelaster. I tillegg har denne masteren et fokus på hvordan prosjektering av skip er påvirket av nye miljøvennlige krav og hvordan man kan håndtere endringer forårsaket av det, men samtidig fremme verdiskaping. Disse null-utslippsregelverk har som hovedformål å redusere klimagasser, både globale (drivhusgasser, GHG) og lokale utslipp (som NO_x, SO_x). En bøyelaster som skal forsyne Johan Castberg feltet i Barentshavet er brukt som case for å evaluere verdi-robusthet over en usikker fremtid. Strukturen på denne maseteren er tredelt, hendholdvis i, teknologi, infrastruktur og Responsive systems comparison method (RSC).

Det teknologiske aspektet i skipsdesign er selve kjernen for å redusere utslipp i fremtiden på norsk sokkel. Man kan dele teknologiene inn i to kategorier, 2030 kompatibel og 2050 kompatibel. Innen 2030 er IMO-ambisjonene å redusere GHG med 40 % sammenlignet med 2008 nivå og det er mange muligheter for å nå disse målene. Her presiseres at LNG med en ekstra utstyrs reduksjon på 10 % er den beste muligheten. LNG har en redusering på ca 20 % og grunnen til at bare en ekstra reduksjon med 10 % er nødvendig har med at alle bøyelastere har et VOC reduserende system allerede, som reduserer utslippene med allerede minimum 10 %. ULSFO er en annen mulighet som representativ for dieselbaserte drivstoff, men her trengs det ekstra utstyr som kan substituere den reduksjonen LNG har. I 2050 er 70 % reduksjon målet og dette betyr at allerede innen 2030 må nybygg tenke på å ha tilstrekkelig reduksjon på plass. I denne masteren er den mest gjennomførbare nullutslipps muligheten ammoniakk(NH_3) for langdistanse shipping og flytende hydrogen for kortdistanse shipping.

Ved å introdusere hydrogenbaserte drivstoff en spesiell barriere dukker opp, nemlig infrastruktur. Det er et ganske omfattende infrastruktur som vil trenges for å forsyne bøyelastere samt andre maritime segmenter. Dette er utfordrende aspekter, men denne masteren forslår noen metoder for å optimalisere strekningen langs den norske kysten. Videre så er relasjonen mellom skipets størrelse og fart illustrert for å fremstille den svært viktige relasjonen mellom hvor mye drivstoff man trenger for en gitt distanse. Disse analysene viser forskjellen på ammoniakk og hydrogen, hvor dette med rekkevidde gjør at sistnevnte blir mindre attraktiv for bøyelastere.

Hoveddelen av denne masteren går på metoden som er brukt for å utvikle verdi-robuste skipsdesign for forsyning av Johan Castberg. RSC metoden heter den og består hovedsakelig av syv steg, men i denne teksten så er disse stegene simplifisert til tre faser. Fase 1 handler om case-beskrivelse og markeds analyse. Fase 2 benytter Epoch-Era metode, og til slutt fase 3 handler om resultater og post-evaluering. De tre fasene er ment til å skulle representere RSC metoden i en mer typisk oppgavestruktur med teori, metode og resultater.

Fase 1 bruker teori som bakgrunnsinformasjon til å forstå hva maritime interessenter verdsetter og dynamikken i bøyelastmarkedet. Ut i fra dypdykket i teorien er det en del essensiell kunnskap som kommer frem. Først og fremst vises hvordan man kan forså usikkerhet og at ”usikkerhet leder til risiko/muligheter som er enten minsket/utnyttet som igjen resulter til ønsket utfall.”. Videre viser teorien at shippingmarkeder er sykliske og at verdiskapning må skje selv om miljøforandringer i markedet er unngåelig. I tillegg legger teoridelen vekt på hva verdi og verdiskapning er og hvilke design metoder som kan bli brukt for å tilfredsstille interessenters behov. RSC er brukt som et eksempel på Set-Based design metode, som betyr at et større ”tradespace” er evaluert.

Et tradespace består av et større nummer med skipsdesign hvor hovedmålet er å finne ett eller noen få spesielt høyt-presterende design. Evalueringen i tradespace er gjort gjennom det som heter Epoch-Era metode. En epoch(epoke) er en kontekst der variabler er konstante over en tidsperiode, mens en era(æra) består av flere epoker slått sammen som dermed skaper et skiftende miljø over en lengre tidsperiode. En tradespace-evaluering blir gjort med å kombinere et design-space (endogene variabler) og epoke-space (eksogene variabler).

Resultatene er gitt i fase 3. Multi-attributt nytte (MAU) er brukt til å beskrive oppfattet nytteverdi for interessenter over forskjellige æra. Samtidig så er break even fraktrater og kostnader relatert til investeringer og operasjoner et viktig mål for utfall. For å slå sammen MAU og kostnader, er resultatene presentert i det som kalles en paretofront. Design som ligger på paretofronten vil gi best nytte per investert penge og slike analyser er gjort for hver epoke i denne masteren . Derfor vil ønsket design forhåpentligvis ligge innenfor paretofronten for flere skiftende kontekster (epoker).

Resultatene som er funnet i fase 3 indikerer at ett mindre fartøy med ca 625 000 bbl gir høyest nytteverdi i case-studiet for å forsyne Johan Castberg fra 2022. Ammoniakk og LNG maskinerisystemer er mest verdsatt, men differansen mellom dem er marginal. LNG blir foretrukket hvis mer konservative beslutningskriterier er brukt, mens ammoniakk er foretrukket hvis beslutningstakeren er sett på som opportunistisk eller er villig til å ta noe høyere risiko. Videre så gir resultatene også indikasjoner på at ett større skip kan bli valgt, men da er det bare LNG som presterer med gode nok resultater. Men et større skip vil minske nytteverdien noe. Separat fra case-studiet om Johan Castberg, er et 2050 scenario gjennomført. I dette tilfellet er det høyere konstant produksjonsnivå som gjelder for Barentshavet som region. Resultatene forslår en noe større båt på 800 000 bbl, hvor ammoniakk blir det klart beste alternativet.

Denne masteren konkluderer med at ammoniakk allerede fra 2030 kan være en foretrukket løsning for maritim propulsjon. Nullutslippsløsninger er ønsket raskest mulig og det at ammoniakk både er gjennomførbart med tanke på miljø og økonomiske aspekter er viktig informasjon for redere og andre interessenter hvis de ønsker å ta del i utviklingen mot et nullutslipp-samfunn. For mer risikoavers beslutningstakere er LNG det mest verdirobuste valget i den nærmeste fremtiden, selv om LNG ikke vil bli tilstrekkelig i et 2050 reglement-scenario.

Preface

This thesis is the final cheaper of my five year Master of Science degree in Marine Technology with specialisation in Marine System Design at Norwegian University of Science and Technology, Trondheim. The workload is equivalent to 30 ECTS.

Writing this thesis during the spring of 2020 have provided much reflection on this project topics. On one side, the global maritime industry has been struck by the reduction in demand caused by the coronavirus. At the same time, oil prices fluctuated enormously, causing markets to show how highly volatile things can be. putting it in perspective, value robustness in ship design to deal with the uncertain environment feel even more relevant in June than when I started this work in January 2020.

On the other side, 2020 will mark as a year where the maritime community changed. Regulations like the IMO 2020 sulphur Cap is the first significant change to this conservative industry. I do believe that the knowledge and groundwork in this thesis will be beneficial for anyone who will be a part of the transformation towards zero-emission in the maritime industry.

I want to thank my supervisor Stein Ove Erikstad for providing motivational and encouraging dialogues in these strange quarantine times. I also want to acknowledge my classmates for supporting friendships during five years in Trondheim.

In the end, I want to dedicate this thesis to my parents, who have supported me throughout my studies. Following your footsteps have been much fun. Thank you!

Trondheim, 9 June, 2020.

Matias Bøe Olsen

Matias Bøe Olsen

Contents

List of Tables

List of Figures

Abbreviations

Aframax = Average Freight Rate Assessment Max
BP = Battery Pack
CAPEX = Capital Expenditure
CAPM = Capital Asset Pricing Model
CPV = Customers Perceived Value
CSR = Corporate Social Responsibility
DP = Dynamic Positioning System
ECA = Emission Control Areas
EGR = Exhaust Gas Recirculation
EEDI = Energy Efficiency Design Index
EO = Engine Option
FOC = Flag of Convenience
FR = Flettner Rotor
GHG = Green House Gases
HFO = Heavy Fuel Oil
HT-PEMFC = High-temperature proton-exchange membrane fuel cell
IMO = International Maritime Organisation
JC = Johan Castberg
JTBD = Jobs-to-be-done
LASH = Lighter Aboard Ship
LCC = Life Cycle Cost
LNG = Liquefied Natural Gas
LPG = Liquefied Petroleum Gas
MARPOL = The International Convention for the Prevention of Pollution from Ships
MGO = Marine Gas Oil
OPEX = Operational Expenditure
P & I = Protection & Indemnity
PEMFC = Proton-exchange membrane fuel cell
PEST = Political, Economic, Social, Technical
RSC = Responsive Systems Comparison Method
SCR = Selective Catalytic Reduction System
SECA = Sulphur Emission Control Areas
SOFC = Solid-oxide fuel cell
SOLAS = International Convention for the Safety of Life at Sea
SWOT = Strength, Weakness, Opportunity, Threat
TC = Time Charter
UIP = Uncovered Interest Parity
ULSFO = Ultra Low Sulphur Fuel Oil
VOC = Volatile Organic Compounds
WACC = Weighted Average Cost of Capital
WoW = Waiting on Weather

Chapter 1

Introduction

1.1 Background

In 2022 the opening of Johan Castberg field will begin a new era for the production of oil on the Norwegian Continental Shelf. A decision in late 2019 concluded that shuttle tankers would supply the Floating Production, Storage and Offloading (FPSO) unit in the Barents Sea. At the same time, new regulations will affect the conceptual ship design of the shuttle tanker supplying the offshore installations. Especially the visions established by the International Maritime Organisation (IMO), of 40 % and 70 % reduction of GHG within 2030 and 2050 respectively are relevant factors for developing a ship design that can do its job in changing environments.

Ship design is a challenging process due to its complex relations. Therefore, traditional ship design is often used earlier designs as a baseline for modern designs. Since a ship is a costly product, the shipping industry has been modest in adopting technologies that have an economically demanding profile. However, the trend is clear, and the willingness to embrace new technologies are increasing globally along with the ratifying of regulations. It is difficult to predict the future outcomes of any regulations because it creates several aspects of uncertainty. Likewise, this uncertainty is critical to understand, and the main objective of this thesis is to investigate how to create value across uncertain environments.

To design a value robust shuttle tanker for a future environment, three categories of the theory are essential to understand within the conceptual form. The first is the design theories, which type of methodologies can be used to establish a design. Second, which technologies are available and how can a designer include new technologies into the vessel. Thirdly, how can a ship design create value? In this master thesis, these three categories are approached and introduced individually. However, to see the whole picture in ship design, these three factors have to be merged, and the essential question in this thesis appears.

- *How can new zero-emission technologies create value robustness in ship design?*

The answer to that question is complex and have interrelated aspects. Figure 1.1 is mapping each topic covered in this thesis. The intention is to gather all relevant knowledge and information necessary for understanding how to create value in ship design while handling with uncertainties. The figure is divided into levels of detail that are illustrating the in-depth of the paper. Level I is representing a macro level, where it is essential to understand the greater picture. Level III and IV relate to more involved relations and details. The latter level, with The Responsive Systems Comparison (RSC) method, is meant to encapsulate the challenges of value robust ship design.

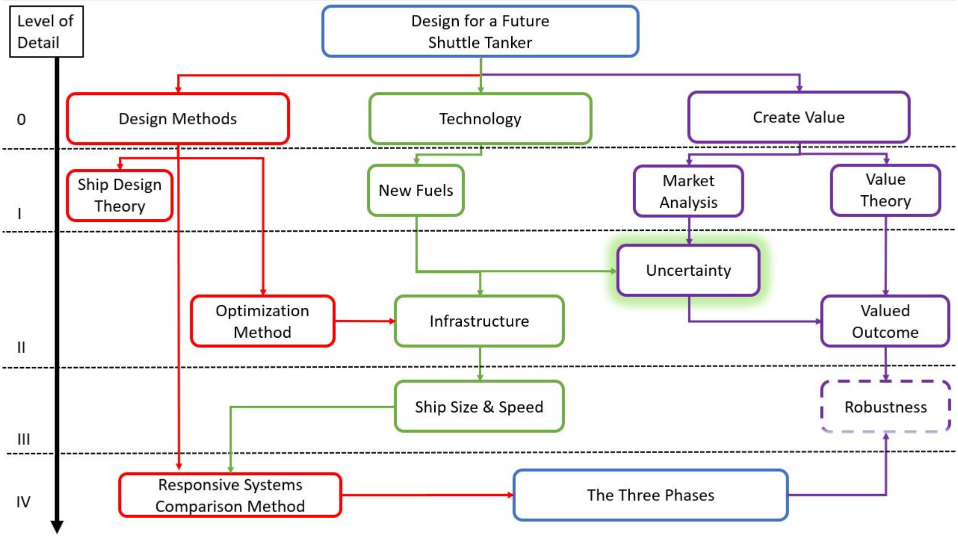


Figure 1.1: Mapping of the Three Aspects of Future Ship Design

The Responsive Systems Comparison (RSC) method is an example of a set-based design methodology. The primary purpose is to create a large tradespace, including many relations and different complexities related to ship design. Then find a few designs that perform well over different context and temporal changes. The evaluation of tradespace is done for the conceptual case of supplying Johan Castberg with a shuttle tanker that meets future requirements. Another two central research question arises.

1. *What type of ship design gives the most value in supplying Johan Castberg from 2022 and into the future?*

2. *In a 2050 perspective which technologies and ship designs can supply oil fields in the Barents Sea in a value robust way?*

1.2 Structure of the Report

Finding answers to these questions of creating value robustness in ship design is complicated, and the structure of this report will try to provide a methodology that can be used for further work on these topics. The RSC method is a great tool, but it is not intentionally meant for ship design. Therefore, this thesis introduces three phases that simplify the RSC to a more traditional research approach of method and results. The three phases are;

1. Case description and market analyses.
2. Tradespace development consisting of design space and epoch space
3. Results and Post-Processing

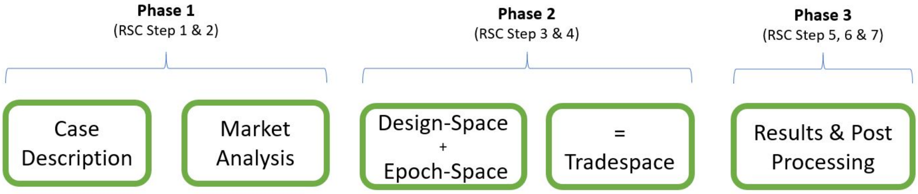


Figure 1.2: Three phases: RSC Applied to Ship Design

The further structure of the thesis is given in six main chapters presented in this section. Where the first three chapters are separate related information, while the three last chapters about the three phases provide the methodology of encapsulating the chapters.

Chapter 2 provides the main relevant literature used later in the thesis.

Chapter 3 introduces the most relevant technologies that can provide a zero-emission profile for the shuttle tanker.

Chapter 4 provides essential information for understanding the hydrogen-based fuels and their properties constraints and opportunities. The chapter goes into detail when the amount of mass required is further investigated.

Chapter 5 provides the most theory. This chapter provides information that is relevant for any ship designer that want to design value robust designs across uncertainty. This chapter introduces concepts that are necessary to understand for realising why we do the analysis we do. If the reader wants to understand the basics behind value robust ship design, a deep dive into this chapter is highly recommended.

Chapter 6 provides a market analysis of the North Sea shuttle tanker market and introduces the case about supplying Johan Castberg. It is based on the knowledge from the previous chapter.

Chapter 7 uses the main parts of the tradespace evaluation presented from the RSC methodology.

Chapter 8 examines the results from the running of the model made from the previous two phases.

Finally, if the reader wants to explore this thesis without in-depth reading, the green boxes provide the fundamental knowledge and information supporting the main objectives.

Chapter 2

Literature Review

In this chapter, the most relevant references are described as how they are used in this thesis. The topics presented here will be further addressed in detail in the chapters following. The most theory-based material in this thesis are given in Chapter 3, Chapter 4 and Chapter 5.

For evaluating fuel configurations relevant for maritime usage today, and in the future, information has been gathered from the industry and relevant companies. The work done by DNV-GL on several aspects of the industry has especially been valuable. The free access website Alternative Fuel Insight, AFI (by (DNV-GL, 2020)) have provided an overview of each fuel and been particularly important in deciding which fuel configurations that are best regarding regulations and emission. Furthermore, the maritime forecast to 2050 (DNV-GL, 2019a) was studied to understand the future outlook as experienced by the maritime industry. The pre-thesis project (Olsen, 2019) was used to make conclusions on which fuel alternatives that were further examined. In the pre-thesis, information was gathered from correspondence with market actors like Equinor, Norsepower, Yara and Stena. Likewise, shuttle tankers were observed through the Marine Traffic website.

In the Chapter 4 about infrastructure the school textbook by (Woud and Stapersma, 2017) is used to describe the relationship between ship size, speed and required power. The book is relevant for understanding why the amount of mass used for fuel will depend on the dimensions of the vessel. Optimisation theory and Dijkstra's algorithm is used as presented in the textbook by (Lundgren et al., 2010). The objective of Dijkstra's algorithm is to calculate the shortest path between relevant potential ports along the coastline of Norway.

There are two branches of the relevant theory presented in Chapter 5, how to understand value under uncertainty and ship design theory: The fundamental for understanding uncertainty is the work by (Mcmanus and Hastings, 2005), where they provide a detailed decomposition of the four categories in their framework. They summaries their findings concerning uncertainty as this: ”Uncertainty leads to risks or opportunities, which are handled technically by mitigations or exploitations, which hopefully lead to desired outcomes.”. Furthermore, they define some relevant terms in their paper, e.g. Robustness, which becomes extraordinarily essential for this project.

Identifying value as a measure of performance in an environment that is changing along with uncertainties becomes important for ship design. (Anderson and Narus, 2017) describes value within business markets. A product has to be better than the next best alternative to create value. (Christensen et al., 2016) puts value in a more simplistic view. According to him, value has to be based on the concept of Jobs-to-be-done (JTBD). In a shipping related example, a shuttle tanker has to transfer crude oil, and that is the sole purpose. New innovations to the vessel (like technological improvements) cannot decrease customer experience.

For identifying value within markets macro analysis theories like value chain analysis and PEST analysis (Political, Economic, Social, Technological) is described. For more semi-micro and micro-level analysis, porter five forces and SWOT analysis is used. The textbook by (Hollensen, 2012) has been relevant for describing all these methods.

Ship design theories are included to outline the different methods used in developing vessel as a product that can create value under uncertainty. The illustration of ship design as an iterating process is provided by (Evans, 1959). Evans design spiral can be seen as a point-based design. (Levander, 2012), expands ship theory towards what is called system-based design, where the mission of needs is included as a baseline for further detailed work on the ship design. System based designs use the ”design catalogue” as a toolbox for the further detailed aspects of ship design. Design catalogue is a method described by (Pahl et al., 1977). Set-based design, as described by (Singer et al., 2009) is the procedure of expanding the first stages of ship design to explore a larger tradespace.

Utility theory is one instrument to measure value. In this thesis, multi-attribute utility (MAU) theory is used to capture the different preferences and tradeoffs between stakeholders. (Keeney and Raiffa, 1993) is the main contributor to MAU, and provides some conditions to systematise the objectives identified.

(Stopford, 2009) a book about maritime economics is used to describe the shipping markets behave in a cyclical matter. The dynamics of the shipping industry is vital to understand, so that, value robust designs created can perform over the lifetime despite switching cyclical contexts.

Now it is understandable that ship design is intricate and all the described theories can be seen as a brick in the process of designing value robust design under environmental and technological uncertainties. The responsive comparison (RSC) method created by (Ross et al., 2009) is used as a benchmark to capture all these aspects of ship design. RSC method is an example of a set-based design where a large tradespace based on needs and value identification is evaluated. RSC includes seven steps in general, but the relevance depends on the design objectives. (Gaspar et al., 2012) have adapted the RSC method to align with ship design and what he describes as the five aspects of complexity in ship design. Both Ross and Rhodes RSC framework and Gaspar appliance to ship design is used to create the three phases simplifying their model to fit the theory-method-results analogy.

The RSC method by (Ross et al., 2009) are the foundation for the simplified three phases introduced in this thesis. The three phases are an attempt to interconnect between understanding how to create value robustness under uncertain conditions and future ship design.

Chapter 3

Technologies Available for Zero-Emission Shuttle Tankers

”Regulators! Mount up!”

- Warren G, *Regulate*

3.1 Zero Emission & Regulations

The term zero-emission expresses the complete abandonment of hazardous emission. The term can be divided into Green House Gases (GHG) and local emissions such as SO_x, NO_x and Particular Matters (PM). In the transition towards 2050, a large portion of the world merchant fleet needs to be fuelled by zero-emission fuels. GHG should be reduced significantly for reaching the Paris Agreement (2015) and IMO visions for 2050. At the same time regulations worldwide and in regional Emission control zones (ECAs) local emissions are required to be emitted at a minimum Figure 3.1.

Figure 3.1: ECA Zones

As of 1. January 2020 the IMO sulphur cap, introducing a 0.5 % sulphur limit within the fuel, is the first significant regulation that affects the whole maritime industry. In the timeline shown in Figure 3.2, the future regulations already planned are shown. For this paper, a short description of each regulation is given in this section. They are presented as in the pre-thesis (Olsen, 2019).

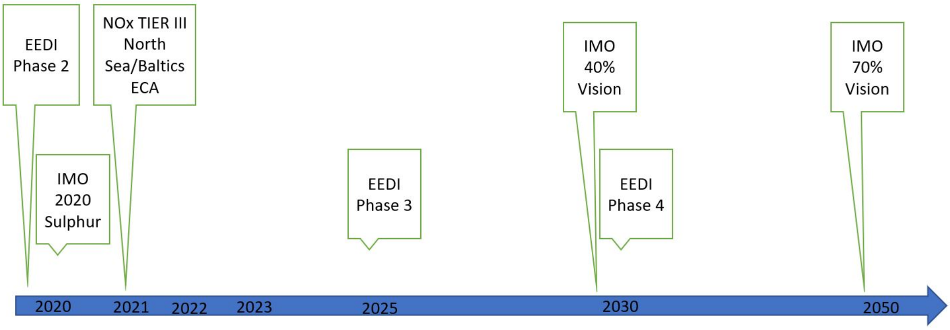


Figure 3.2: Regulation Timeline

ECA-Zones

Emission Control Areas (ECA) are stricter control zones that are established to minimise emissions from vessels, as defined in MARPOL. There are four existing ECA-Zones: The Baltics, North Sea, North American ECA and US Caribbean ECA. Since 2015 these zones include the SECA (Sulphur Emission Control Area) which does not allow a sulphur content in the fuel higher than 0.1 %. There are indications of future possible ECA zones within the Mediterranean, Japanese, Singaporean, Australian and Chinese waters. Besides, the extensions of the North Sea and American zones are also in progress (Figure 3.1).

IMO 2020 - Sulphur Cap

Sulphur oxides are harmful to human health and productivity. In the atmosphere, sulphur oxides cause acid rain, that is devastating to crops, forest and oceans. For these reasons, IMO have had regulation on sulphur content in existing fuels for a long time. However, the pre-2020 global limit of 3.50 % m/m (mass by mass), have not been efficient in handling the problem. IMO are therefore implementing regulation of sulphur content to 0.5 % on fuel after 1. January 2020 in all global waters. The sulphur cap is a game-changer for the industry since heavy fuel oil (HFO) cannot be traditionally consumed anymore.

NO_X Tier III

Ships that are keel-laid after 1. January 2016 and operating in North American ECA zones are obliged to Tier III emission regulations, which mean that they need to emit 80 % fewer nitrogen oxides than Tier I compliant engines. This will also apply to the North Sea and Baltic waters for ships keel laid after 1. Jan 2021 (DNV-GL, 2017a).

EEDI Requirements

Energy Efficiency Design Index (EEDI) is a technical measure aimed to promote usage of more energy-efficient equipment and engines and consequently reduce emissions. The EEDI is calculated from a reference line for each vessel type segment. From these baselines, reduction in emissions will be reduced in phases of 5 years. The first phase was implemented in 2015 and ran until the end of 2019. In the first phase, a reduction of 10 % to the baseline was implemented. In the second phase, a new reduction will happen, indicated to be a reduction of 20 % (IMO, 2019b). EEDI requirements are only applied to new vessels.

EEDI is the first vision out of the ”Initial IMO strategy on reduction on GHG emission from ships” (IMO, 2019b). The other two visions include to ”reduce CO_2 emissions by 40 % by 2030 and 70 % by 2050 compared to 2008 levels” and ”to peak GHG emissions as soon as possible” (Figure 3.3).

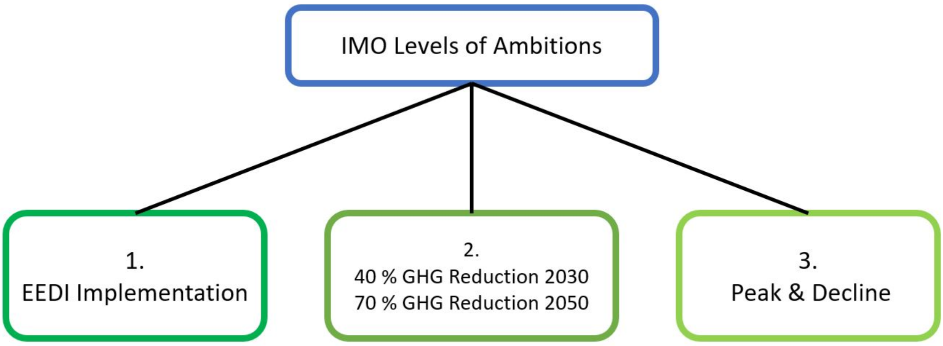


Figure 3.3: IMO Goals

EEDI requirements are the most ambitious mitigating actions for maritime emission regulations. The yes-voting countries represent about 75% of global carbon dioxide emissions from international shipping. On the other side, five eligible parties, China, Brazil, Saudi Arabia, Chile and Kuwait voted no. The two former countries are huge maritime actors, and their absence will be noticed (IMO, 2019a).

3.2 The Promising Technologies

In the project study of (Olsen, 2019) all possible alternative fuels spoken of in the market were analysed regarding their environmental profile, technological feasibility and economical impact. HFO was used as a reference fuel for evaluating other fuel types. Table 3.1 summarises the investigation from the pre-thesis.

Table 3.1: Overview of Fuel Compliance with Regulations. (Olsen, 2019)

	IMO 2020	ECA Zones	NOx Tier III	EEDI 2015	EEDI 2020	EEDI 2025	IMO 2030	IMO 2050
HFO	No	No	Partial	No	No	No	No	No
MGO	Partial	No	Partial	No	No	No	No	No
ULSFO	Yes	Yes	Partial	No	No	No	No	No
Scrubber	Yes	Yes	Partial	No	No	No	No	No
LNG	Yes	Yes	Partial	Yes	Partial	Partial	Partial	No
LPG	Yes	Yes	Yes	Yes	Partial	Partial	Partial	No
Battery	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hydrogen	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ammonia	Yes	Yes	Partial	Yes	Yes	Yes	Yes	Yes
Methanol	Yes	Yes	Partial	Partial	No	No	No	No
Biofuels	Yes	Yes	Partial	Yes	Yes	Yes	Yes	Yes

In conclusion, the zero-emission fuel alternatives are hydrogen, ammonia and biofuels. Furthermore, wind as propulsion and battery solutions can provide a zero-emission solution to any ship design. Biofuels is unfortunately extremely dependent on the origin of production, meaning that it has to be produced from waste that already has been in circulation. There will not be enough biofuel to supplying the maritime industry without creating more waste (cutting wood, rainforest, etc.). Hence, biofuels are seen as a step in the wrong direction, and it is excluded in further investigation. Other fuel possibilities like LNG, LPG, methanol, MGO and ULSFO can be seen as transition fuels for the shipping industry since they will be 2030 compliant, but not 2050 compliant. Figure 3.4 have plots the relation between volumetric and gravimetric densities of different fuel types. This figure is vital for understanding the difficulties in changing from diesel-based fuels since they provide the most mass per volume.

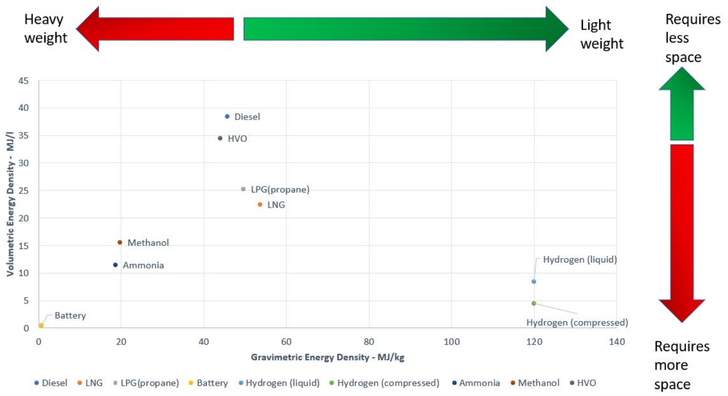


Figure 3.4: Density Map for the Most Important Fuels

In the next section, a detailed evaluation of each zero-emission alternative is presented as done in pre-thesis (Olsen, 2019). Nuclear power solutions were not assessed in the pre-thesis, and hence it is presented at the end of this section.

The Promising Fuel Technologies are: **Ammonia & Hydrogen**
Supplementing Propulsion Technologies are: **Battery & Wind**

3.2.1 Ammonia

Ammonia is a promising fuel due to its energy properties and environmental impact. Despite this, ammonia is in 2020 not used in any marine fuel applications, and at the moment there are no engines that can burn ammonia. Anyhow, things are changing. The industry has given signals of development of ammonia compliant engines. The PSV Viking Energy will be the first zero-emission offshore vessel by using ”green” ammonia (Skipsrevyen.no, 2020).

Today, ammonia is produced through the Haber-Bosch process, and the chemical formula for the process can be seen in (Equation 3.1). Nitrogen (N_2) is an abundant resource found in the air. Hydrogen can be produced from both natural gas, hydrocarbons, but most interesting produced from renewable sources using electrolysis (see section 4.1).

$$3H_2 + N_2 \rightleftharpoons 2NH_3 \tag{3.1}$$

Ammonia is carbon and sulphur free. CO_2 and SO_x will, therefore, not be emitted. Furthermore, PM can be assumed not to be emitted as well (Niels de Vries, 2019). There will be NO_x emission due to the nitrogen content in NH_3. However, it is difficult to measure the size of emission compared to reference fuels. Anyhow, it is reasonable to say that compliance options (SCR or EGR) have to be applied in order to meet Tier III regulations.

The historical price range of ammonia can be seen in Figure 3.5. As seen, the price is stable at around 300 USD/(tonne NO_x). It is lower than the normal over the last decade. The price is profoundly affected by the price of natural gas due to its production from it.

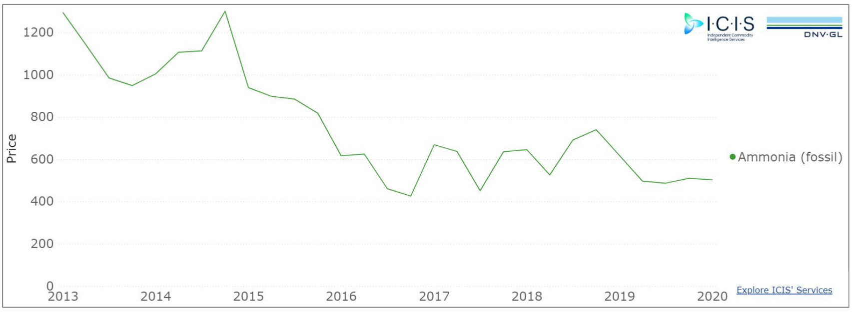


Figure 3.5: Historical Ammonia Prices. Screenshot from (DNV-GL, 2020)

3.2.2 Hydrogen

Hydrogen can be stored for marine applications, in two ways; compressed and liquid. Liquefied hydrogen (LH_2) needs to be stored at $-252.87\,°C$ to avoid vaporising. This results in some difficulties. Firstly, the hydrogen will start to boil at higher temperatures. Secondly, energy is needed to keep the hydrogen liquid, or significant insulation have to be applied. The gravimetric energy density for LH_2 is 119.9 MJ/kg, which makes it extremely attractive, with over 2.5 times the gravimetric energy density for diesel fuels. Unfortunately, the main barrier for hydrogen as a fuel is the volumetric energy density, which is only 8.49 MJ/l for LH_2 (see Figure 3.4). This means that hydrogen requires much more space than other alternative fuels. Storage tanks will require to store liquid hydrogen at a temperature of $-252.87\,°C$, which is $90\,°C$ lower than of LNG, this will eventually affect the capital expenditures (CAPEX).

For compressed hydrogen (690 bar) the volumetric properties are even smaller, 4.5 MJ/l. Compressed hydrogen is a potential option for short sea shipping opportunities, like ferries and other smaller vessels. For longer distances, liquefied storage is the only feasible solution for hydrogen as a marine fuel, due to the volumetric and gravimetric properties.

H_2 can be produced from either renewable (wind, solar) or gas (natural gas, biogas). The price of H_2 depends therefore on electricity prices and the reformation procedure of gas. Hydrogen can provide a zero-emission profile since it will only emit H_2O through the process of electrolysis. This means that it will comply with all regulations both in the short and long term. Due to the energy density properties discussed, hydrogen will have problems with deep-sea shipping. However, in a short sea shipping setting, hydrogen might become vital to achieving IMO goals.

If H_2 is used alone as fuel, the Proton-exchange membrane fuel cell (PEMFC) is the most promising alternative fuel cell. The PEMFC establish the most power per size and provides the lowest relative cost. Used together with LNG, MGO, Methanol or biofuels, High-temperature proton-exchange membrane fuel cell (HT-PEMFC) or solid-oxide fuel cell (SOFC) are the alternatives (DNV-GL, 2020). The same C-tank technology that stores LNG can be used to liquid hydrogen, according to Moss Maritime (Bøhlerengen, 2019).

3.2.3 Batteries

Batteries are an electrochemical device that stores electrical power and can satisfy all energy demands on a vessel. The purpose of batteries in marine applications can range from having a ship fully electric, or have batteries as a hybrid solution. Batteries can be charged either with conventional fuel or with shore power. If the former charging method is chosen, the mission is not to change to alternative fuel, but rather improve the efficiency of the system and reduce fuel consumption.

There are three methods for improving the electric grid through batteries as a hybrid solution; spinning reserve, peak shaving and dynamic load transition ramps (MAN, 2019). For **spinning reserve** the power generation capacity (storage) of the system is connected to the grid but unloaded. This could be arranged by replacing an auxiliary system with a battery system. The spinning reserve is available when an increase in power demand occurs. **Peak shaving** is the method when the battery is discharged to shave the peak load demands. The principle is to keep the hotel load constant in general, while the battery takes the peak. When the load is lower than constant load, the battery is charged (MAN, 2019). **Dynamic load transition ramps** are the technique to soften the steepness of the load transitions. Too steep load variations might increase emissions and fatigue to the engine (MAN, 2019). The principles of the three modes is shown in Figure 3.6.

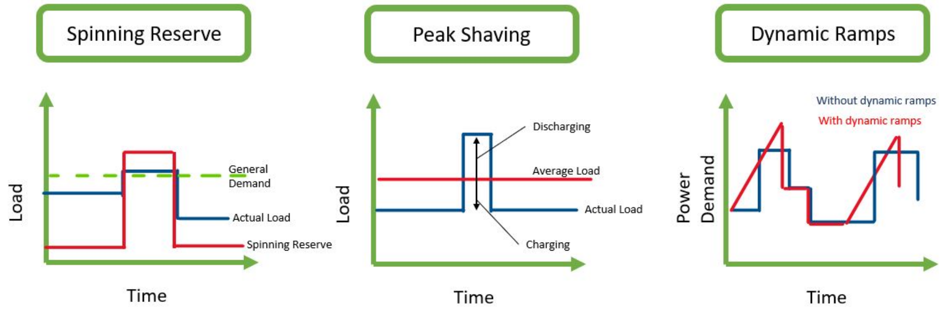


Figure 3.6: Three Hybrid Modes for Batteries (MAN, 2019)

Lithium-ion batteries are the most used battery type. Maritime lithium-ion batteries are categorised in three different cell chemistries; Nickel manganese cobalt oxide (NMC); lithium iron phosphate (LFP) and, Lithium titanate oxide. NMC has a long life cycle with satisfying energy density. LFP has a stable cathode which reduces the thermal runaway risk (MAN, 2019).

When creating the dimensions of a battery, two main parameters are important, the energy storage and the power rate (charge/discharging transfer of energy). This rate is expressed as the C-rate, which is the rate of discharging a battery relative to the maximum capacity. A C-rate of 1 is equal to a completely discharging the battery from 100 % to 0 %, of ”The State of Charge” (SOC), in one hour. The C-rate is used to compare different types of batteries, across size and types.

$$C - Rate = \frac{Power}{Capacity} \tag{3.2}$$

The lifetime of a battery is varying on the type and charging profile during operation. However, a lifetime of around ten years can be considered, meaning that a change of batteries packs at least once is necessary for a vessel with a lifetime of 20 years. ”If the capacity of the battery is increased and the C-rate reduced, the lifetime can be prolonged.” (MAN, 2019).

Batteries in commercial applications such as vehicle industry have seen a rapid decreased in price for instalments. MAN estimates that for a battery system to be implemented in 2019, on a newbuilding, is approximately 500 USD/kWh (MAN, 2019).

If the electricity comes from a renewable energy source batteries can be considered a fully zero-emission option. SO_x, NO_x, PM and CO_2 are not emitted. Batteries will comply with all IMO regulations. Fully electric vessels are only available for short sea shipping at the moment. Nonetheless, for the deep sea segment, vessels can already establish batteries for the optimisation of energy performance. In a study by MAN, batteries for peak shaving and the spinning reserve is most actual on auxiliary systems. In the same study MAN conclude that for a deep-sea vessel with a two-stroke engine, a battery pack will not save enough fuel to be beneficial in replacing the main engine. (MAN, 2019).

3.2.4 Wind as Propulsion

In the seek for future alternative fuels, it is a paradox that for only over 100 years ago, the whole world merchant fleet where sailing emission-free. Wind-assisted propulsion was before the diesel engine a superior alternative for maritime shipping. This idea is coming back to the design board for future vessels. There is some traditional design that could be interesting for future ship design. Wind can be a factor in improving a vessel EEDI Index, and meet regulations. DynaRig (Figure 3.7) design is using automated soft sails and can survey as main propulsion. It is available on some mega yachts. Kites use the principle that winds in higher altitudes provide more energy than on surface level. Figure 3.9 illustrates these concepts.

Figure 3.7: Dynarig Concept

Figure 3.9: Kites Concepts

Flettner Rotor

A Flettner rotor, named after Anton Flettner who developed the concepts in the 1920s, might be the most promising technology. When wind meets the spinning rotor, the airflow accelerates on one side of the rotor sail and decreases in the opposite side. This change in airflow creates a pressure difference that creates a lift force that is perpendicular to the wind flow direction. This is called the Magnus effect (Figure 3.10).

Figure 3.10: Magnus Effect. (Norsepower, 2019)

Norsepower, a Finnish company, has available rotor sails of 18, 24, and 30 meters (Norsepower, 2019). They further assume, a 5 -20 % reduction of fuel without lowering operation profile. The CAPEX cost is according to Norsepower, depending on the size of the product and the site of production. Flettner rotor is applied to 8 ships since its introduction, where one of these being a tanker, Mærsk Pelican seen in Figure 3.11. The rotor needs some energy to start up.

Figure 3.11: Flettner Rotor Installed on Mærsk Pelican Tanker. (Norsepower, 2019)

3.2.5 Nuclear Power

There is also some buzz in the shipping industry around the usage of nuclear power for propulsion systems. Traditionally, this method is used in military vessels such as submarines and aircraft carriers. The primary purpose of military usage is the ability to power a vessel for longer distances without the need for refilling. Nuclear power has also been used for some ice breakers. However, for commercial practice, only four vessels have been built, and only the Russian lighter aboard ship (LASH) vessel Sevmorput (Figure 3.12) is in operation today. Small nuclear reactors might be actual for energy purposes in a zero-emission perspective since there is no GHG emission and especially for longer distances. The main barrier is the global public perception of nuclear power as something that can cause catastrophic outcomes. Chernobyl in 1986 and Fukushima 2011 have created a significant negative influence on politics and the public opinion towards nuclear energy usage. The technologies around nuclear power for maritime commercial purposes is not further examined in this paper. Nevertheless, it is an intriguing aspect to keep in mind for future zero-emission deep-sea shipping.

Figure 3.12: Svemorput Nuclear Powered LASH vessel. (Norsepower, 2019)

Chapter 4

Evaluation of Infrastructure for Future Fuels

”Thou follow me, and I will be thy guide”

\- **Virgil** to Dante, *The Divine Comedy*

4.1 Infrastructure

A critical barrier for new alternative fuels is the infrastructure, and it is remarkably relevant for ammonia and hydrogen. Since ammonia (NH_3) consists of hydrogen, the critical factor regarding infrastructure for these fuels is related to the production of hydrogen. This production has to be ”green” (A zero-emission production) in order to have full effect in a consumption perspective (hydrogen can also be produced from oil and gas). Hydrogen is easiest produced in electrolysis, where the only requirement is electricity. Electricity can come from different sources like hydro, solar or wind power. Solar and wind are abundant resources but are variable in delivered effect, causing some concerns for how to deliver a constant supply of fuel.

Hydrogen production has to be established in central locations, such as close to cities or ports. The reason for that lies in the fact that building infrastructure, in an emerging industry, is costly; hence it is vital to look for synergies. The onshore transport industry is more likely to adopt hydrogen due to the properties of hydrogen facilitates shorter distances and lower required power. Maritime hydrogen infrastructure is, therefore, more beneficial when connected to the onshore network.

Furthermore, it is essential to not only look at the shuttle tanker segment but all vessel types. Ferries, offshore supply, cruise and fishing are the largest contributes to domestic emissions. Using AIS data, it is possible to evaluate the movement of the different segment vessels. In regard of all domestic maritime emission, DNV-GL identified Bergen, Ålesund, Tromsø, Kristiansund and Stavanger as the cities with the most potential as a hydrogen port. (DNV-GL, 2019b).

Hydropower

Norway has over 1600 hydropower plants, and this accounts for around 96 % of installed capacity in Norway. Besides, there are around 1000 storage reservoirs providing flexibility to the Norwegian electricity grid (around 75 % of the production is flexible) (Energifakta, 2019). Moreover, hydro plants can create electricity on demand, and hydro related electricity can provide ”green” production of hydrogen. Hydropower is used for the onshore grid and daily life usage from Norwegian citizens. So, the infrastructure is available and producing hydrogen through electrolysis in Norway, would provide ”green” hydrogen. Hydropower can not be just built near a facility as with the other alternative, but it gives the unique advantage for the Norwegian grid to produce ”green” hydrogen through electrolysis.

Solar

Solar instalments are easy to establish. As an example, the Norwegian trailer company ASKO are using solar panels to produce hydrogen for their new hydrogen-fuelled trailers. In their region centre in Trøndelag, a 9000 m^2 are installed on the rooftop producing 300 kg hydrogen per day (ASKO, 2017). Similar solar panel construction can be installed where needed. However, the required area would be many times larger than ASKO’s industrial area, in order to produce enough fuel for a shuttle tanker (20 000 kW). Using the relation between area and mass, it would require around ca 33 times as large space (297 000 m^2). Putting it perspective it would equal to 41 (68*105) football fields.

Figure 4.1: ASKO hydrogen production centre (ASKO, 2017)

Wind

Wind is the other alternative, and it is somewhat more complicated. Onshore wind parks are costly and demand political engagement both locally and nationally. Anyhow, there are already a handful of wind parks in Norway that can be apart of the hydrogen infrastructure. Looking on existing wind parks, the following locations given in Table 4.1 would be relevant for hydrogen production along the coastline.

In media Smøla has been seen as the most viable option since the wind park produces around 100 MW more than that are consumed locally at the island (E24, 2017). Smøla is located just outside of Kristiansund. Also, Equinor's methanol production facility at Tjelbergodden, where gas from the Norwegian Sea arrives, is located few kilometres away from Smøla—giving hydrogen production more reliability in that region. Rogaland has the largest cluster of wind parks and produces the most energy. However, many of these are located inland at Jæren. Egersund and Tellnes are closer to the sea, but this is further south from the largest city Stavanger.

For the shuttle tanker operating in the Barents Sea, it will be essential to have hydrogen infrastructure as close as possible to the oil fields due to the hydrogen properties. In Berlevåg, hydrogen is already in production, and it is an exciting location. However, a constraint for Berlevåg is the distance from the rest of the European market. Tromsø and Hammerfest are the most promising ports. Tromsø is the largest city in the region, while Hammerfest is closer to the offshore industry and have existing land-based maritime and offshore industry (Melkøya). An issue in the northern part of Norway is the distances, meaning that hydrogen has to (most likely) be transported with trucks over longer distances.

Table 4.1: Locations Wind Parks

No.	Wind Park name	Nearest City	Effect	Status
1	Raggovidda	Berlevåg	200 MW	Active
2	Kjøllefjord	Honningsvåg/Meham	40 MW	Active
3	Havøygavlen	Hammerfest	45 MW	Active
4	Snefjord	Hammerfest	160 MW	Application received
5	Dønnesfjord	Hammerfest	48 MW	Under Construction
6	Fakken	Tromsø	60 MW	Active
7	Kvitfjell	Tromsø	200 MW	Active
8	Raudfjell	Tromsø	100 MW	Under Construction
9	Smøla	Kristiansund	150 MW	Active
10	Guleslettene	Florø	197 MW	Under Construction
11	Midtfjellet vidkraft	Stord	150 MW	Active
12	Egersund	Egersund	110 MW	Active
13	Tellnes	Flekkefjord	200 MW	Active

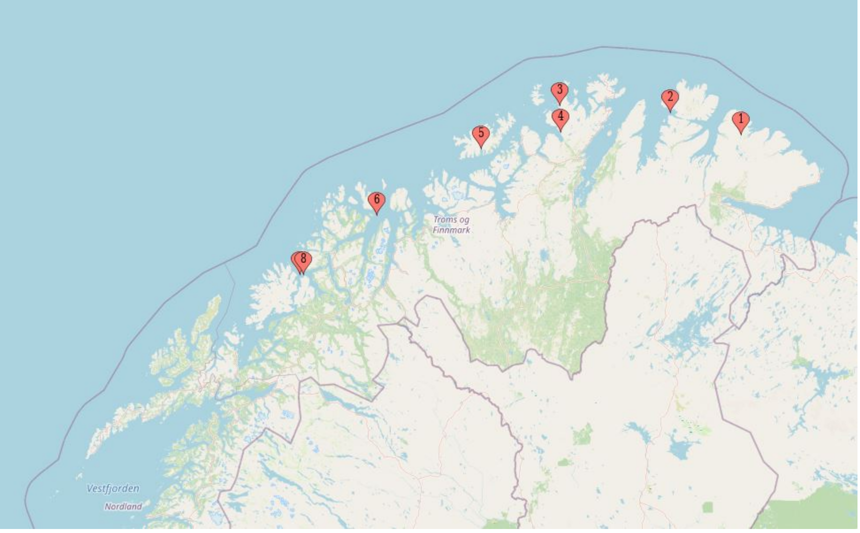


Figure 4.2: Wind Parks Locations in the Northern Part of Norway.

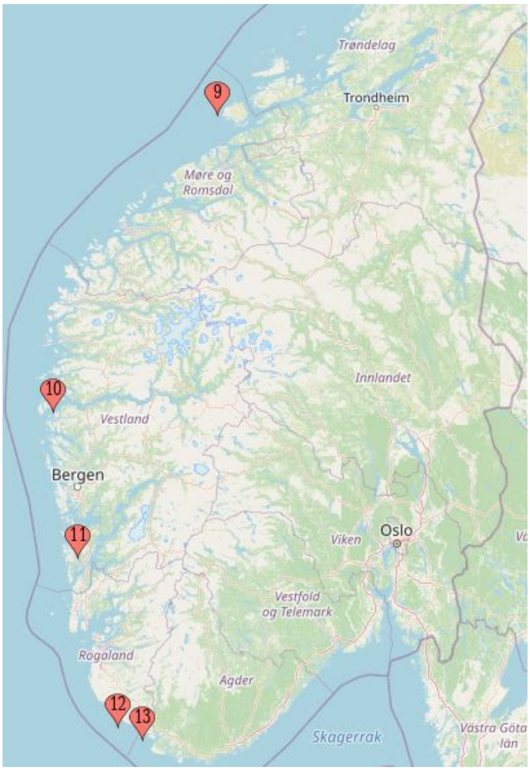


Figure 4.3: Wind Parks Locations in the Southern Part of Norway.

While Figure 4.2 and Figure 4.3 show the geographical locations for onshore wind in Norway an additional option is offshore wind. Offshore wind parks could also be available for hydrogen production. Hywind Tampen is under outlined to give electricity to the Snorre and Gullfaks fields (Equinor, 2019). These fields have recently got an extension of their lifetime. Hydrogen production is probably most relevant in this area when the platforms are supposed to shut down.

A final aspect for hydrogen production is the locations that use fossil resources. In Norway today Yara and Equinor are the largest consumers of hydrogen, and they mainly produce it to make ammonia and methanol at Herøya and Tjelbergodden respectively. These to locations produces around 180 000 tonnes of the 225 000 tonnes hydrogen in Norway (DNV-GL, 2019b). The oil refineries at Mongstad (Equinor) and Slagentangen (ExxonMobil). Producing Hydrogen from natural gas might be ”green” if the CO_2 are captured and stored. GHG capturing will require technology for CO_2 storage and becomes an additional cost in the infrastructure value chain. The locations are seen in Figure 4.4

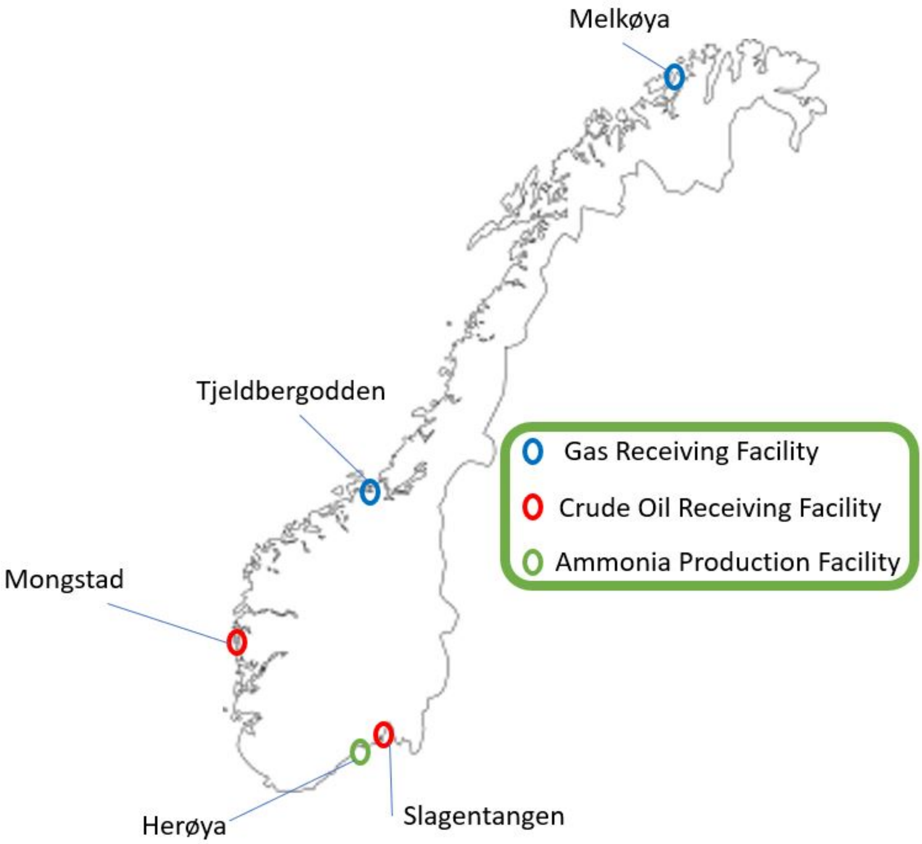


Figure 4.4: Industry Facilities.

Ammonia Production

As mentioned in earlier sections, ammonia production is possible when hydrogen and nitrogen are present. Nitrogen N_2 is natural in the air, and therefore only hydrogen is needed. Yara produces ammonia at Herøya with a capacity of the plant up to 500 000 tonnes ammonia. For achieving that an amount of 90 000 tonnes of hydrogen is needed (DNV-GL, 2019b). Furthermore, Yara indicates that there is a low probability of increasing production in Norway. Mainly because of competing production facilities in low-cost countries, including their plant at Trinidad and Tobago. The cost of producing ammonia in Norway, as Yara indicates, might be a barrier for ammonia infrastructure. However, it can be more attractive to produce ammonia for the sole purpose of maritime fuel.

Vessels and Import

It is possible to store ammonia on bunker vessels. Such a practice can give more flexibility in options for the refilling of fuel. Possible scenarios can be having a hub where production and storage happens. LPG vessels are suitable due to LPG's properties are similar to that of ammonia. This type of tanker is also used today for the transport of NH_3 and new technology are not required.

Import of ammonia might be relevant both for supplying a fuel demand and price levels. The obvious problem is that the government will lose control of overproduction. If the requirement is zero-emission, import of ammonia produced of fossil fuels is not relevant. If hydrogen is the preferred technology, it is actual to store hydrogen as ammonia due to the high density of hydrogen atoms per ammonia molecule.

4.1.1 Evaluation of Infrastructure

In this section, a calculation of mass needed for the propulsion of a shuttle tanker is made concerning the distance between possible infrastructure nodes. An acknowledgement is that both ammonia and hydrogen will require frequent fuel refilling, compared to traditional diesel fuel due to the properties and the required mass. Hydrogen will require even more frequent bunkering.

The most apparent location for serving a shuttle tanker is where oil unloads. In Norway, this is Mongstad and Slagentangen (Figure 4.4), where the former is the most suitable due to location and ownership (Equinor). Nevertheless, the distance between Johan Castberg in the Barents Sea and Mongstad is 800 nautical miles. The distance will, therefore, be a constraint, especially for hydrogen. The amount of mass required for a particular distance will be dependent on the size and speed of the vessel. For that reason, it is essential to understand the relations between required power and resistance in water due to the speed and size of the vessel. The essential relation that is derived is given in the green box. In the next subsections, these relations are derived in further detail as presented by (Woud and Stapersma, 2017).

Power increases with the exponent of 3 for speed

Resistance varies with the exponent of 2/3 for displacement

Power, Speed and ship size

The effective power (P$_E$) needed for propulsion is critical to evaluate before an estimate of mass can be calculated, for any ship design. The power needed for towing a ship at speed V$_s$ with a resistance R is as in Equation 4.1.

$$P_E = R \cdot v_s \tag{4.1}$$

Resistance R is the required force that the propulsion system is needed to overcome in order to move the vessel. The resistance consists of three main components. (1) Frictional (viscous) resistance, resultant of tangential forces acting on the hull because of boundary layer around the ship hull. (2) Form residence (pressure), the resultant force of the normal forces on the hull caused by the difference in the pressure in front and stern of the ship, when separation at the stern creates a pressure drop. (3) Wave resistance, a drag force caused by the waves generated by the movement of the vessel. Equation 4.2 show that the relation between ship resistance is seen as approximately proportional to the square of the vessels speed (Woud and Stapersma, 2017).

$$R = c_1 \cdot {v_s}^2 \tag{4.2}$$

Which results in the effective power of as seen in Equation 4.3. Furthermore, an increase in speed will be highly influential on the required power. If doubling speed required power will increase with a factor of 8.

$$P_E = c_1 \cdot {v_s}^3 \tag{4.3}$$

So, this factor c$_1$ are interesting in understanding the effect of the hull on the resistance and power. This factor is taken from a general dimensionless resistance C$_E$. It is possible to derive it from hydrodynamics and the total resistance. From the hydrodynamics total resistance is given as in Equation 4.4.

$$C_T = \frac{R}{\frac{1}{2} \cdot \rho \cdot A_s \cdot {v_s}^2} \tag{4.4}$$

Where ρ are the density of water, A$_s$ is the wetted surface of the ship hull. A$_s$ is normally not available in a design phase. Anyhow, it can be related to displacement volume (∇) by

$A_s \propto \nabla^{\frac{2}{3}}$ (Woud and Stapersma, 2017). That gives:

$$C_E = \frac{P_E}{\rho \cdot \nabla^{\frac{2}{3}} \cdot {v_s}^3} \tag{4.5}$$

From the relation between volume displacement and wight displacement (weight of the ship) $\Delta = \rho \cdot \nabla$:

$$C_E = \frac{P_E}{\rho^{\frac{1}{3}} \cdot \Delta^{\frac{2}{3}} \cdot {v_s}^3} \tag{4.6}$$

This means that the dimensionless C_E are depending on ship size, speed and hull. This resistance can be written as the function of all other non-dimensional factors that are influencing the problem (Woud and Stapersma, 2017):

$$C_E = (Re,\ Fr,\ Roughness,\ Hull\ form,\ External\ factors) \tag{4.7}$$

Where Reynolds number Re and Froude number Fr makes (as seen in Equation 4.8) C_E depend on speed and ship size.

$$Re = \frac{v_s \cdot L}{\nu}\ ,\ Fr = \frac{v_s}{\sqrt{g \cdot L}} \tag{4.8}$$

External factors are sea state and water depth under the keel. Hull form can be described as prismatic coefficient c_p and geometrical parameters like L/B.

In the end it is possible to see how the c_1 relates to C_E. When including the Equation 4.6 in the original equation Equation 4.1, it becomes clear that c_1 is a product of (speed-dependent) specific resistance C_E and density and displacement, as seen in Equation 4.9 and Equation 4.10.

$$c_1 = C_E \cdot \rho^{\frac{1}{3}} \Delta^{\frac{2}{3}} \tag{4.9}$$

$$P_E = C_E \cdot \rho^{\frac{1}{3}} \cdot \Delta^{\frac{2}{3}} \cdot {v_s}^3 \cdot \tag{4.10}$$

The relation between P_E and displacement, if C_E and v_s are assumed constant, and the displacement is changed from $\Delta_{original}$ to Δ the relation to P_E as seen in Equation 4.11. This means that the resistance varies with the power of 2/3 of displacement if all other factors (hull, fouling, sea state, etc.) are the same (Woud and Stapersma, 2017).

$$P_E = (\frac{\Delta}{\Delta_{original}})^{\frac{2}{3}} \cdot P_{E,original} \tag{4.11}$$

To summarise, Equation 4.10 explains the relations between power and ship speed and size. Power increases with the exponent of 3 for speed and resistance vary with the exponent of 2/3 for displacement. A doubling of speed increases power with factor eight. Power can, therefore, be plotted as a function of ship speed and size. In Figure 4.5, the contour plot shows the relation between power required for a vessel capacity and a vessel speed. The function used is an empirical formula (Equation 4.12) that replicates Equation 4.10, where q is cargo capacity in tonnes, V is the speed in knots and k is a constant relevant for each vessel type (Erikstad, 2017). For a shuttle tanker, such constant have a value of approximately 0.0197. The constant is calculated from the reference vessel Aurora Spirit (Teekay).

$$kW = k \cdot q^{0.5} \cdot v^3 \tag{4.12}$$

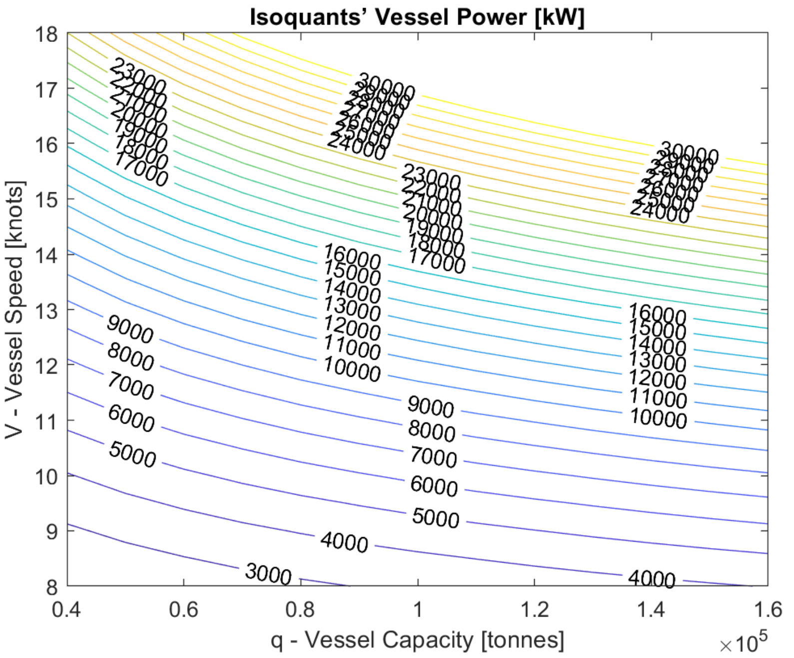


Figure 4.5: Isoquant of kW as a function of ship size and speed

From this plot, it is possible to observe the reduction in power when speed is reduced. At the same time, it is seen how power is affected when speed is assumed constant and capacity are increased or decreased. As an example, a typical Aframax North Sea shuttle tanker has a cargo capacity of 80 000 tonnes crude oil. If a reduction from 14.5 (often design speed for shuttle tankers) to 10 knots, the power decreases from around 16 000 kW to 5000 kW. That is a theoretical reduction of 69 %. Of course, some factors can change this during daily operations of a vessel, but the results indicate encouraging possibilities. With less required power, less mass is expected. Likewise, longer sailing time is workable.

Mass estimation

From the density properties, it is possible to derive the amount of mass through the formula in Equation 4.13.

$$mass[kg] = \frac{\Big(P_E[kW] \cdot 3600[\frac{s}{h}] \cdot Roundtrip\, time[h]\Big)}{\Big(Total\ Efficiency[-] \cdot Gravimetric\ energy\ density \cdot 1000[\frac{kJ}{kg}]\Big)}\ , \tag{4.13}$$

As known from earlier sections, power and roundtrip time depends on the speed and the size of the vessel. Power depends on ship size and speed. While total efficiency and gravimetric density (Table 4.2) depends on the engine and fuel used, total efficiency is assumed to be 50 % for both Hydrogen and ammonia. Roundtrip can be estimated as the sum of sailing time T$_S$, waiting time T$_w$ and operation time T$_o$ Equation 4.14.

$$T_s = \frac{d}{24 \cdot v},\ T_w = Wow\ etc.,\ T_o = \frac{2 \cdot \gamma \cdot q}{w_{LL}} \tag{4.14}$$

Table 4.2: Gravimetric Density Properties

	Gravimetric density [MJ/kg]
Ammonia	18.6
Hydrogen	120

Using Equation 4.13 it is possible to visualise the amount of mass needed as a function of power and roundtrip time. In Figure 4.6, the quantity of mass for hydrogen is shown. Figure 4.7 plot the volume in cubic meters that is required for power and roundtrip time. Roundtrip is given in hours, and can also represent the sailing time alone in these images. Furthermore, in Figure 4.8, the amount of mass for ammonia is given and in Figure 4.9, the cubic meters is shown. MATLAB is used to make these plots and the scripts are given in appendix section E.1

The four graphs indicates the difference in expected tonne mass for an equivalent measure of sailing time. Hydrogen requires much more space and also more tonnes of mass to sail the same distance as if ammonia was the preferred alternative. Remembering that 1000 m^3 equals a cube of sides with 10 meters, it is possible to see that the feasibility of hydrogen in longer distances fades away gradually.

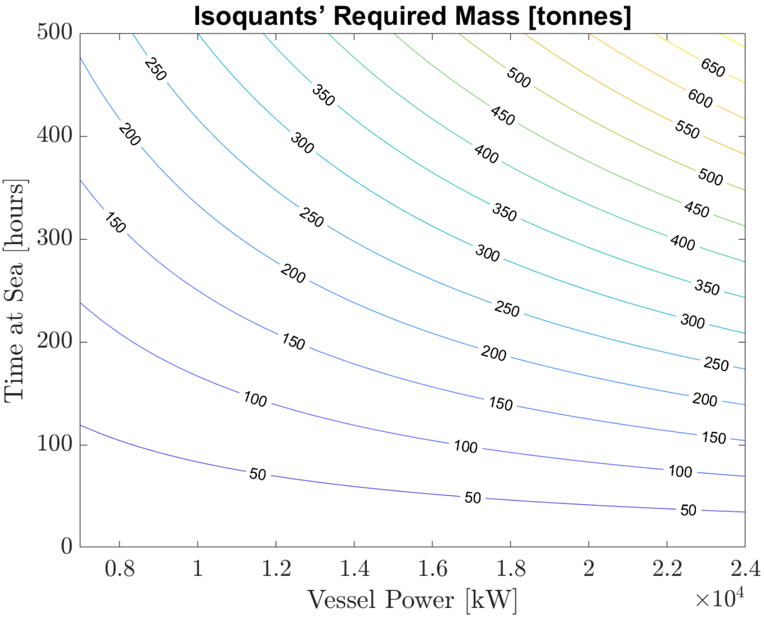


Figure 4.6: Hydrogen mass needed as a function of power and sailing time

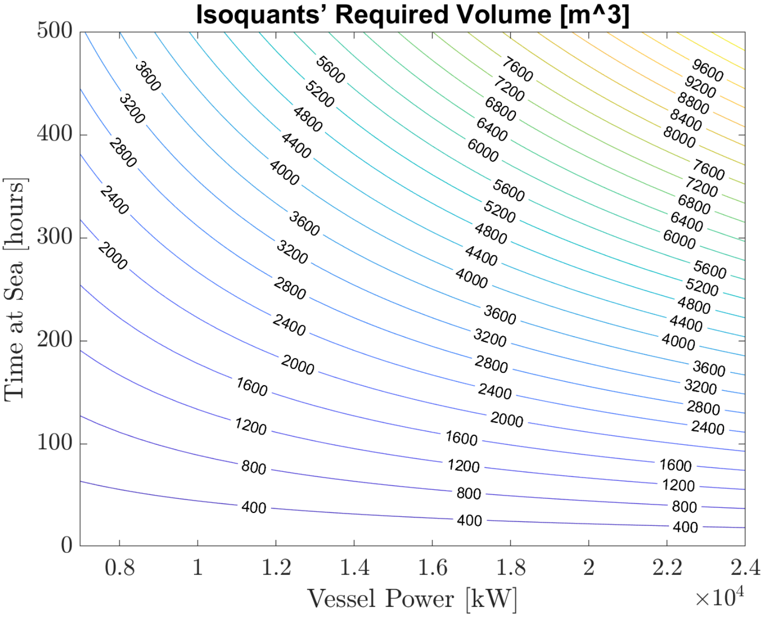


Figure 4.7: Hydrogen volume needed as a function of power and sailing time

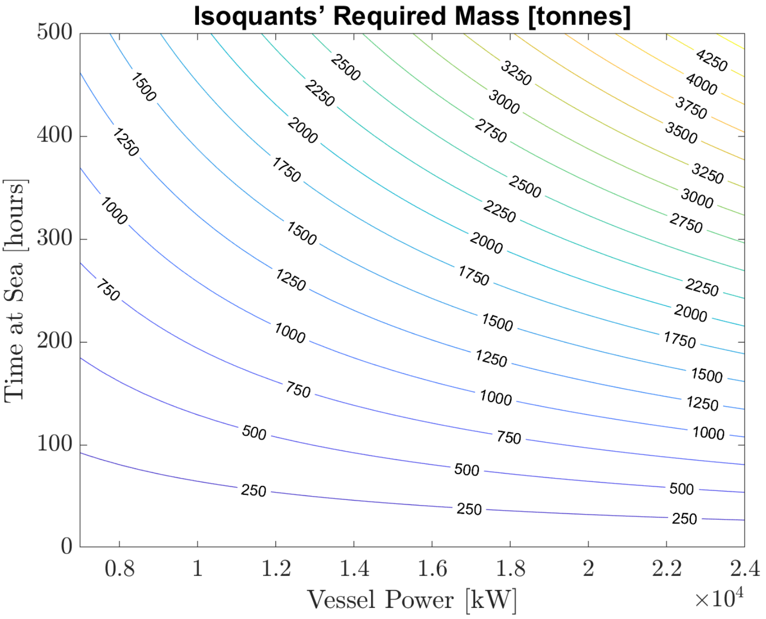


Figure 4.8: Mass ammonia needed as a function of power and sailing time

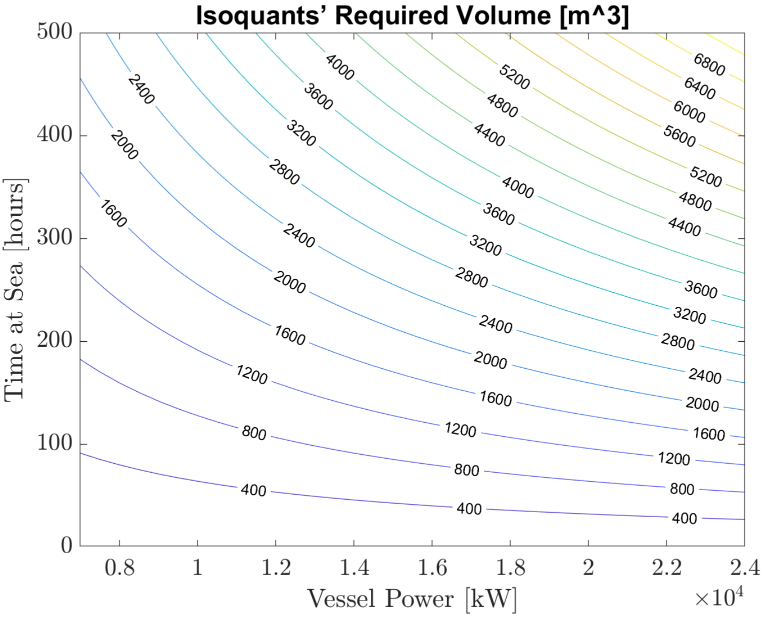


Figure 4.9: Ammonia volume needed as a function of power and sailing time

4.1.2 Optimisation of Infrastructure - Shortest-Path Problem

Volume for mass depends on the available area in the design of the vessel. Larger tank sizes than 1000 cubic meters are assumed not realistic, which means that a vessel with a specific power could sail for around 100 hours for hydrogen. The distances from Johan Castberg to Mongstad are 800 nm, so several stops for refuelling has to be expected on a roundtrip. That further means that a comprehensive system of infrastructure is needed.

Table 4.3: Potential Infrastructure Locations

Node	Port Location
1	Johan Castberg
2	Berlevåg
3	Honningsvåg
4	Hammerfest
5	Tromsø
6	Harstad
7	Å i Lofoten
8	Bodø
9	Aasta Hansteen
10	Sandnessjøen
11	Brønnøysund
12	Rørvik
13	Trondheim
14	Kristiansund
15	Aalesund
16	Florø
17	Hyvind Tampen
18	Mongstad
19	Bergen
20	Stavanger
21	Krisiansand
22	Slagentangen
23	Fredrikshavn (DK)

If every potential port along the Norwegian coastline is a node with a weighted positive value, it is possible to find the shortest path through Dijkstra's Algorithm (Appendix section A.1). The first thing to do is to establish the distance between every node. In appendix section A.2, the distances between nodes are calculated and given. A limit of 300 nm was set to the system, so it was not necessary to calculate all node distances, but the distances that are shorter than 300 nm are included in the model. Each node is located along the coastline except the node Aasta Hansteen and Hywind Tampen. Aasta Hansteen is included as a geographical representation of a cluster of oil fields where shuttle tankers operates. It is also a location that might be strategical in order to exclude fuelling in ports in Nordland county. Hywind Tampen is an offshore wind farm that will supply Snorre and Gullfaks platforms. Tampen might be usable for producing ”green hydrogen”. The list of nodes is given in Table 4.3. Keep in mind; this list is based on strategic geographical location, not necessarily on the feasibility.

Since the amount of mass needed for fuel depends on both ship size and the speed the dimensions of the vessel are essential. However, in the case of hydrogen as a direct outcome of low speed, lower power is assumed. In other words, only distance is relevant in this example.

Results using only Distance as parameter

Using Dijkstra's Algorithm and the "shortestpath" function (section E.2) in Matlab the optimal and shortest path between Johan Castberg and Mongstad (node 1 and node 18); Johan Castberg - Tromsø - Aasta Hansteen - Kristiansund - Mongstad, with a total distance of 838 nm. The actual path can be illustrated as a node network (Figure 4.10) in the flowchart made from Matlab indicated as the thick green line. Figure 4.11 shows the distance from Johan Castberg to Slagentangen. The thick red line suggests infrastructure along Johan Castberg - Tromsø - Aasta Hansteen - Kristiansund - Florø - Stavanger - Slagentangen.

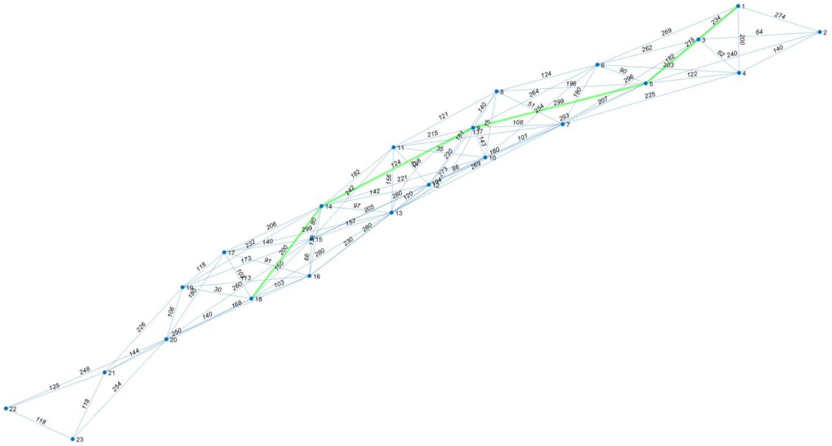


Figure 4.10: Johan Castberg-Mongstad Distance

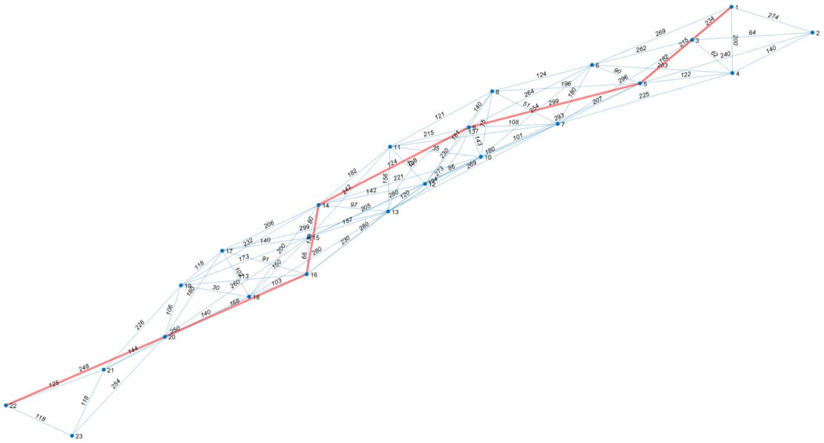


Figure 4.11: Johan Castberg-Slagentangen Distance

Results using weighted values

Another way of evaluating where the most suitable location for installing critical infrastructure is to weight the arcs according to their feasibility. Some of the listed nodes include ports that will be too small. Other nodes have existing infrastructure. Therefore each port or distance have been evaluated on the following parameters;

- Distance. +2 points for every 25 nm away from 300 nm, indicating that 300 nm is roughly the optimal distance between each filling.
- City. Points are given according to how large the city is, from lowest to highest. +10 small and remote area, +5 small connected +3 medium connected and +1 large connected.
- Port. If the port location is infeasible to handle shuttle tanker. Due to the main dimensions. +10 points if infeasible. +5 feasible with building new platforms.
- Existing usable infrastructure. Indicating possible hydrogen producible wind parks. +10 if no infrastructure, +5 if possible ”fossil” infrastructure, + 2 for small infrastructure. 0 for comprehensive infrastructure.
- Offshore/Onshore. Offshore locations are given a cost penalty of +10 points.
- ECA zone. Ports North of 62 N (ECA zone) is given a +1 value.

Figure 4.12 illustates the optimal travel between Johan Castberg and Mongstad if the weighted units is used. The green line then takes the route along Johan Castberg - Aasta Hansteen - Trondheim - Mongstad. Furthermore, Figure 4.13 shows the results from the weighted shortest path for Johan Castberg - Slagentangen. The route then becomes Johan Castberg - Tromsø - Sandnessjøen - Aalesund - Stavanger - Slagentangen.

Concluding remarks on optimisation of infrastructure

The shortest path method is a useful tool to get an indication of where development of infrastructure should be. Nonetheless, it is an indication and not exact science. For example, the suggesting of Aasta Hansteen as a node is a piece of hypothetical information added to the model, meaning that the feasibility not necessarily is genuine. Anyhow, it is interesting that Aasta Hansteen got chosen in three out of four scenarios, showing that having offshore infrastructure might be beneficial. By comparing the results of this shortest path with the proposal from DNV-GL (Bergen, Ålesund, Tromsø, Kristiansund, and Stavanger), it is striking to see that all those locations are chosen nodes in these simulations. Despite all this, it is clear to conclude that the hydrogen is not the best option for a shuttle tanker. However, for other ship segments with shorter required distances, it should be much more actual.

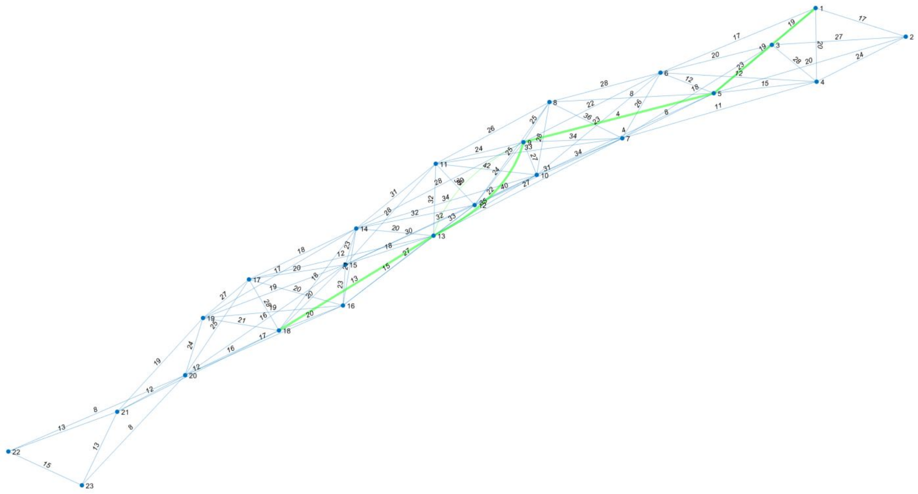


Figure 4.12: Johan Castberg-Mongstad Weighted

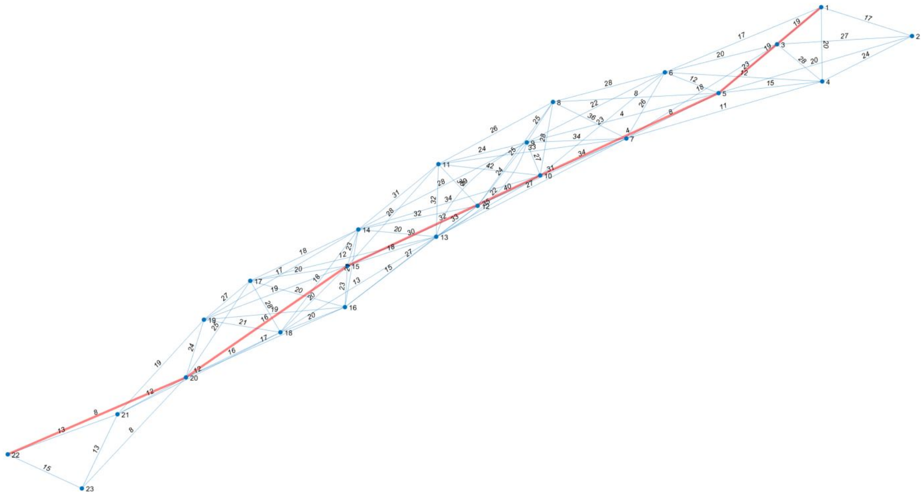


Figure 4.13: Johan Castberg-Slagentangen Weighted

Chapter 5

Uncertainty, Value and Utility in Ship Design

> ”**Fugayzi*, fugazi. It’s a whazy. It’s a woozie. It’s fairy dust. it doesn’t exist. It’s never landed. It is no matter. It’s not on the elemental chart. It’s not real.”*
> \- **Matthew McConaughey** as Mark Hanna, *The Wolf of Wall Street*

5.1 Understanding Uncertainty in Ship Design

There are many forms of uncertainty and many types of risk associated with it that affects the design decisions of a complex system like ship design. H.McManus and D.Hastings have made a framework for understanding uncertainty and related mitigation and exploitation. They describe the framework in the simple form of; ”Uncertainty leads to risks or opportunities, which are handled technically by mitigations or exploitations, which hopefully lead to desired outcomes.” (Mcmanus and Hastings, 2005). Furthermore, it includes making a decomposition or a taxonomy under each category, as seen in Figure 5.1.

Uncertainty causes Risk handled by Mitigation resulting in Outcomes

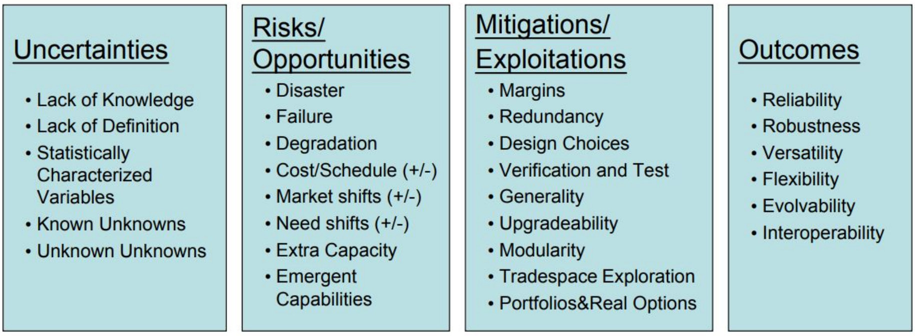


Figure 5.1: Framework for handling Uncertainties (Mcmanus and Hastings, 2005)

Uncertainties are unknown things or partly known things. They are factual and measurable, and there is no judgement in the uncertainty. It can both be better and worse. In the perspective of a ship designer, the dynamic uncertainties, *lack of knowledge* and *lack of definition*, are essential to understand. In the case of lack of knowledge, facts are not known or only partly known, implying that knowledge needs to be gathered or created. Next, when speaking of a lack of definition, things in the system is either not specified or not defined. Non-defined aspects are not necessarily negative due to project development. In the early designing stage, it can be challenging to avoid defining much of the system early. It is accordingly vital to systematically reduce the amount of defined uncertainty throughout the project lifetime at the appropriate time.

As information is gathered in time, the uncertainties change. The other uncertainties listed are related to the whole spectre from no knowledge to well categorised *statically variations*. Examples of the statistical variations are different price levels. It is difficult to say if it will fluctuate up or down, but statistics can help model it.

Known Unknowns are things that are known as not known. For example, it is possible to know that ”green” hydrogen or ammonia technologies will provide different pricing values, but the exact price is not known. In the end, *unknown unknowns* are defined as things that are not known. Typically unknown unknowns can be categorised into measurable variables as 100 years wave and similar descriptions. In other words, in 100 years, something will happen.

Risk and Opportunities are a direct consequence of the uncertainties to a system. Risk is associated with the downside while opportunities are related to the upside. Risk of an event is famously defined as Severity x Probability, while the opportunity is the opposite, Value x Probability.

Risk = Severity (Consequence) X Probability

Opportunity = Value X Probability

Mitigations are measures made to avoid or to manage risks. Exploitations are a similar approach to opportunities. The listed strategies for consideration in Figure 5.1 are well known and in a ship design perspective, these are methods regularly directly used.

Outcomes are the desired attributes that characterise the interaction with uncertainties. The definitions linked to the relevant term are often confused and is necessary to be adequately explained. Under the terms are defined as by (Mcmanus and Hastings, 2005). The second term, robustness is the main focus further in this thesis. Thus, it is extra relevant.

- Reliability: The probability that the system will do the job it was asked to do.
- **Robustness: The ability of the system to do its basic job in unexpectedly adverse environments**
- Versatility: The ability of the system, as built/designed, to do jobs not originally included in the requirement definition, and/or to do a variety of required jobs well
- Flexibility: The ability of the system to be modified to do jobs not originally included in the requirements definition
- Evolvability: The ability of the system to serve as the basis of new systems to meet new needs and/or attain new capability levels.
- Interoperability: The ability of a system to ”play with others”, both with systems originally intended and future systems.

5.2 Shipping Cycles

Martin Stopford characterises and reveals that shipping markets have throughout time evolved in cycles (Stopford, 2009). These cycles can be divided into three components; short business cycles, long cycles and seasonal cycles. Short cycles are the most representative for shipping markets. A complete cycle can last between 3 to 12 years form peak to peak while it will fluctuate up and down continuously in that period. The long cycles are the underlying trend and are either upswing or downswing in up to approximately 60 years. The upswing is indicating a positive environment for business. The seasonal changes are fluctuation within a year, which is typically related to seasonal variation in demand around the world. Figure 5.2 illustrates the three components of shipping cycles.

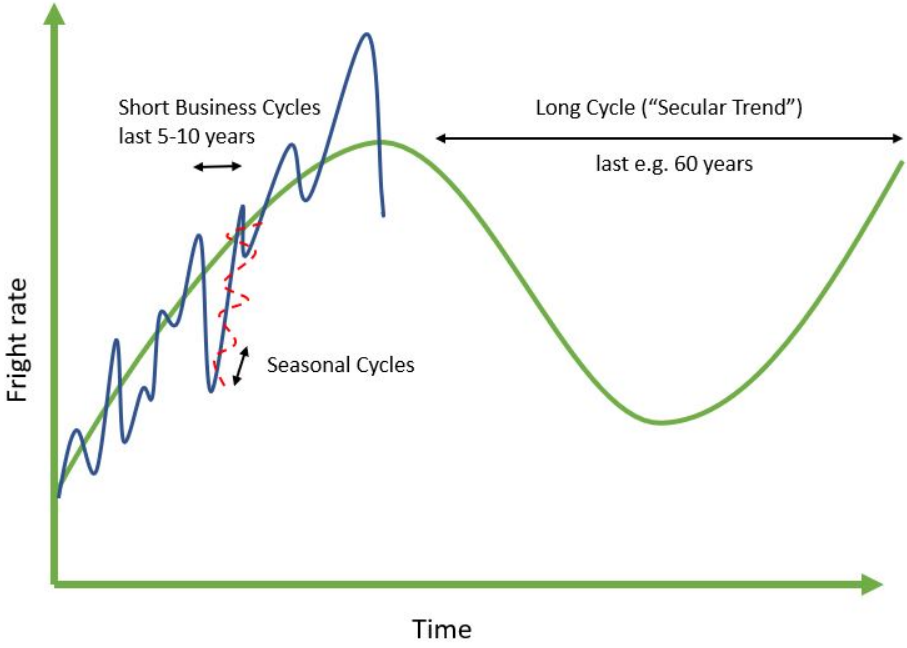


Figure 5.2: Shipping cycles described by (Stopford, 2009)

A ”typical” shipping cycle (short cycle) consists of four stages, Trough, Recovery, Peak/-Plateau and Collapse. These stages are not consistent in the length of time, and there are no firm rules that decide the timing or regularity of the cycle. Nevertheless, (Stopford, 2009) describes the stages like this:

- **Stage 1: Trough.** Surplus in shipping capacity is observable (such as queuing in port and slow steaming to save fuel). Freight rates drop to operating cost of the least efficient ships. Low freight rates lead to negative cash flow, and financial pressure will develop. Decisions will be on hold, and the prices of old ships will sink to scrap price.

- **Stage 2: Recovery.** In this stage, the supply and demand move towards a balance. However, uncertainty is still present, but confidence and optimism grow. As positive liquidity is experienced second-hand prices increases and newbuildings market will improve.

- **Stage 3: Peak/Plateau.** Supply and demand tighten and shipping companies can operate on full speed. Freight rates might be many times the operating cost (Typically 2 to 3 times). High earnings provide excitement and an increase in second-hand prices, and newbuilding both rise substantially. Modern ships can be sold in the second-hand market at a higher price than when newbuild. Orders increase slowly at first, and then rapidly.

- **Stage 4: Collapse.** Supply overtakes the demand and freight rates will fall. It will reduce operating speed, and the less attractive vessels will struggle to find cargo. Liquidity is likely to be still positive, and thus shipowners will hesitate to sell the ship at discount prices compared to the peak prices. Often business cycles downturns and economic shocks are significant factors.

5.3 What is Value in Ship design?

5.3.1 An Overview of Ship Design Strategies

The first and oldest method is the **point-based design**. In maritime design, Evans (1959) has been one of the vital contributions in trying to explain the design process. Evans design spiral indicated the iterative process of ship design. The point-based design follows the propose -analyse -evaluate -decide procedure, which limits the design phase in focusing on one or a few possible designs

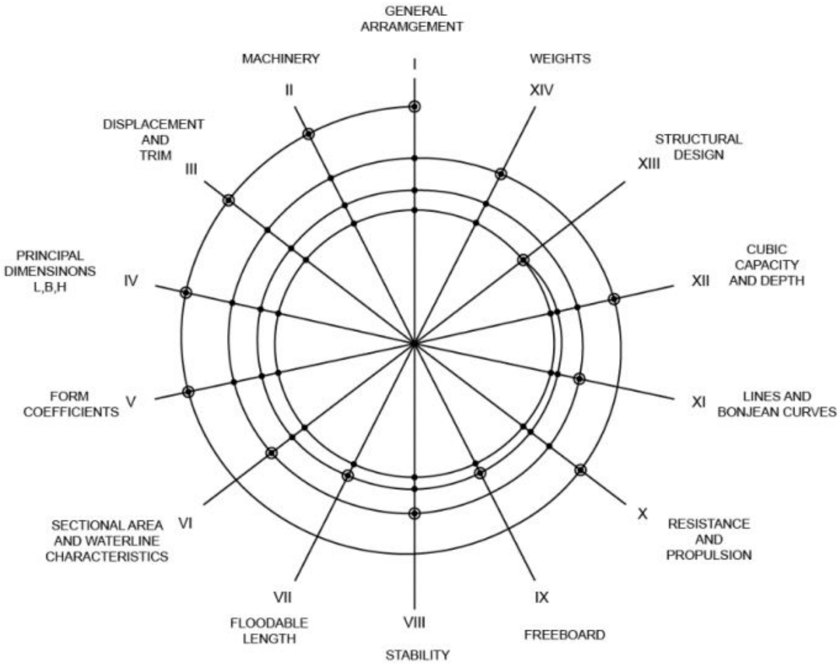


Figure 5.3: Evans Design Spiral (Evans, 1959)

System-based design methods are another well-used method. It includes the systematically developing of functions and solutions to it. In general engineering design theory, Pahl & Beitz (1977) introduced the ”German” school of engineering design, where the usage of design catalogues as an encyclopedia for engineers (Pahl et al., 1977). Such a catalogue should include all functions and representative possible feasible solutions to the function. (Levander, 2012) takes this systematic approach a step further into ship design. He introduces his **System based ship design** where he creates the ship ”mission” as essential for future ship function description. A mission describes stakeholders ”wants” or ”musts” and is the baseline for deciding witch functions that are matching those expectations. The functions that can be selected are chosen from an existing ”design catalogue” of existing solutions.

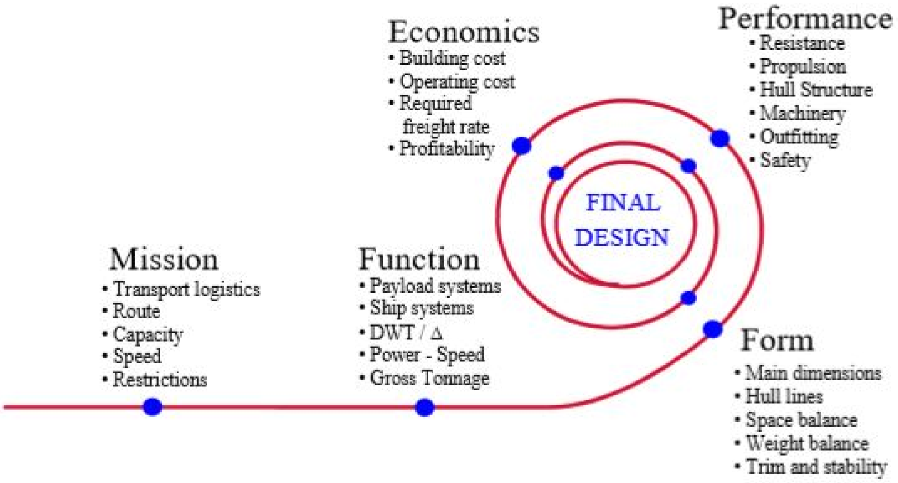


Figure 5.4: Sytem-based ship design (Levander, 2012)

Optimisation models are mathematical approaches to design. It can include optimisation of cost such as maximise revenue or minimising cost. It can also include space allocation or functional optimisation of the ship design. This method is very appealing since the best alternative can be found. However, problems often become extremely complex and will require a detail level difficult to achieve. There are many forms of optimisation, such as Simplex and Dual problem methods to Heuristic optimisation methods. In ship design, optimisation methods might be best suited as a tool to evaluate sub-functions such as machinery or space allocations.

Set-based design is the method of generating and selecting designs. Developing an understanding of the design space is crucial in this approach. Instead of having one or a few options, set-based consider a large number of design alternatives and establish their feasibility before any commitment. (Singer et al., 2009) explains establishing feasibility in design by three concepts:

1. Narrowing sets gradually while increasing detail.
2. Staying within a set once committed.

3. Maintaining control by managing uncertainty at the process gates.

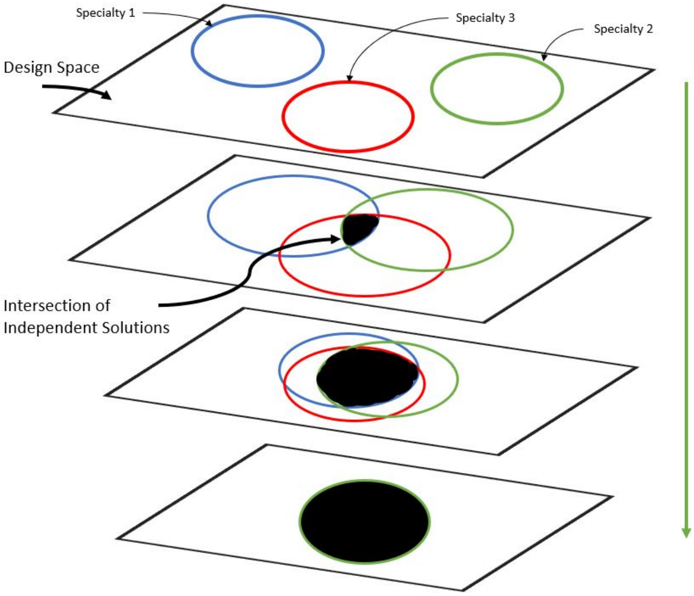


Figure 5.5: Set based Design Procedure (Singer et al., 2009)

Design phase of developing a ship represents a critical stage where the committed cost is at a much higher rate than the incurred cost (Singer et al., 2009), which results into the fact that a mistake in the design phase, can cause more severe monetary loss at a later stage. Set-based design methods provide a way to delay critical decisions to as late as possible or to a time where knowledge has become higher. Hence, stakeholders can become more influencing in the design process because of delaying committed cost.

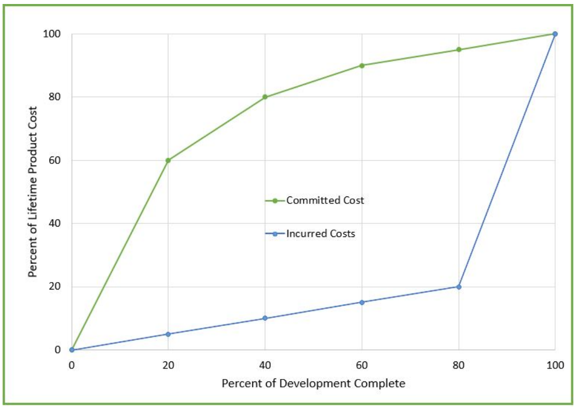


Figure 5.6: Committed vs Incurred cost in ship design (Singer et al., 2009)

5.3.2 Needs, Function and Form

In traditional ship design, it is reasonable to establish the difference between function and form. The form includes the descriptions of the design, including parameters like the draft, length, beam etc. On the other side, the functional space includes the performances of the design, such as cost, behaviour at sea, speed etc.

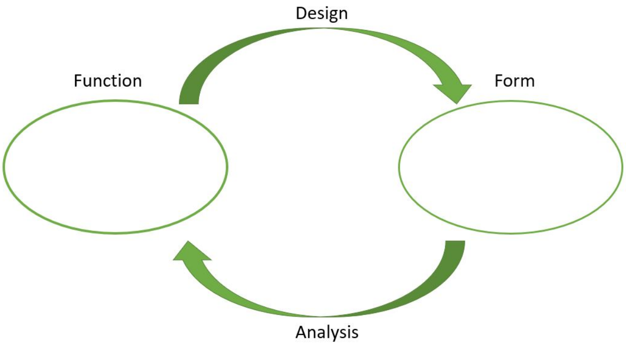


Figure 5.7: Function - Form Mapping

The traditional engineering approach is the mapping from form to function or in other words, deductive reasoning. It means that logically derived premises can justify the conclusion. In this traditional approach, an engineer will have the design parameters and can use its analysing toolbox to establish the functions.

However, in ship design, the contrary mapping is essential. In this circumstance, there are no vessel and the desire to design one can be expressed through the functions. This approach will provide an infinite solution space (different forms). At the same time, different functions might constraint design options. Trivial solutions might be feasible, but good design implies the desire to discover the best feasible solution concerning the constraints.

The newest ship design methods challenge this classic approach by introducing the needs mapping before establishing functions. The value generated in a design can be described as the best solutions that satisfy all needs. Needs are the sum of the expectations and utility that affects every stakeholder. Evaluating these needs in ship design is a complex process. However, establishing the needs before a design phase will increase the likelihood of designing a value robust product, that can handle uncertainty and complexity in the ship design or give a more flexible solution throughout the lifetime.

The mapping of needs is often done through market analysis or similar evaluations of business potential for a market.

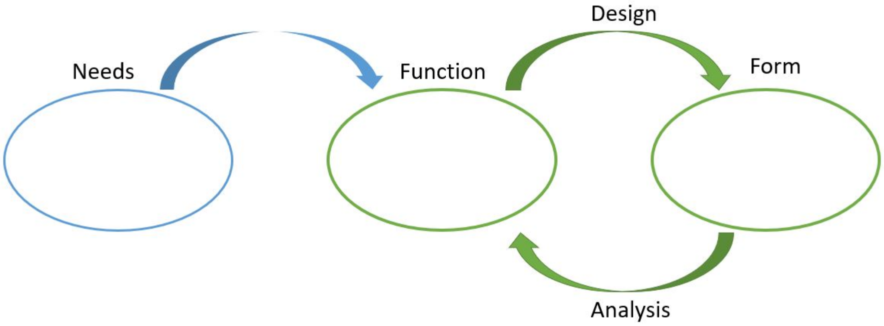


Figure 5.8: Needs included in Function - Form Mapping

5.3.3 Value

Value is described in different ways in different theories. Anderson and Narus establish a definition of value in business markets as ”the worth in monetary terms of the technical, economic, service, and social benefits a customer company receives in exchange for the price it pays for market offering” (Anderson and Narus, 2017). They further summarise this definition into a suppliers perspective and define the equation illustrated in Figure 5.9. The value minus price for a product has to be better than the next best alternative:

$$\boxed{(\text{Value}_s - \text{Price}_s) > (\text{Value}_a - \text{Price}_a)}$$

Figure 5.9: Value for the suppliers product should be greater than the next best alternative

Where, the s denotes the value and price of the supplier. Moreover, a denotes the corresponding for the next best alternative. In a shuttle tanker perspective, this equation could represent the vessel and the time charter the operator has to meet. The difference between value and price for our vessel has to greater than the next best solution.

Another perspective on customer value is given by (Christensen et al., 2016), where an introduction of the concept Jobs-to-be-done (JTBD) is given. JTBD theory is based on the fact that “When we buy a product, we essentially “hire” it to help us do a job. If it does the job well, the next time we are confronted with the same job, we tend to hire that product again. And if it does a crummy job, we “fire” it and look for an alternative.” (Christensen et al., 2016)

Christensen investigates the fact that innovation success rates are low on a worldwide basis and he argues that marketing theory focuses too much on ”customer profiles and on correlation unearthed in data and not enough on what customers are trying to achieve in particular circumstances”. (Christensen et al., 2016, pp. 57) Furthermore, he argues that successful innovators and thus prosperous value design are those who have identified this poorly performed ”jobs” in customers experience.

In a shuttle tanker zero-emission perspective, the ability in achieving a job affects the profitability of a vessel. Charter break-even freight rates can become higher with a more expensive design. Since innovation in ship design often involves complex solutions, it is fundamental that innovation, such as environmental solutions, do not worsen customer interference.

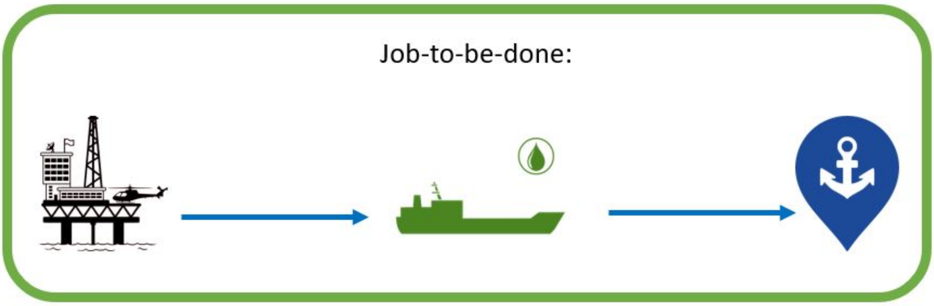


Figure 5.10: JTBD is to transport Crude oil

5.4 Value Identification within Industry and Markets

It can be beneficial to clarify the industry and market definitions. An industry is a group of firms that can offer the same products or class of products that which are substitutes for each other. (Hollensen, 2012). While a market is a group of actual sellers and buyers. There can be several markets within an industry.

5.4.1 Porters Five Forces

Porter (1980) debates that competition within an industry is based on the underlying economic structures and beyond the behaviour of other competitors (Hollensen, 2012). Porters then introduce the five forces that describe competition on an industry level. These five forces are market competitors, new entrants, suppliers, customers and substitutes.

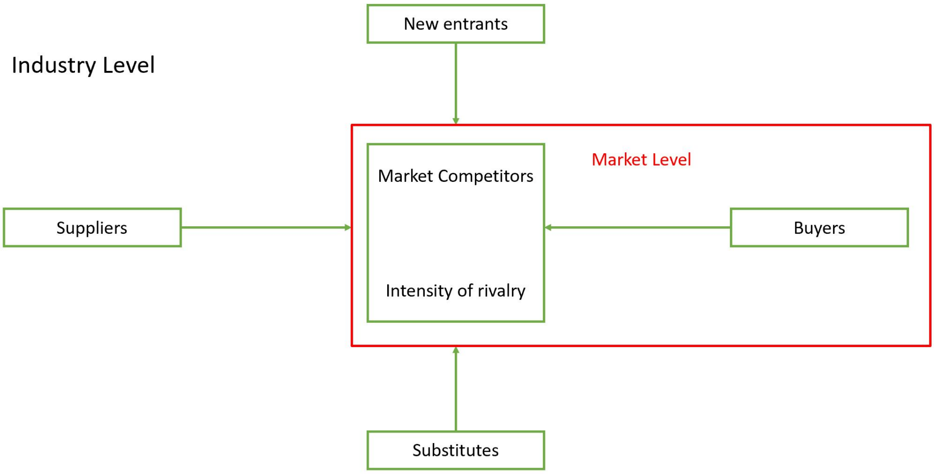


Figure 5.11: Porters Five Forces (Hollensen, 2012)

Market competitors

Market competitors describe the intensity of the rivalry between competitors within a market. In this subdivision, a description of market share is given through numerous factors. These factors can, as an example, be the market growth, the number of firms in the market, structure costs, how easy it is for a customer to switch firm or exit barriers.

New entrants

New entrants can explain the degree of which an increase in competition in the industry might turn out. In general new entrants is a function of the complexity and level of barriers. If there are high barriers, such as product technology or brand identity.

Suppliers

This subclass describes the power of suppliers to the firm structure, such as raw materials or components of a product. Higher power of supplier will give higher costs. It is possible to reduce the suppliers' power by integrating business backwards into supply.

Buyers

The bargaining power of buyers can be described as the effect of which buyers can reduce the prices of the supplier. Companies that will reduce the power of buyers can attempt to increase their customer base or threat to integrate forward into the buyers' industry. An example can be dropping a distributor if he was the main buyer, and sell directly to the distributors' customers.

Threat of Substitutes

The threat of substitutes is hugely related to the attractiveness and profitability of the industry. In a thriving industry, it is more likely that competitions will arrive as substitutes to a firms product. Companies can make a strong personal connection with the customers, like brand communication, in order to increase the likelihood to maintain customers. Similarly, an increase in switching cost might reduce the threat of substitutes.

5.4.2 Value Chain Analysis

If looking closer into a firms performance with customers, success depends on both the needs and the company ability to ensure a superior response compared to the competitor. A representation of such type of fulfilling is ”the perceived value to the customers’ perceived sacrifice.” (Hollensen, 2012), which is also called customer perceived value (CPV). CPV can be measured as in Figure 5.12, however, this is not a mathematical formula, but rather an illustration of what the customer ”gets” for what they ”gives”.

$$\text{CPV} = \frac{\textit{"Get"}}{\textit{"Give"}} = \frac{\textit{Product Benefits} + \textit{Service Benefits}}{\textit{Direct Costs} + \textit{Indirect Costs}}$$

Figure 5.12: Illustration of CPV based on (Hollensen, 2012)

Competitive advantage is gained when the value chain is analysed thoroughly. Investigating perceived value can be done by traditional strategic marketing methods (like the 4-P mix: Product, Price, Place (distribution), Promotion). At the same time, relative cost advantages depend on the configuration of the activities in the company value chain compared to competitors. Moreover, business resources and competences are the main factors affecting the varying between companies CPV’s.

Value chain analysis is a macro-level investigation and is therefore not so relevant in this project. However, it is crucial to understand that value chain analysis implies a linear process ignoring the outside inputs. Many companies can get different input in the value chain at different stages. The value chain becomes more like a value network, and this is what is called a value net. A value net is generated when more complex relationships are established in creating value. There are two main symmetries in the value net creation, vertically and horizontally network partners. Vertically, customers and suppliers are represented as equal partners in creating value. Horizontally, the relation between competitors and complementors are issued as a purpose to know a firm business inside out and to crate value net with other actors. In general, the horizontal network describes the finding of who is the firm friend and who is the firm enemy (Hollensen, 2012).

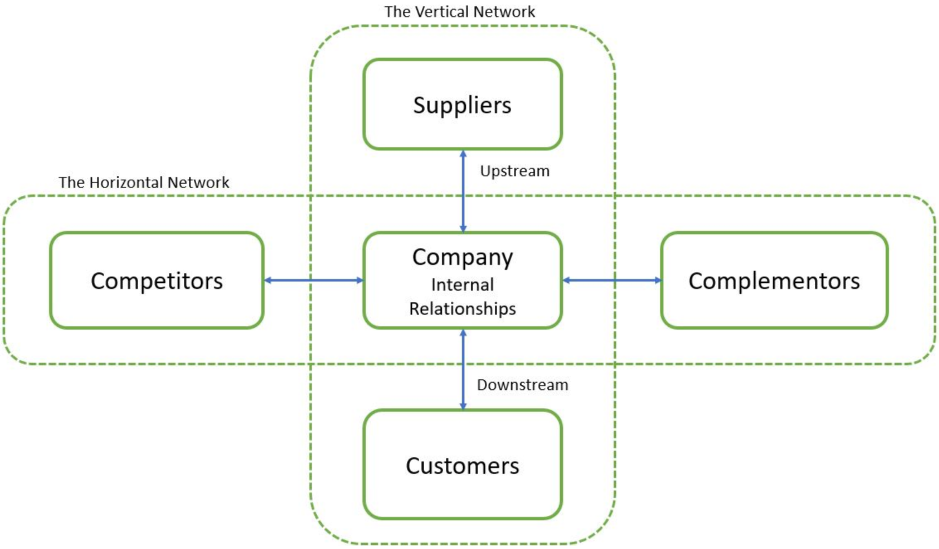


Figure 5.13: The Value Net (Hollensen, 2012)

5.4.3 Strategies for Identifying Value

PEST

PEST is a strategic management framework that evaluates macro factors that affect any industry. PEST is an acronym for Political, Economic, Social and Technological analysis.

Figure 5.14: PEST

SWOT

SWOT is another strategic management to help identify a products competitive profile within markets. SWOT is an acronym for Strengths, Weaknesses, Opportunities and Threats. The two former are seen as internal factors, while the latter two are external. SWOT is a beneficial exercise when examining different solutions in a project planning process.

Figure 5.15: SWOT

5.5 Utility

Utility is a term meant to capture the total satisfaction that is received from consuming a service or goods. In other words, utility is a measure of identified value. Utility theory has gradually evolved throughout history from Jeremy Bentham first developed the philosophical, ethical theory of Utilitarianism, the concept of maximising utility. In modern economic theory, utility functions have been used to find consumer preferences. A utility is either cardinal or ordinal. Cardinal utility is a quantification of the preferential order. The ordinal utility is a rank-ordering of the alternatives.

Despite the term cardinal and ordinal utility is pretty straight forward, utility is not always that simple. One example is the Bernoulli's St.Petersburg paradox within expected utility theory, that indicates a risky bet where the expected value is infinite. However, the play is not very promising for any players. Furthermore, in expected utility, von Neumann-Morgenstein four axioms are given for rational choice;

1. Completeness, the choice of deciding.
2. Transitivity, the options have to be internally consistent.
3. Continuity, the alternative can handle small changes.
4. Independence, the preferences are independent of irrelevant alternatives.

Prospect theory (Kahneman and Tversky', 1979) introduces the fact that humans are not always rational and can make choices that contradicts the axioms of von Neumann and

Morgenstein. Loss aversion is introduced in prospect theory and also experimental verified and indicates that stakeholders are more likely to care about avoiding losses than acquiring gains.

5.5.1 Multi-Attribute Utility

The utility will depend on context and stakeholder and can differ from scenarios. Multi-Attribute utility (MAU) theory is an attempt to measure utility across single-attribute utility functions. There are two methods for approaching MAU; value methods and comparison methods. Value methods include functions made independent of alternatives, such as cardinal utility or mapping between function-form. Comparison methods use comparing of alternatives to create utility rankings. Some well-known methods are, for example, the analytical hierarchy process (AHP) and rank-ordered centroids (ROC). If independence is assumed between the single individual utilities, MAU can be calculated by the equation Equation 5.1.

$$MAU = \sum_{i}^{N} k_i U_i(X_i) \tag{5.1}$$

Where U is the utility value derived from the attribute X, and k is the weighting factor, where the sum becomes 1.

This relation is also called the Keeney and Raiffa conditions (Keeney and Raiffa, 1993). They also present the possibility to establish an objective hierarchy, where properties have to be;

1. Complete, cover all critical aspects,
2. Operational, measurable and relevant,
3. Decomposable, splitting and grouping have to be possible,
4. Non-redundant, avoiding counting things twice or more,
5. Minimal. Keep it as small as possible.

As an example, counting things twice might give the attribute a double valuation and thus, it becomes a redundant attribute.

5.6 Value Robustness

Shipping cycles will happen, and the uncertainty related to future circumstances will create risks/opportunities, that has to be mitigated/exploited. Therefore, it is essential to create value robust design across the lifetime of the vessel. It is, of course, difficult to predict any future state of the business. Stopford ((Stopford, 2009)) tells it elegantly by saying

”it is a gambling game”, where each shipowner is like a poker player, where three main conclusions from risk management can be obtained. Firstly, for every winner, there must be a loser (carrying cargo or not). Secondly, shipping cycles are not random. Thirdly, each player has to assess the competitors and view their playing strategy (Stopford, 2009).

In the end, a shipowner will measure value robustness by the ability to create positive cash flow across a lifetime and short-run cycles. However, remembering that robustness is the ability to do the primary job in an unexpectedly adverse environment is essential. In an environment where the focus is on reducing GHG or local emissions, value robustness also includes emission reduction ability. The utility trade-off between break-even freight rates and new technology are essential for creating industry progress towards providing zero-emission solutions.

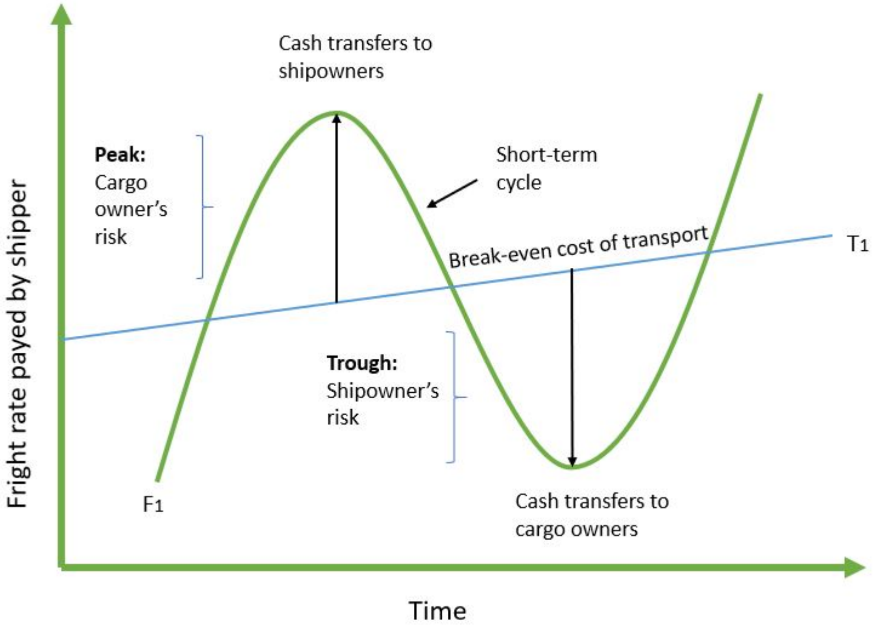


Figure 5.16: Risk Relation based on (Stopford, 2009)

The main risk takers are the shipowner and the cargo owner, and they perform a balancing game of supply and demand. As seen in Figure 5.16, they are oppositely related to the risk measuring game, any movement in freight rates will affect these two stakeholders. Likewise, since supply and demand are never exactly equal, the prices will fluctuate. Anyhow, the shipowners are the one that will be deciding to stay in the market or not (sell or buy ships). Cargo owner will have to pay required price. The exception is when the cargo owner moves upstream in the vertical network and provides their own transport.

In ship design, immense monetary decisions affecting many stakeholders have to be exercised early in the product development process. Often these decisions might be challenging and significant for further work and the lifetime profitability of the vessel. Consequently, it is essential to try to capture the value robustness of a vessel lifetime as precise as possible within the design phase. In the next chapters, a set based ship design method, RSC, try to capture the establishment of value robustness in a complex and uncertain environment.

5.7 Responsive Systems Comparisons Method

The Responsive Systems Comparisons Method (RSC) is an MIT-Developed(Massachusetts Institute of Technology) method by (Ross et al., 2009), that offer a methodology that tries to include the complexity in design and evaluate it over uncertain contexts. The objective of RSC is to develop value robustness during the lifetime for any product. In a maritime perspective, the product is the vessel. (Gaspar et al., 2012) introduces the RSC method as a possibility to create value robust designs over the five aspects of a complex system. Furthermore, the method can be seen as an extension of set-based design since it provides a large data-set of possible solutions. At the same time, RSC also provides a substantial focus on what stakeholders values and ”needs” are and how designers can approach their values and needs. Lets first explain the five aspects of complexity before introducing the RSC.

5.7.1 The Five Aspects of Complexity

A typical description of complexity is given through the five aspects structural, behavioural, contextual, temporal, perceptual (Gaspar et al., 2012). Figure 5.17 illustrate these five aspects of complexity in ship design.

Structural is related to the form in the traditional form-function mapping. It especially focuses on the ship as a large system that contains subsystems. A ship is also interacting with a larger structural aspect such as maritime transport system, which again is a part of a logistic chain system.

Behavioural aspect is related to the technical or engineering analysis that derives the functions from the forms. Any stimuli to a system crate a behaviour responding to the stimuli. These stimuli can be both internal(Propulsion) and external(waves). Moreover, it is the part where engineering methods such as finite element methods regression analyses of computational fluid dynamics can be used (Gaspar et al., 2012). However, behavioural aspects include also the performance towards other areas, such as environmental or safety behaviour.

Contextual aspect is given through exogenous variables that affect the design. In other words, factors or different stimuli that are not in control of the ship designer. These contextual aspects are considered fixed and predetermined during the elucidation phase. (Gaspar et al., 2012).

Temporal aspect is the change or shift in context during a lifetime. A typical shift can be demand, technology, freight rates, regulations or general market shifts Gaspar et al. (2012).

Perceptual aspects are related to the system stakeholders and how they interpret the changes appearing during the lifetime of the vessel. ”How is decision X perceived by stakeholder Y” Gaspar et al. (2012).

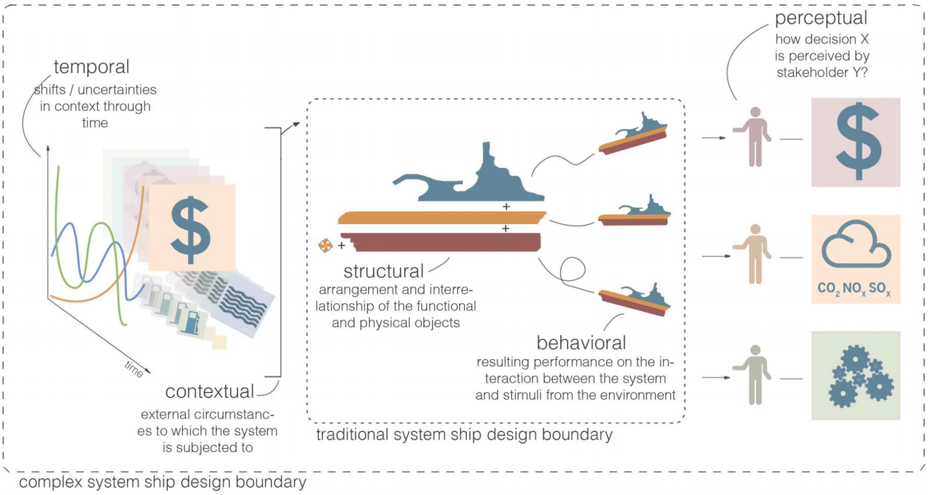


Figure 5.17: Five Aspects of Complexity in Ship Design (Gaspar et al., 2012)

5.7.2 Explanation of The Seven Steps in RSC

The RSC consists of seven steps, that are resembled in the flowchart in Figure 5.18, as explained by (Ross et al., 2009). The seven steps can be classified into three phases when applying it to ship design. The first phase is a pre-analysing state (Step 1 & 2 in RSC) including market analysis and value investigation (Establishment of needs). The second phase (Step 3 & 4 in RSC) is the combination of design space and epoch space to create a tradespace through the Epoch-Era methodology. The last phase (Step 5, 6 & 7 in RSC) is analysing and post-processing of results. The seven steps is explained under, while inFigure 5.19 illustrates the three phases simplifying the RSC to fit ship design.

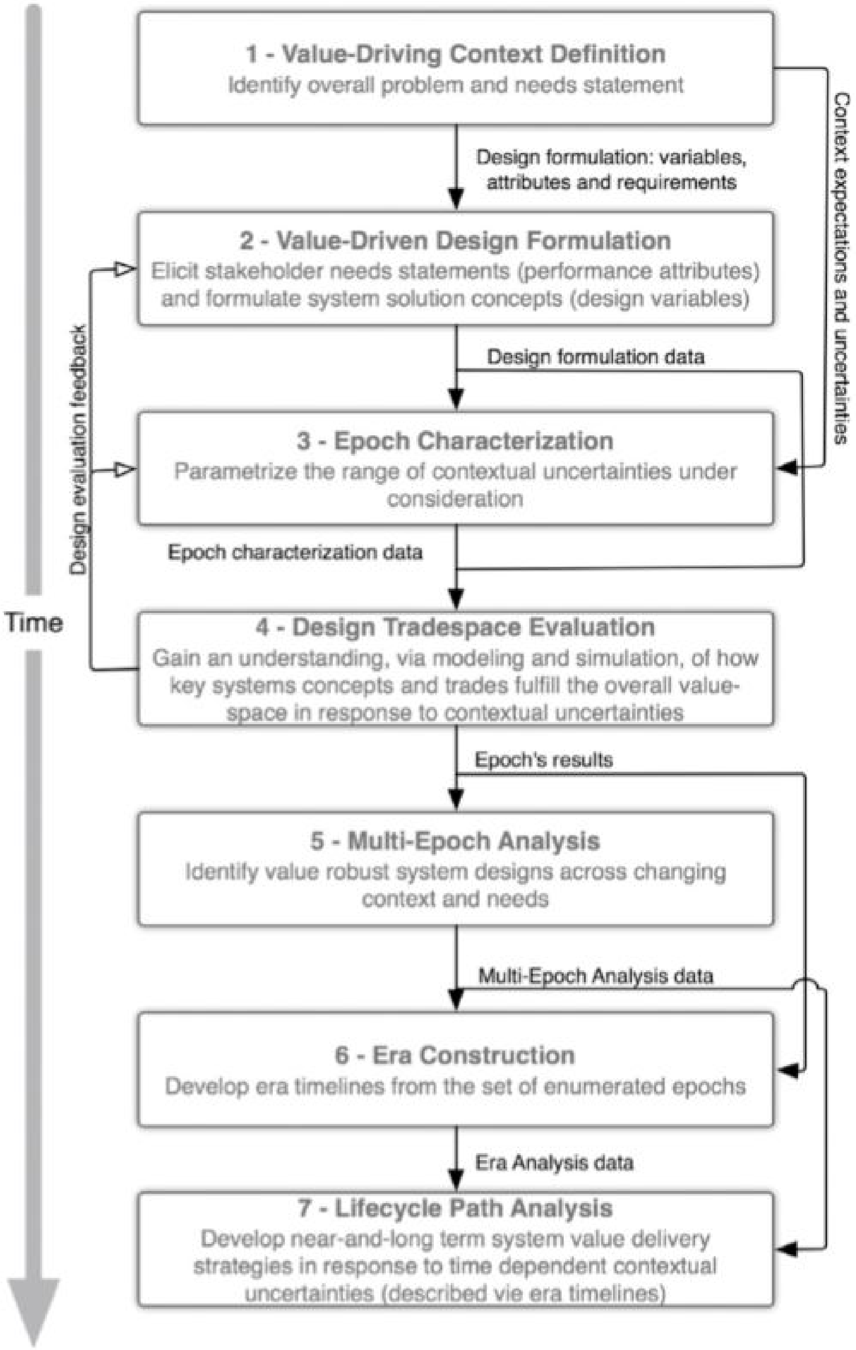


Figure 5.18: Flowchart of RSC as given by (Ross et al., 2009)

1. **Value-driven context definition**
   The first step should capture the overall problem or need statements. This includes a value proposition and the contextual description of the product. The main goal is to establish expectations and what should be considered value robust designs. This step will include the market and value analysis.

2. **Value-driven design formulation**
   The second step establishes the attributes and design variables. The attributes are linked to the stakeholders' needs and expectations. The design variables give solutions and decomposition of the structural aspect of stakeholders expectations.

3. **Epoch Characterisation**
   An epoch is a contextual situation, where the exogenous variables stay constant. In this step, a range of epoch parameters should be evaluated.

4. **Design tradespace evaluation**
   The tradespace evaluation is establishing an understanding of how any design reacts to a different context (epochs), and in which degree it fulfils the utility/needs established in the attributes.

5. **Multi-Epoch Analysis**
   In the multi-epoch stage, it is desirable to analyse the design space over contextual changes. Value robustness is here given as high performance over many epochs.

6. **Era Construction**
   An era is a timeline consisting of a set of epochs. An era can be seen as a potential lifetime.

7. **Life-cycle Path Analysis**
   In this last step, an evaluation of performance regarding the era construction is conducted. Comparing different design solutions within the short or long term system response to contextual uncertainty.

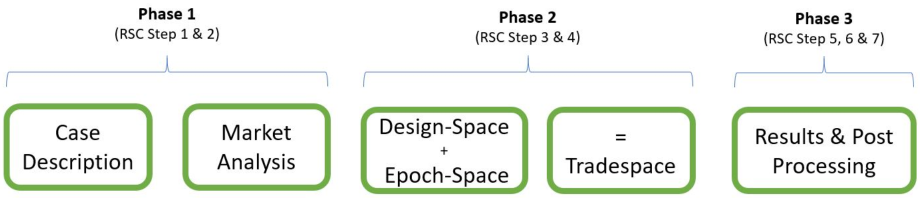


Figure 5.19: The Three Phases: RSC Applied to Ship Design

5.8 Decision Under Uncertainty

5.8.1 Pareto Optimality

By applying MAU theory on the different context that is developed throughout phase 2 (Epoch-Era), it is possible to decide which designs that perform with a high perceived value. Such an investigation is based on the method called the Pareto front. By plotting MAU and total cost for each design into a scatter diagram, each design can be visualised according to their values. The Pareto front will indicate those design alternatives that perform with the highest perceived utility for different costs. The different unique designs that are positioned align the Pareto front will be the designs that are giving the stakeholders the most value per cost. If looking upon a single context, the Pareto front display the best performing ship designs. Figure 5.20 illustrates the Pareto front as the orange line along with those designs that maximise MAU with the cost.

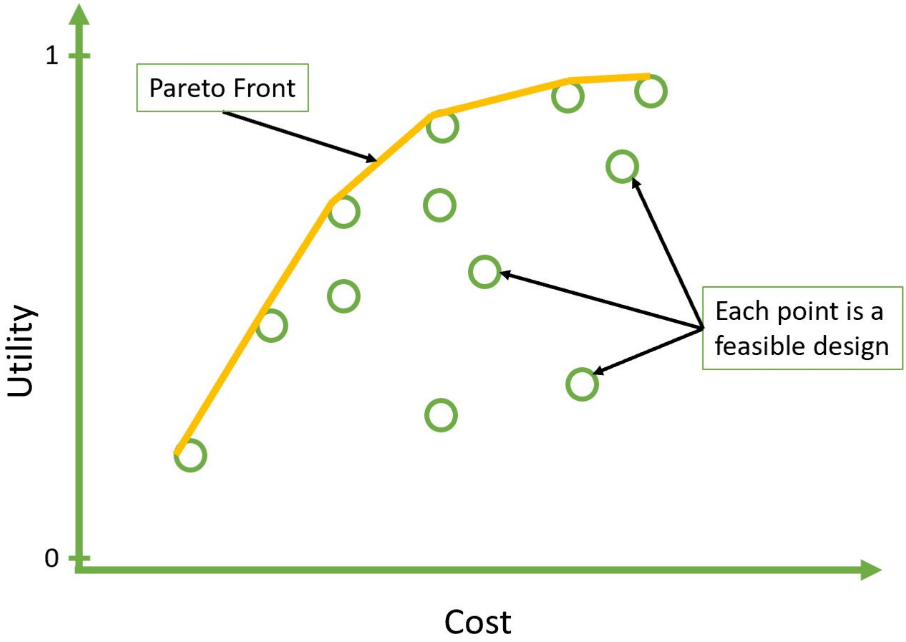


Figure 5.20: The Pareto Front

The Fuzzy Pareto Front

If a design is performing well over every shifting context, it would be an exceptional alternative. However, the possibility for a vessel to be a part of the Pareto front for every context over the temporal aspects is simply not particularly realistic. In that regard, the fuzzy Pareto front makes sure that a percentage of the more costly design become a part of the Pareto frontier. Expressing that vessels performing with a somewhat minor value perceived through utility and cost will become a part of the solution. The fuzzy Pareto front can be practical when the amount of designs along the Pareto front is inadequate, or they differ a lot between each context. Figure 5.21 shows the fuzzy Pareto front as the dotted orange line. All designs within the space between the Pareto front (thick orange line) and the fuzzy front (dotted line) will be a part of the solution.

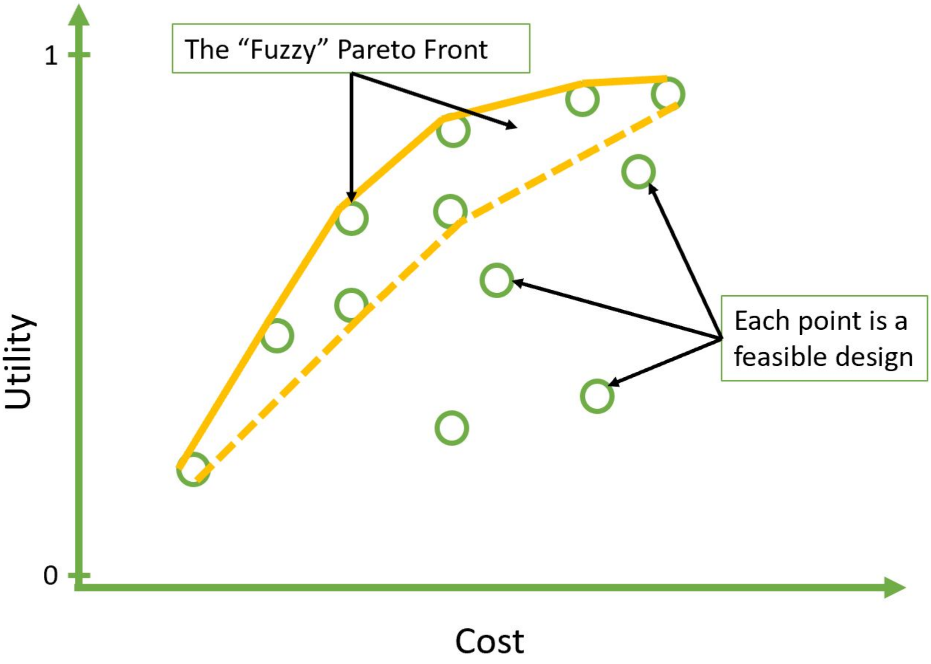


Figure 5.21: The Fuzzy Pareto Front

In a tradespace evaluation such as in the Epoch-Era methodology, the Pareto front is a reliable tool for indicating which designs that perform well. Sometimes it can tend towards one single design, but usually, it will not give a clear path to the complete right design. The reason for the lack of completeness that the changing temporal behaviour of the relevant epoch variables causes notable change upon the vessel. If there are several ship design that is indicated as great options, there is needed more specific decision making.

5.8.2 Alternative Decision Criteria

When the decision-maker (e.g. shipowner) has established a set of discrete alternatives, the shipowner can analyse different performances through a payoff matrix. A payoff could be ranging from monetary, such as cost, revenue or profits or non-monetary like technology and environmental performance. Figure 5.22 shows the principles of a payoff matrix. By plotting the responsive solutions for each alternative for each state of nature, the payoff matrix can be built. There might also be a probability related to each state and the occurrence of it.

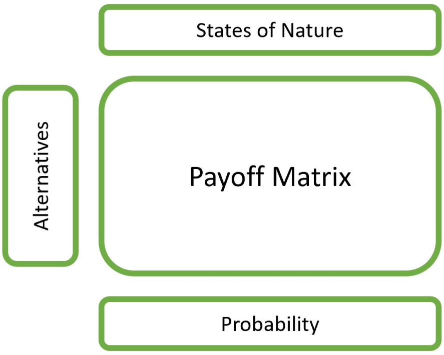


Figure 5.22: Illustration of the Payoff Matrix Based on (Erikstad, 2017)

As the payoff matrix is established, it is not necessarily obvious which design that is the rational choice. It will depend on the risk the decision-maker is willing to take. Below some alternative decision criteria are listed as based on (Erikstad, 2017).

1. **Maximin payoff**. In this case, the shipowner (decision maker) want to find the minimum payoff across the states of nature for all designs. Then the shipowner will choose the maximising alternative of those minimum alternatives. This method is seen as conservative and pessimistic since it not will necessarily choose the alternatives that will create the highest performance.
2. **Maximum Likelihood**. This one is straight forward; the shipowner wants to pick the most likely scenario (state of nature). The likelihood can be measured through the probability section in the payoff matrix. Finding the probability of uncertain scenarios might be a difficult game. Nonetheless, it is possible to select some probabilities based on the current information available. The barrier for this selection method is that serious relevant information might be ignored. Additionally, those state of alternatives that have low probabilities might give high returns and therefore is not ideal to ignore.
3. **Bayes Decision rule**. This is based on maximising the expected value. It is calculated by adding the product of each state of nature and probability for each design. The design that performs the best after the calculation should be the decided design. This method takes all the information into account, and that is the big benefit of this method. Again the probabilities are difficult to establish, and the results will be affected by the work done evaluating probabilities.

4. **Minimum Regret**. In this instance, a decision-maker wants to examine the difference between the best payoff and other alternatives for each state of nature. This difference is seen as regret. The alternative that has the lowest regret across each state of nature should be the preferred option.

5. **MAU**. It is the most ”value robustness” related criteria. The design that should be chosen is the one that performs with the highest multi-attribute utility. That could be in a single epoch or a multi-epoch analysis. Likewise, it can be in a single era analysis or a multi-era analysis.

6. **Min Cost, Max Profit, Max Revenue** This is the basic optimisation decision criteria used widely generally in business. It chooses the monetary best option, regardless of the state of nature or probability.

Chapter 6

Phase 1: Case Description & Shuttle Tanker Market Analysis

> *"I demolish my bridges behind me...then there is no choice but to move forward"*
>
> - **Fridtjof Nansen**, *Explorer*

6.1 The Case: Shuttle Tanker Supplying Johan Castberg

In 2022 Johan Castberg is estimated to start its production of crude oil. The oil field is located north in the Barents Sea at 73,26 N and 17,47 E, around 100 km north of the Snøhvit field and more than 150 km from Goliat (Equinor, 2019). Veidnes in Honningsvåg have for a long time been viewed as a possible delivery location through pipelines. However, other concepts have been evaluated, including the possibility of using shuttle tanker for transportation. This latter concept was chosen in late December of 2019 (E24, 2019). RSC methodology is applied for exploring this opportunity.

The closest oil refinery is at Mongstad, and it is used as the hub for offloading, in the case study. The case study estimates that a lifetime of a vessel that can supply Johan Castberg is 20 years. During these years the regulations that will be taken into account are the IMO 2020 sulphur cap, EEDI requirements for 2030 and reduction ambitions of at least 40 % within 2030. When approaching Mongstad, the vessel would need to comply with ECA regulations, and that will also include NO_X Tier III requirements (Olsen, 2019).

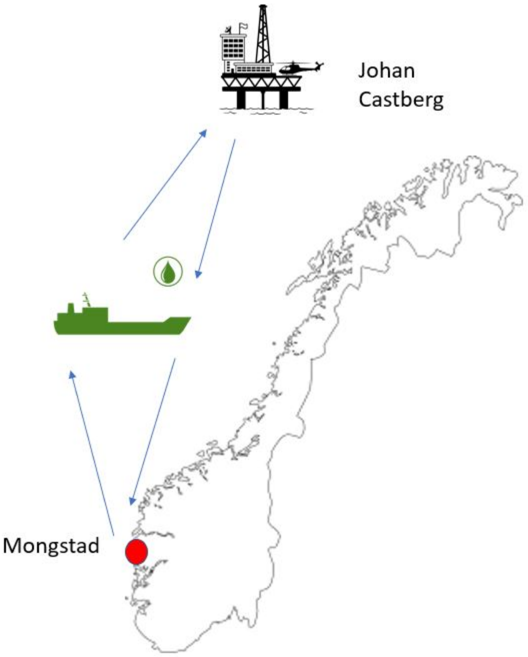


Figure 6.1: Conceptual Illustration of The Case: Supplying Johan Castberg with a Shuttle Tanker

6.2 The Shuttle Tanker

The Shuttle tanker can be categorised into a ”tailormade” or a ”market tanker”. The latter is used in calm waters, such as outside of Brazil and West Africa. On the other hand, in the North Sea, the tailormade shuttle tanker has to be used because of the weather conditions. Tailormade shuttle tankers come with two possible solutions; bow loading system (BLS) and/or a submerged turret loading (STL) system (Larsen, 2019).

BLS enables the shuttle tanker to load oil from an offshore FPSO or platform safely. The system consists of a hawser system, meant to establish a connection and deal with the forces acting between the marine structures. Further, a hose is used for loading of the crude oil. A telemetry system, a radio-based safety system, is used to control and monitor the transfer of oil. This practice is the so-called ”Green Line”, meaning that every item must be operative (green) for the oil to be transferred. If not, the system will automatically stop. BLS can be used in tandem loading (Larsen, 2019) (MacGregor, 2019). According to professor Kjell Larsen, NTNU, connection can be made with Hs = 3.5-4.5 and disconnection Hs = 5.5 m (Larsen, 2019).

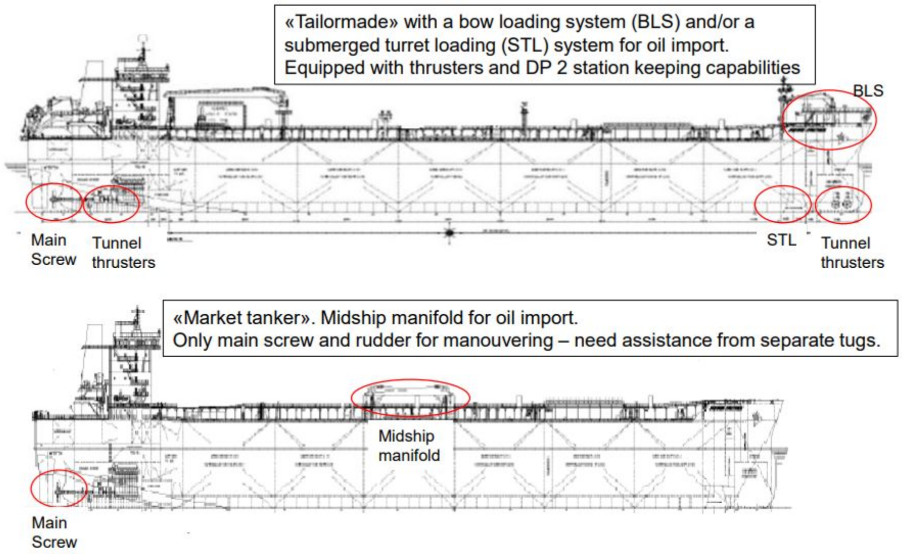


Figure 6.2: Tailormaide & Market Shuttle tanker as given by (Larsen, 2019)

STL system consists of a mating cone underneath the vessel that can receive the STL-buoy, which is a moored buoy on the seabed. This STL system is designed to be operative during rough weather, and at Heidrun field in 2001, two shuttle tanker stayed in operation during a 100-year storm with Hs = 16 meters and maximum wave height reported to be over 25 meters. Normal connection with DP is Hs = 4.5 (Rutkowski, 2019).

Both systems use DP-Systems for positioning during operation. DP 2 is required where loading of hydrocarbons and if they are not moored or anchored to the installations. DNV-GL assumes that 90 % of loading are in DP-mode (DNV-GL, 2017b).

Shuttle tanker designs loading rates are between 8000-9000 m^3/hour offshore, while onshore the terminals typically can handle a loading of 12000 m^3/hour. DNV-GL estimates that these processes will roughly take 24 hours and 18 hours, respectively. This time will certainly depend on size and amount of cargo that is transmitted, but the values are used as standard estimations of on/offloading (DNV-GL, 2017b).

Submerged Offshore Loading System (OLS) is a system without a hawser and only connected through the hose. OLS consists of a buoyancy element where the hose is connected, and the oil can flow to it through a riser. BLS system on the vessel is normally used, and DP 2 is needed (Olsen, 2019).

6.3 Analysis of North Sea Shuttle Tanker Market

6.3.1 Porters Five Forces

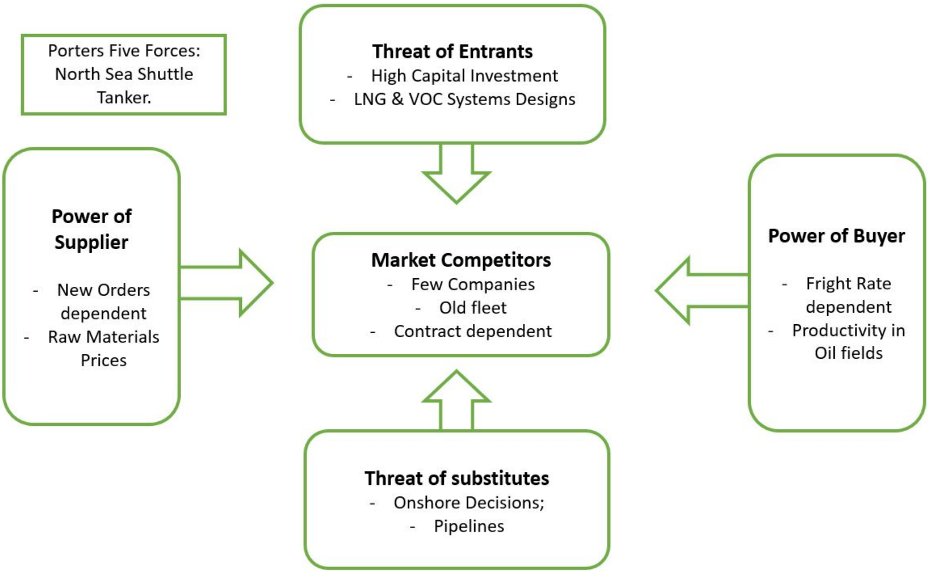


Figure 6.3: Porters Five Forces for the Shuttle Tanker Market

Market competitors. The biggest rivalry within the North Sea market is between the two largest companies Knutsen O.A.S and Teekay. They have 10 and 11 tankers, respectively. Teekay has six new vessels in order while Knutsen has three new orders. Other companies are also in the market. Stena has two vessels in operation, while Neste and Ugland have one each. However, these latter vessels are between 18-20 years old and can be expected to be phased out. AET is the rising competitor with two vessels operating (built 2015) and two new vessels in order. Appendix section B.2 show ordered and active shuttle tankers.

15 of these active vessels are 16 years and older. Therefore, are the 11 new vessels in order in line with the out-phasing vessels.

Exit barriers for any customer when chartering a vessel are dependent on the contract. A long-term contract makes it difficult to substitute any vessel, while spot or short contracts makes it easier to choose the vessel that provides the best alternative for the best price.

New entrants. As developing a shuttle tanker is a high capital investment, it is difficult to enter this market segment. However, newbulidings are in order, and these new vessels have designs with contemporary solutions. For example, Teekay and AET are at the forefront of developing shuttle tankers that meet future regulations. Both Teekay's Aurora Spirit and AET sister ships Eagle Blane and Eagle Balder, are equipped with VOC recovery system and fulled by LNG. Teekay is an operator already, so the company itself cannot be called a new entrant. However, the mentioned techniques can be categorised that way. In the case of AET, they are actively trying to enter the market and thus, it is a new entrant.

Suppliers. It can be distinguished between suppliers in this market. Shipyards might be seen as the supplier for the vessel as a product. In this circumstance, the power of the shipyard lies in the price of raw materials and the price they can offer. Additionally, the power depends on the shipyards capability to facilitate for new orders. At the same time, the price is a consequence of choosing a geographical location and different exchange rates (e.g. Building a vessel in South Korea will provide higher cost than compared to China).

Buyers. Oil companies chartering the shuttle tanker can be seen as the buyer. The power of the buyer lies in the productivity of the production fields and the number of vessels available.

A general issue is related to the amount the buyer can integrate its business downstream. As an example, when former Statoil used its wholly-owned company Navion for transporting oil. In this case, Statoil did not rely on other shuttle tankers. Navion was sold to Teekay in 2002.

Substitutes. The substitute to shuttle tankers are pipelines connected to onshore. Any pipeline between the oil platforms and onshore are making shuttle tankers obsolete. In the case of Barents Sea and Johan Castberg, it was decided not to establish a land-based terminal at Veidnes. As an example of a substitute, during the establishment of Johan Sverdrup oil field in the North Sea, a brand-new pipeline to Kårstø was established.

6.3.2 PEST for The Shuttle Tanker Market

P
Political

Political. In the Norwegian sector, political factors are mainly affected by the Norwegian government. The Norwegian government is one of the most stable in the world. Although Norway is outside the EU, it follows EU regulations closely. BREXIT might impact the close relation that shuttle tankers operating in the Norwegian sector have with the British sector. New British-Norwegian deals that are supposed to be negotiated during the first years of the 2020s will be of high interests for the shuttle tanker companies.

Furthermore, in the Barents Sea, the Arctic Council have an essential role in policymaking for the region. Besides, internally in Norway, there are numerous discussions about how

Norway should safely regulate the northern areas. As global warming melts the ice in arctic areas, new areas for seismic exploration opens.

Norway is highly committed to the Paris agreement and are reducing emissions along with EU. Further Norwegian government have enforced both EEDI and NO_x requirements. ECA zones are also applicable south of 62 N and east of 4 E. Norway and EU are very likely to adopt further regulations, and this is something to have in mind when designing of shuttle tankers.

Norway has been at the forefront of using LNG technology and have continuously supported technology that can deliver new energy sources. Infrastructure for hydrogen production is expected to grow. Also, Norway has a fund called the NO_x fund that gives subsidies to NO_x related technologies and instalments.

E
Economic

Economic. Shuttle tanker operational cost is profoundly affected by the fuel prices. Operational cost and related fuel price will simply depend on which type of fuel the vessel have for propulsion. Oil prices also have an impact on decision making. As an example, Johan Castberg first decisions were made when the oil price per barrel was around 120 USD. After the oil price drop of 2015, Equinor had to reduce spendings in the project gradually. The oil price will continue to fluctuate in the future, and it is challenging to foresee prices in the long run.

The global markets have seen high growth for a more extended period. Many speculate in possible recessions are to be expected. The fragile situation in stock markets, as seen with the coronavirus economic shock, might be something to consider. However, in a 20 years lifetime of a shuttle tanker, markets will fluctuate.

Exchange rates for the Norwegian krone have increased during the spring. In February 2020 the all-time highest NOK to Euro was registered. The effect of change in exchange rates can be evaluated through the macroeconomic IS-LM model for an open economy. In the GDP-Equation 6.1 , exchange rates are affecting the exports and imports. A depreciation in exchange rates will increase export and decrease imports.

$$y = C + I + G - IM/\epsilon + X \tag{6.1}$$

y is GDP, C is consumption, I are the investments, G is government spending, IM is import and X is export. Under the Marshall-Lerner assumption and short-run/fixed prices assumptions (ϵ = E). It is expected that the depreciation effects will increase net exports

(Blanchard et al., 2017).

An increase in net exports will increase GDP, and this will again increase imports, which again will decrease net exports which will again decrease GDP. A decrease in GDP will also decrease consumption and investments. Hence it might be inconclusive effects of depreciation in exchange rates.

Depreciation exchange rates will imply a decreased domestic interest rate. The decrease in interest rate will increase investments. Increased Investments will increase GDP.

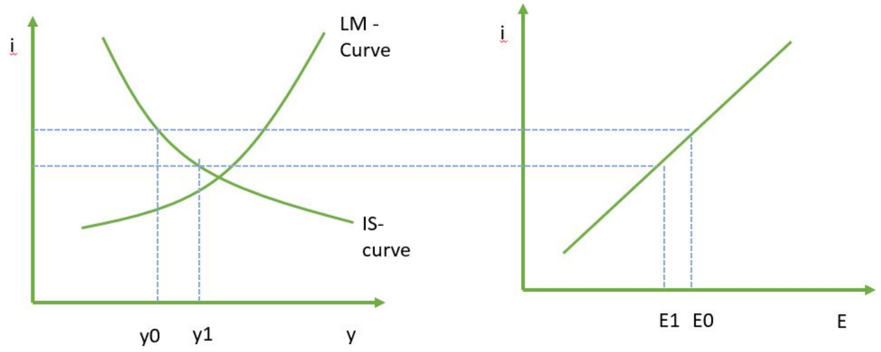


Figure 6.4: A depreciation in exchange rate could increase net exports and then increase GDP. A decrease in interest rate should be expected.
Left:IS-LM relation. **Right:** Uncovered Interest Parity condition.

Norway’s main exports are oil and gas, and with a decreasing oil price, the positive effects on exports might not be much, even adverse. Likewise, a weak NOK gives less consumer and investor power compared to foreign currency (Blanchard et al., 2017).

S
Social

Social. The social perception of the oil industry is an indispensable factor for further shuttle tanker operations. In recent years an increasing part of the Norwegian population wants to reduce/stop oil exploration. Regardless, the majority of Norwegians and in the political landscape supports continuing the oil and gas business.

A company also have what is called Corporate Social Responsibility (CSR). A definition of CSR is what a business puts back int the local or state economy in return for what it takes out (Hollensen, 2012). One side of CSR will also include ”green” solutions an practices, like meeting regulations and have a sustainable business profile.

T
Technological

Technological. A shuttle tanker is a complex system that consists of many different technologies that are crucial to the operation. In a zero-emission perspective, the technologies advancement within the engine and propulsion are the most compelling innovations. Optimisation of operation profile in the different ship modes (transit, field operation, port) are important factors in reducing total emission as well. Chapter 3 provides the most information about technologies and is recommended for extended investigation. As a reminder Table 6.1 provides the essential summary .

Table 6.1: Overview of Fuel and Regulations. Original: Table 3.1. (Olsen, 2019)

	IMO 2020	ECA Zones	NOx Tier III	EEDI 2015	EEDI 2020	EEDI 2025	IMO 2030	IMO 2050
HFO	No	No	Partial	No	No	No	No	No
MGO	Partial	No	Partial	No	No	No	No	No
ULSFO	Yes	Yes	Partial	No	No	No	No	No
Scrubber	Yes	Yes	Partial	No	No	No	No	No
LNG	Yes	Yes	Partial	Yes	Partial	Partial	Partial	No
LPG	Yes	Yes	Yes	Yes	Partial	Partial	Partial	No
Battery	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hydrogen	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ammonia	Yes	Yes	Partial	Yes	Yes	Yes	Yes	Yes
Methanol	Yes	Yes	Partial	Partial	No	No	No	No
Biofuels	Yes	Yes	Partial	Yes	Yes	Yes	Yes	Yes

6.3.3 SWOT for Hydrogen-Based Fuel Options

Ammonia

Strength. Entering the Shuttle tanker market with ammonia as fuel configuration is giving some interesting considerations. Strengths related to ammonia are the first-mover advantage, which means that there is little competition in this segment. It is expected that cooperation between shipowner and equipment supplier will be straightforward to conduct. In addition, the known zero GHG emission profile and deep-sea compliant are also pros.

Weakness. The biggest weakness is related to the absence of technology and innovation required to establish sustainable engine configurations lasting a shuttle tanker lifetime. There is no infrastructure, and the cost related to develop new fuel is a considerable barrier.

Opportunities. The opportunities are related to the increased demand for zero-emission solution and the regulations evolving.

Threats. The fact that no experience with ammonia as fuel can be a significant threat to the development of ammonia as fuel. These type of decisions is called a ”high risk - low data” decision, which means that the risk of choosing it as fuel is high, and a decision is based on limited knowledge. Ammonia is also toxic to humans and should be adequately handled.

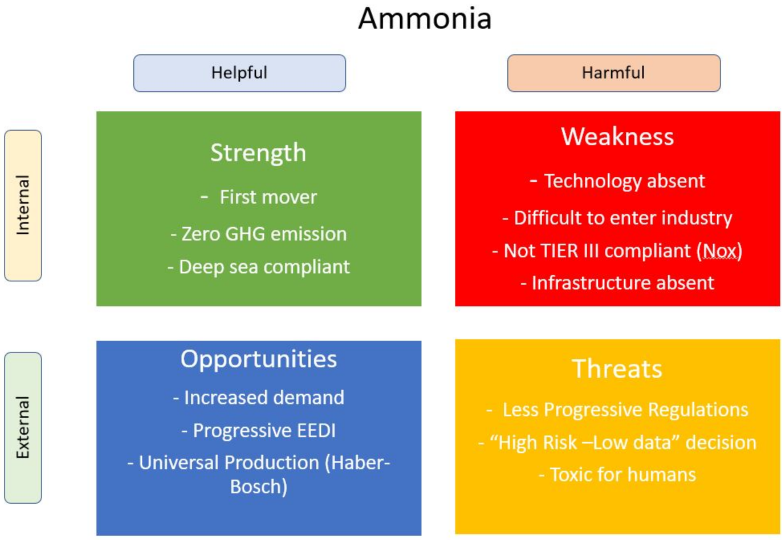


Figure 6.5: SWOT for Ammonia as fuel

Hydrogen

Strength. Hydrogen also is relative to first-mover technology. It also provides zero emissions for both GHG, NOx and SOx.

Weakness. Hydrogen space requirement is the most substantial barrier, which means that it is not feasible for deep-sea shipping. Hydrogen is also easily ignited and has to be handled gently.

Opportunities. Hydrogen demand have increased, and infrastructure is therefore expected to be developed. It is also possible to use hydrogen for other industries like truck and cars. The synergies from multiple industry development can provide reduced cost and higher willingness for hydrogen as fuel.

Threats. Hydrogen does not have the best public view. Mostly due to vigorous accidents, such as the Hindenburg zeppelin explosion. Likewise, in 2019 a hydrogen station exploded in the outskirts of Oslo. It is also a high risk-low data decision, mainly because of the price levels are high.

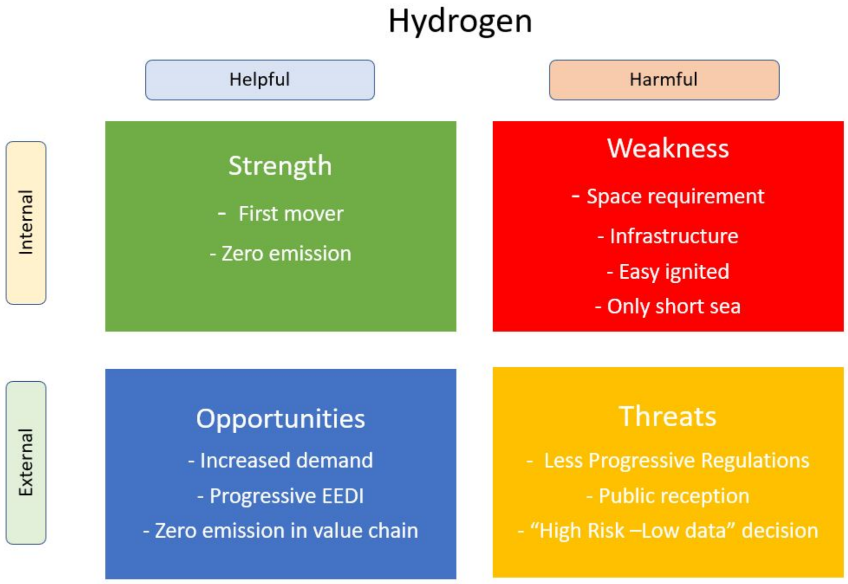


Figure 6.6: SWOT for Hydrogen as fuel

6.4 Stakeholders- Shuttle tanker

6.4.1 Shipowner

Shipowner Values:
Robustness, Reputation, Utilisation, Contract,
Break-Even Freight Rate

A shipowner preferences depend a lot on the circumstances, conditions and contract the vessel will operate within. A charterparty is the name of a maritime contract between shipowner and charterer. The shipowner can operate a ship in the spot market or long term employment. The spot market is, by definition, a market where commodities are traded for short term delivery. In this situation, a shipowner would appreciate high freight rates and abundant supplies of spot cargo. In a dedicated market, vessels operate in more extended contracts. These contract can be from 6 months up to the vessel lifetime. Reasonable contract length in general for a shuttle tanker is around 5-7 years, while shuttle tanker lifetime is typically 15-20 years.

Regarding new technology, shipowners, are foremost interested in the bottom line of the investments. High-risk decisions into new areas of expertise can be costly if the owners cannot earn money on the new assets. It is therefore likely that a shipowner investing in environmental-related equipment and propulsion systems want long term contracts for their vessel. These contracts could be between 7 - 15 years, and reasonably have real options in the specification of the contract. Real option practice indicates flexibility for both shipowner and charterer. A vessel with new and expensive specifications would be challenging to trade in a shuttle tanker spot market. The reason for this is that the spot market will demand a more competitive profile. The annual cost for newbuildings is usually high in the early operational years, resulting in the long term contracts with real options.

Bareboat is another charterparty alternative for any shipowner. In this trade, the shipowner delivers an ”empty” ship for the charterer. The charterer has responsibility for crew, maintenance and other operating costs during the time of the contract. For a shuttle tanker companies, this is not standard practice, since they want to provide crew and competence themselves

Shuttle tankers are expensive assets, and shipowners value good relations with banks or other financial institutions. They will provide loans depending on the asset and the reputation and quality of the shipowner. In some cases, it is also possible to lease the vessel from financial institutions, but the shipowner does not own the ship and is, therefore, more restricted in options. The shipowner can, for example, not sell the ship, as they usually can rely on as an economic income decision. However, there is often a call option (the right to buy at a later time) related to this type of charterparty. As time goes, the call option will be lower due to the drop in the value of the vessel.

Furthermore, for the shipowner, the regulations required at the operating waters are essential, likes of ECA, NO$_x$ TIER II/III and EEDI requirements. Regulations will change the specification of tenders and such influence changes in the vessel design. A typical procedure today is to design for retrofitting engine system. Hence, establish options that can increase the flexibility of the vessel.

6.4.2 Charterer & Operator

Charterer Values:
Market Relations, Operability, Reliability, Safety

Charterers in the oil industry are willing to accept high charter rates to deliver the relevant cargo. However, the charterer must not pay more than the competitor, which means that the charterer offerings are related to market fluctuations. If the market is competitive for the shipowners, and charterer freight rates are diminishing, charterers tend to establish long term contracts. On the other hand, if the market is good and rates are high, charterers want to prefer spot contracts. In the shuttle tanker market, the dynamics are somewhat different. The main reason lies in the fact that there are few shuttle tanker companies and thus commitments depend on the situation both for shipowner and charterer. The charterer for a shuttle tanker is the operator of oil fields, such as Equinor. Operators would typically give tenders that suits their market situation and choose the cheapest option. Nonetheless, they will accept the current shuttle tanker market price spectrum. In other words, a shipowner cannot provide vessels supporting tenders were the shipowner will lose money.

The operator of an oil field will have the responsibility for daily operations, including project management and chartering. Oil companies can generate tenders based on specifications of preferences, for both new vessels and existing vessels. Typically for existing vessels and spot market, brokers are used to attaining actual vessels. Due to the dynamics of shuttle tankers and the oil industry, operators are influential for creating an environment where new technology is appreciated and preferred. Operators will in the shuttle tanker segment ordinarily bypass vessels that are twenty years and older. This process is basically because of the risk of using an older vessel in this particular ship segment. Finally, the aspect of redundancy is fundamental to the operator. In this case study, only aspects surrounding one vessel design is conducted. Nonetheless, it could be relevant for an operator to charterparty several vessels to reach redundancy in the system.

6.4.3 Shipyards

Shipyards Values:
Competitiveness, Competence, Price, Continuity

In general, shipyards views competitiveness and market positions as the main factors affecting their business. Competitiveness is vital to get any contract for newbuildings. A shipowner can be competitive on price, but also within competence. In the shuttle tanker market, both are important—price due to the size and competence because of the vessel complexity. The shipyard position in the market towards competitors is mattering for them, so they can be the ”preferred supplier” when shipowner wants to request a new vessel.

Moreover, shipowner demands affect the shipyard position in many ways, including market requirements like classification, regulations, flag state and operational requirements. A shipowner usually comes with a specification with design, equipment and inventory that the shipyard has to acknowledge. Typically, are general arrangement and main engine decided by the shipowner, while inventory and other equipment are provided as a list of possible suppliers that the shipyard can select arbitrarily from. The shipyard might have some preferences in dialogue with the shipowner, such as a wish to use local suppliers. In such event, the provided specification list are their options.

Shipyards avoid decisions based on uncertainty since ship investments are time-consuming, and that can provide a lack of defined information resulting in undesired outcomes. Shipyards will, therefore, prefer contracts that are given in series and will hesitate with novel designs. Moreover, new designs require competence and modifications in the building process. Shipyards are accordingly less likely to push the industry towards environmental options and would pass the buck in that regard to the shipowner.

Contracts are in USD, and usual payments are given in equal instalments where each amount is paid at milestones of the building process. The last instalment is at delivery and the acceptance of the vessels. Extra cost to the designs during building time is estimated and decided before delivery. Interest cost through the building period is also added to the final calculations.

6.4.4 Classifications Society

Classification Societies Values:
Innovation, Relation,

Classification societies are companies that maintain and establishes technical standards for construction and operation of offshore constructions and vessels. These companies are often focusing on innovation and advisory for the shipping industry. Furthermore, they modify their regulations so that they can approve new equipment and innovative solutions. For any operating vessel, a re-classification has to happen every fifth year at the dock.

6.4.5 Bank & Financial Institutions

Bank & Financial Institutions Values:
Risk, Reputation, Sustainability

As mentioned following subsection 6.4.1, a ship is a high capital asset that often is financed through loans at banks or other financial institutions. Reputation is as important in shipping relations, and the amount of loan a shipowner can apply depends on it. From the financial literature, a dept can either be predetermined or rebalanced. When rebalanced, it can be either be periodically or continuously rebalanced. The amount of cash that have to be repaid depends on CAPEX and details in the contract between shipowner and financial institution. A rest value is the estimated number the vessel is worth at the end of the planned engagement period, where the dept has to be repaid. If a higher rest value is to be expected, then a lower amount of money has to be allocated to repay debt. However, a higher risk is associated with higher rest value.

6.4.6 Governing Rules & Regulations

Governing Rules & Regulations Values:
Jurisdiction (Globally & Locally), Innovation, Stability, Growth

Government rules and regulations are the fundamental institutions influencing maritime construction. Every ship has to follow the maritime codes. These codes are, first of all, connected to the International Maritime Organisation (IMO). IMO is a UN agency (171 member states) including mostly nations that have involvement in shipping. Each member state has a particular set of opinions and objectives that drives their decision making. Likewise, conflict of interests is unavoidable, and it is also the main reason why it takes a longer time to introduce new regulation. Anyhow, IMO codes such as SOLAS (Safety of Life at Sea) and MARPOL (Marine Pollution) have been global adapted and conducted effectively. MARPOL decides zero-emission regulations at sea, and member states willingness to adapt new solutions are depending on MARPOL to include zero-emission sufficient regulations. The enthusiasm for adoption lies in the individual flag state and port state.

Flag State

The flag state of a vessel is the jurisdiction where a vessel is registered or licensed and which laws it is operating. A vessel can only register in one jurisdiction. The flag state has the responsibility to enforce regulations and have authority over all vessels sailing under its flag. Different state members have ratified different regulations which can affect the different commitment between flag states. Flag of Convenience (FOC) is a business practice where ship owners register a vessel in a different country then the shipowner. There might be many nuances, like taxation or labour laws, that make a FOC a better option than the shipowner's home country.

In Norway, there are two registries NOR Flag and NIS flag. NOR flag has no trade restrictions within Norwegian waters. NIS flag is the Norwegian international ship register, is a more international adjusted register, but will also have some restrictions in some port and some areas in the Norwegian Continental shelf. NIS is made for competing with other FOC. For these considerations, any vessel needs to choose its flag state wisely according to where they will trade and operate.

Port State

A port state is the local authority where the vessel will operate. A port state applies different restrictions within the port and national state. Therefore, a FOC, that often have loose requirements worldwide can be denied in a port. An example of port restrictions are decisions that have been in the news picture lately about banning the open-loop scrubber in several ports globally.

6.4.7 P & I Clubs

P&I Clubs Values:
Jurisdiction, Risk management, Safety, Reputation

P&I (Protection & Indemnity) insurance are the mutual maritime insurance that is provided by P&I Clubs. These clubs are providing cover for losses that shipowners or cargo owners might experience. Such losses can be, e.g. damage to cargo, war risks, oil spill. P&I are associations that provide a risk pooling form of risk management for its members. Members are mainly shipowners, ship operators and (bareboat)charterers. Members pay a premium that covers a specific time (a year or a voyage), then the money is put together with other members premium in the club's pool. If no accident happens, the members will pay less in future years. If a massive accident happens that is larger than the pool, P&I members have to pay immediately to cover any costs. The thirteen most comprehensive P&I clubs are also a part of an International Group of P&I Clubs, which provide the same principle of risk pooling for even more significant accidents.

P&I Clubs value a shipowner ability to operate and its reputation a lot. The vessel should be used for the right purpose, and it should follow the rules and regulations as well as government information. P&I portfolio of members should provide as low risk as possible and P&I and their premium will depend on ship owners ability to meet P&I's criteria and demands.

6.4.8 Leading Equipment Suppliers

Equipment Suppliers Values:
Innovation, Reputation, Competitiveness

The leading equipment suppliers have a traditional market approach to its business. They want to be as competitive as possible while simultaneously providing the best possible price alternative. For that reason, leading suppliers have an innovative role in shipping, but at the same time, they have to supply a portfolio of prominent products. Much of the customer target is to become a part of the ”makers list”—a list of equipment options that the shipowner provides to the shipyards. Leading engine suppliers target shipowners directly since choices of primary propulsion system are made by the shipowner. Finally, leading equipment suppliers targets local production companies with licence construction of their selling products.

6.4.9 Public

The Public Values:
Corporate Responsibility, Innovation, Progress

In the end, public opinion is the main provider of the change in an industry. Shipping is not a topic that is at the forefront of public discussion, but shipping is also affected by the increase in global warming awareness. The public opinion will guide politicians and legislative organs, which again will sustain pressure on international governing rules and regulations.

Chapter 7

Phase 2: Epoch-Era Development

> *"In the midst of each epoch, I fully realise that a new epoch will dawn."*
>
> \- **Marcel Duchamp**, *Artist*

7.1 Design Space

Design space is the set of possible designs based on the endogenous design variables. The design variables should be reasonably chosen in a range within existing vessels as an indication to main dimensions. Anyhow, it is vital to have some slack to the range for including new possible designs. The whole point of Epoch-Era method is to evaluate as many feasible designs as possible and find those with high performance.

The web-portal SEAWEB provides relevant information for all existing shuttle tankers operating or in order. This data set can be seen in appendix section B.1, and it provides beneficial information for establishing a relevant range for a shuttle tanker. Shuttle tankers operate worldwide, and the vessel serving various locations will have different characteristics. Understandable some of the data provided from SEAWEB is not precisely relevant for the North Sea operating vessels. Therefore, it can be favourable to only look at the vessels operating (or intended) in the North Sea. To create a more representative data set for North Sea shuttle tankers, the vessel that is smaller than 100 000 dwt are excluded. The excluded vessels are operating in areas much different from North Sea market (like oil transport within Russian territory within the North-East Passage.) From the shipbroker firm Galbraiths, the vessels assigned to the North Sea are listed in appendix section B.2.

Design Space Consist of Endogenous Variables

7.1.1 Main Dimensions

The main dimensions are essential for describing the different vessels measures and characteristics. From the data set, it can be seen that typical vessel length overall (Loa) are in the range of 250 - 290 meters. Breadth (B) is in the range of 40-50 meters. Furthermore, depth (Dr) lies around 20-25 meters. Draught (T) is between 15-18.

Although main dimensions are in the mentioned ranges, many of the design will not be feasible since it will give properties that will make an unrealistic relation between the ship characteristics. Infeasible designs could consist of dysfunctional relations within characteristics like e.g. resistance in water, stability and strength of the hull. Therefore, dimension relations are necessary within the start phase of designing. Firstly, the relation L/B have a significant impact on the resistance in water and sea characteristics. A higher number indicates fast vessels, and smaller numbers are related to slow steaming vessels. For shuttle tankers, the L/B is between 5-6.5 [-]. B/D relates to the strength and stability of the vessel. Values for shuttle tankers in the data set are between 1,8 - 2,3 [-]. The B/T most common values are between 2,6-3,3 and are an indication of the stability conditions (Amdahl et al., 2015). L/B and B/D are modelled as constraints for excluding infeasible designs in the design space creation. B/T was not modelled as a constraint as the values range of B and T makes B/T feasible .

L/B Relates to Resistance and Sea Characteristics.
B/D Relates to Strength and Stability.
B/T Relates to Stability.

Speed is also an important factor for this evaluation. Reduction in speed might become a factor that is highly evaluated in the future. The speed range is frequently lying between 14.5 to 15 knots. However, in this design space evaluation, a discrete range with levels 10,12.5, 15 is used.

7.1.2 Equipment

Some equipment and machinery decisions have to be evaluated in the design space creation. Machinery has been divided into four categories;

1. ULSFO
2. LNG
3. Ammonia
4. Hydrogen

Every design is assumed to have a VOC system, and each design will be compliant to IMO2020 sulphur cap. Additionally, STL and BLS system is assumed similar for each design. The same applies to DP technology. DP system is also required and that are either DP2 or DP3 (DP2 is minimum required), but in this modelling, they are not elucidated. These variables are all essential for each ship but do not provide any notable difference in cost. Hence, they are not apart of the modelling, in order to reduce computational variables.

On the other side, design properties like Flettner rotor and battery pack are included. Both are yes/no decisions. In the end, an ”engine option” is added as an optional extra cost that can improve engine performance or can be seen as a retrofit option in order to comply with environmental regulations. Each of these three variables is assumed to reduce GHG with 10 %.

The design variables are summarised in Table 7.1:

Table 7.1: Design Variables

Variable	**Unit**	**Range (min -max)**	**Levels**
Length	m	250 - 290	11
Breadth	m	40 - 50	6
Depth	m	20-24	3
Draught	m	15-18	3
Speed	kn	10-15	3
Machinery	[-]	[1,2,3,4]	4
Flettner Rotor	yes/no	[0,1]	2
Battery Pack	yes/no	[0,1]	2
Engine Option	yes/no	[0,1]	2
			Total designs: 57 024
Constraints			
L/B	[-]	5-6,5	
B/Dr	[-]	1,7-2,3	
			Feasible designs: 37 728

7.2 Epoch Space

Epoch variables are properties that are assumed the same within the same context. Similar to the design space, the epoch space consists of variables. However, epoch variables are exogenous variables, and these variables will fluctuate or change during a shift in contexts. Price levels are one example of such an important indicator, and it will give indications on performance for which machinery system that will perform.

Epoch Space Consist of Exogenous Variables

Hydrogen prices are difficult to predict, due to the lack of information and infrastructure in the current market. However, DNV-GL did an estimation of cost by separating production into the cost of electricity and cost for electrolysis. The two methods established in this report are alkaline and PEM electrolysis. The cost for electricity is estimated to be 0,34-0,67 NOK/kWh in 2020 and 0,38-0,77 NOK/kWh in 2030. The results of the DNVGL estimation are between 20 and 50 NOK/kg, equal to 1900 - 4750 USD/Tonne. It is higher than what can be produced through gas (8-15 NOK/kgH2) (DNV-GL, 2019b, page 19-25). This relatively high cost of producing ”green” hydrogen is an issue for the compliance, and the price should be reduced. Low electricity price will reduce the price. Furthermore, NVE (Norges Vassdrag og Energidirektorat) estimates the possibility of lowering the price of electricity down to 26 øre/kW, at places with high wind potential. DNV-GL estimates a hydrogen cost of production down to 15 NOK/kgH2, which is comparable to hydrogen production through gas. It is required to mention that today’s (March 2020) electricity prices at 10-15 øre/kWh would probably give an even lower hydrogen price. In the end, it would be beneficial to estimate a range in hydrogen price between 380 and 1900 USD/-tonne.

Ammonia prices are, as discussed earlier(Chapter 3), at the moment made from fossil fuels and its current production links the price with gas prices. The historical prices have been between 200-700 USD/tonne. However, since green ammonia is necessary, the production will be heavily related to hydrogen prices.

ULSFO prices are in the range of 250 - 600 and is based on the latest development throughout 2019-2020 from Rotterdam prices (Bunker, 2019). LNG is usually in the same range as diesel-based price levels, but somewhat lower. Therefore, the range of LNG is assumed from 200 - 600.

All of these price ranges is given with a discrete five-level range. Prices are either very low, low, medium, high or very high. This categorising is a technique in the epoch space creation in order to capture fluctuations while at the same time keep fewer variables to the system.

As known, environmental regulations will be taken into effect in the coming 30 years. EEDI requirements and IMO ambitions can be seen as changes in epoch variables. These regulations can be seen as yes/no variables. If yes, then the regulation is ratified, if no, then business as usual. Oil prices had the range between 10-120 [1].

---

[1] Crude Oil was intended to be a part of the model to reflect future investments. However, in the end, it was excluded due to a change in information around production at Johan Castberg. It is, therefore, a part of the initial epoch space, but it does not affect any other variables.

Table 7.2: Epoch Variables

Epoch variable	Unit	Range (min -max)	Levels
ULSFO Price	USD/tonne	250 -600	5
LNG Price	USD/tonne	200 - 600	5
Ammonia Price	USD/tonne	200-700	5
Hydrogen Price	USD/tonne	380 - 1900	5
EEDI 2025	yes/no	0 - 1	2
IMO 2030	yes/no	0 - 1	2
(1) Crude Oil Price	USD/bbl	10-120	5
			Total: 12500

Production at Johan Castberg

The average future production is known information and will be added to the chosen epoch space. It follows the estimation given in the impact assessment by (Equinor, 2017) provided for the Norwegian government. The assumed yearly production rate is shown in the y-axis while time is shown in the x-axis (Figure 7.1). The colours indicate different areas. Table 7.3 show the resulting epoch variables that will be added, and they are based on the Figure 7.1.

Table 7.3: Known Epoch Variables

Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5
10 mill Sm^3	5 mill Sm^3	2 mill Sm^3	1 mill Sm^3	1 mill Sm^3

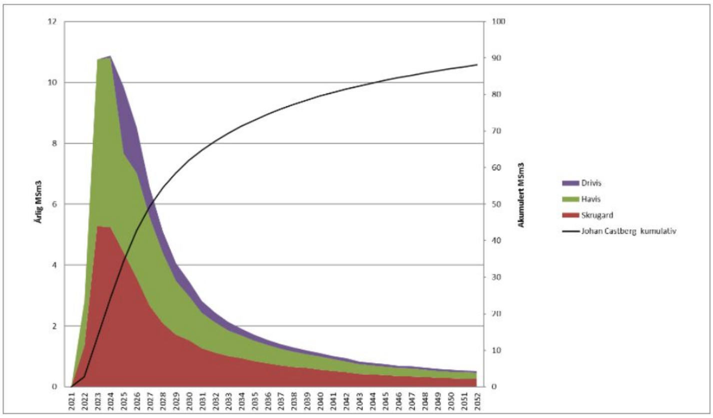


Figure 7.1: Estimated Production at Johan Castberg (Equinor, 2017)

7.3 Tradespace

The tradespace are the variables that either is functions of design space, epoch space or both. The tradespace is created through evaluating and combining the design and epoch space. For each feasible design, a relating value representing some information in the tradespace is modelled. In the following sections, each variable is presented as they are programmed in the MATLAB scripts.

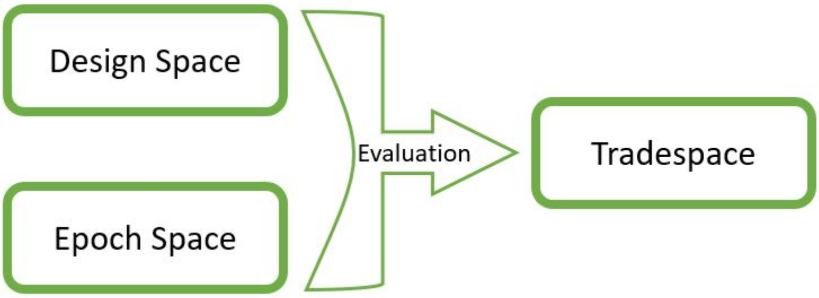


Figure 7.2: Tradespace is the Evaluation of Design Space and Epoch Space

7.3.1 Capacity

Capacity is a function of the main dimensions and will vary across each design. As explained in Chapter 4, the size and speed of the ship affects machinery and power.

Payload

The payload is the cargo that can provide earnings for the ship and for a shuttle tanker it is given in barrels of oil (bbl). The payload is the deadweight minus general supply and crew related weights, like, e.g. food supply, freshwater. It is difficult to estimate how much of a vessel total volume that is the payload, but it is possible to use a reference vessel to establish a percentage of total volume that is the payload.

Aurora Spirit (Teekay) is used as a reference, and its payload capacity is given as 815 000 bbl. This is equivalent to approximately 130 000 m^3 (1 bbl = 0,159 m^3, see section A.3). With main dimensions 276 Loa, 46 B, and 23 Dr, the ”cube” are approximately 290 000 m^3. To get the payload ratio dividing 130 000/290 000 gives approximately a ratio of 0.45 (Figure 7.3). The tradespace payload value is therefore given by the formula in Equation 7.1.

$$Payload = 0.45 \cdot Loa \cdot B \cdot Dr \tag{7.1}$$

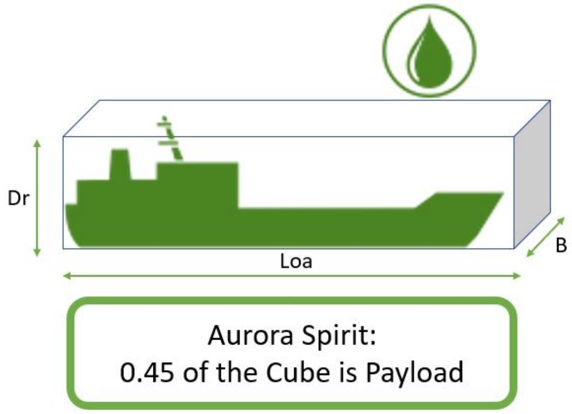


Figure 7.3: Assumption: 0.45 of the volume of the cube is payload

Lightweight

The lightweight is important in the estimation of cost of hull. The lightweight can be given from subtracting deadweight (DWT) from the weight displacement (Δ), as seen in equation Equation 7.2.

$$Lightweight = \Delta - DWT \tag{7.2}$$

Weight displacement is the weight of the ship and can be calculated by multiplying amount of fluid displaced or (volume) displacement (∇) with the density of the fluid (ρ). In this case ($\rho_{seawater}$) is seawater 1,025 tonne/m^3.

$$\Delta = \nabla \cdot \rho_{seawater} \tag{7.3}$$

Volume displacement can be found through the properties of block coefficient, C$_B$, which are the ship fullness of the block displaced under water (Equation 7.4). C$_B$ for a shuttle tanker is relatively large with a value between 0,8 - 0,9. A C$_B$ of 0.85 is used in this evaluation.

$$C_B = \frac{\nabla}{L \cdot B \cdot T} \tag{7.4}$$

In this project DWT and payload is assumed to be equal since the difference is small in most cases. Normally the difference will include the weight of the crew and some equipment. Since the payload is calculated as Sm^3 it is important to change the values to tonnes when using payload in other equations measuring tonnes. 1 Sm^3 = 0.858 tonnes crude oil section A.3.

7.3.2 Power & Sailing Time

Power

As explained in section 4.1 about infrastructure, the necessary power to move the ship through water is a function of size and speed. Remember that required kilowatt increase with speed to the power of three and resistance increase with displacement with the power of 2/3. Again the empirical Equation 7.5 is used to calculate representative design power (kW).

$$kW = k \cdot q^{0.5} \cdot v^3 \tag{7.5}$$

q is the capacity in tonne and v is the speed in knots. k has the value 0.0132, is in this case calculated from the reference vessel Aurora Spirit. That is possible since kW is known for that vessel.

Sailing time and Roundtrips

Sailing time (T$_s$) and amount of roundtrips per year (R$_y$) are both essential for calculating fuel costs. Furthermore, they are both a function of design speed. Sailing time can be calculated as distance divided by speed Equation 7.6 and roundtrips per year are calculated as the number of days a year in operation divided by time to complete a roundtrip Equation 7.7. OH, is the off-hire and are assumed to be four days, while T$_p$ is time in port and T$_o$ is time in operation. The values are 24 and 40 hours, respectively.

$$T_s = \frac{nm}{v} \tag{7.6}$$

$$R_y = \frac{365 - OH}{T_s + T_p + T_o} \tag{7.7}$$

7.3.3 OPEX & CAPEX

OPEX

Annual OPEX can be seen as fuel consumption cost, C$_F$, plus eventually fixed cost, C$_D$ (Equation 7.8), which is according to Galbraiths Oslo office estimated around 15 000 USD/day for Norwegian sector in the North Sea operating in North Europe.

$$OPEX = C_F + C_D \tag{7.8}$$

Annual Fuel Cost

The annual fuel cost can be estimated like in Equation 7.9. Where p$_f$ (USD/tonne) is the fuel price, and SFC is the specific fuel consumption. P is power and T$_s$ is sailing time and R$_y$ is roundtrips a year.

$$Annual\ fuel\ cost, C_F = p_f \cdot SFC \cdot P \cdot T_s \cdot R_y \tag{7.9}$$

.

Values for annual fuel cost are varying with the defined epoch and machinery design. Furthermore, SFC and P, T_s and R_y all varies with the design. Hence, it is possible to see that fuel price is both varying with structural and behavioural aspects along with shifting contexts.

Calculating SFC for engines that do not exist is, of course, challenging. However, according to (Niels de Vries, 2019); ”Hydrogen mixtures can obtain similar properties as methane in both flame stability and flame speed. ”....” Therefore, it is expected that the energy consumption of ammonia, providing ammonia hydrogen mixtures, is considered to be similar as natural gas.”. LNG consist of between 90-99 % Methane. An engine using LNG or hydrogen mixture and VOC needs to be dual fuel, for reference a WIN GD 8X62DF (Dual Fuel) engine is used. It has a specific fuel consumption of 142.5 g/KWh (WinGD, 2019b). Thus both ammonia and hydrogen SFC is assumed the same as LNG. A WIN GD 8X62 engine is used as a reference for ULSFO option, and these engine types are often used for Aframax tankers. The specific fuel consumption for this engine type is 166 g/KWh (WinGD, 2019a).

CAPEX

CAPEX includes the investment cost of constructing a vessel, with all its inventory (Equation 7.10). This will include hull, engine, engine systems(storage), eventual equipment, shipyard work hours and a shipyard margin.

$$\begin{aligned} CAPEX = Hull + Engine + Storage + Equipment \\ + Working\ Hours + Shipyard\ Margin \end{aligned} \tag{7.10}$$

Ship investments are huge capital demanding with a generally high loan on the asset. Therefore, it is required to write off the CAPEX investment during the lifetime. Different methods can arrange these payment periods, but for this case, yearly payments are estimated. In general, an investment should be made if the Net Present Value (NPV) > Investments. NPV is calculated as in Equation 7.11, where WACC is the weighted average cost of capital.

$$NPV = \frac{Cash\ Flow}{WACC} \tag{7.11}$$

Entering investment for NPV, it is possible to find the required cash flow needed to sustain yearly payments. Since CAPEX is calculated for each vessel in the tradespace, it is only needed one value for the WACC. Henceforward, more information around the investment project is needed. The following information is given as from pre-thesis (Olsen, 2019):

The project will be financed with a bank loan, D, of 70 %, assuming that the bank is willing to accept a considerable dept since it has safety in the vessel as an expensive asset. An interest rate on the loan, r_d of 7 % is given, and the dept is re-balanced continuously. The shipowner will finance the rest with equity, E. On financial markets, as of September 2019, the risk-free rate, r_f is 1.22 % while return on market is r_m 7.65 %, while market premium is (r_m - r_f) = 6.42 % (Market Risk Premia, 2019). The corporate tax, τ, in Norway is 22 % (PWC, 2019). The beta for current market asset, β_a, for a shuttle tanker is assumed to follow the estimation of β_a = 1,98 (Gauci-Maistre, 2009). Assuming the opportunity cost of existing operations are reflected in the current assets in the market, Capital Asset Pricing Model (CAPM) can be used to find the opportunity cost of capital (OCC), r_a (Equation 7.12).

$$r_a = r_f + (r_m - r_f)\beta_a \tag{7.12}$$

Using OCC together with the project cost of dept and dept-equity ratio, the project s cost of equity, r_e, is found (Equation 7.13).

$$r_e = r_a + (r_a - r_e)\frac{D}{E} \tag{7.13}$$

Then the WACC can be estimated (Equation 7.14).

$$WACC = r_e\frac{E}{V} + r_d(1 - \tau)\frac{D}{V} \tag{7.14}$$

This gives the following summary, and a WACC = 0.124 is used.

Table 7.4: Data Summary for Calculating WACC

Data	**Symbol**	**Value**
Debt	D	70 %
Debt Interest	r_d	7 %
Equity	E	30 %
Risk Free Rate	r_f	1.22 %
Return on market	r_m	7.65 %
Market premium	r_m - r_f	6.42 %
Corporate tax	τ	22 %
Beta of current market assets	β_a	1.98
Opportunity cost of Capital (OCC)	r_a	14 %
Return on equity for project	r_e	23.2 %
Weighted average cost of capital	**WACC**	**12.4 %**

Annual Total Cost

The annual total cost can be seen as the combined yearly CAPEX and OPEX. Time charter (TC) is the freight rate that is established in a contract when a vessel is chartered for any operation. TC can also be expressed as break-even freight rates. In that case, TC describes the required rate acquired to earn a profit. Obviously, should the TC be larger than the annual cost or else it is not profitable investments. The required break-even freight rate is the main focus for further explanation of results in this modelling. The TC can be evaluated as in Equation 7.15.

$$Time\ Charter\ =\ OPEX\ + CAPEX\ write\ off\ + Margin \tag{7.15}$$

7.3.4 Summary of Tradespace Numerical Values

Table 7.5: Data Summary for Cost Estimation

Data	Value	Unit
SFC (ULSFO)	166	g/kWh
SFC (LNG, NH_3 & H_2,)	142	g/kWh
Engine General	12 mill	USD
Engine Systems LNG	13 mill	USD
Engine Systems NH_3	10 mill	USD
Engine Systems H_2	15 mill	USD
SCR system	1 mill	USD
VOC system	15 mill	USD
Flettner Rotor	1 mill	USD
Battery Pack (- 10 % kW)	ca. 3-4 mill	USD
Engine Option	5 mill	USD
Steel Price	600	USD/tonne

7.4 Era Construction

For a shuttle tanker in the North Sea, the obligations span not more 20 years. As known from the stakeholder analysis, this is typically a length charterer, such as Equinor, uses as a maximum age for their operations. Shuttle tankers can be used in other places in the world and getting new contracts. Concerning all this information, a reasonable epoch interval of 4 years can be suitable, in order to capture some differences in markets along the lifetime. As a reminder, an epoch is defined as a period where the exogenous variables are constant within the period. So a lifetime for a shuttle tanker can include five epochs, and an era is those epochs combined. Era 1, 2 and 3 are used in the same investigations in the timeline from 2022 and beyond. On the other hand, Era 4 is a separate evaluation to analyse ship design in a 2050 regulation perspective.

Figure 7.4: An Era consist of several epochs. Each epoch is a separate distinct context.

7.4.1 Storytelling Approach

Storytelling approach is an alternative method for constructing eras. By selecting stakeholder preferences and expectations, it is possible to identify the corresponding epochs. When relevant epochs are determined, it is possible to manually connect the epochs and create eras based on a narrative set over the expected lifetime to the vessel. The reason a storytelling approach is a preferred method is that the development of eras will require a considerable computational cost and capacity to be completed in its entirety. This difficulty is real since the variables are needed to be investigated multiply exponentially with each variable.

Storytelling can be effective to capture those uncertainties and complexities in a perceptual aspect. Anyhow, it can be difficult to quantify uncertainties, such as how likely or in which degree is it a possibility of happening. Although this possible composition can be by altering epoch variables in terms like e.g. risky or conservative, low vs high (example. growth, environmental regulation). The following four narratives are used in this project:

ERA 1 - Full Environmental Development - Low environmental prices

This era intends to develop a temporal description on a likely scenario with all the knowledge that is around Johan Castberg and Shuttle tanker technology. The results from this era are also used as a baseline for comparing value robustness and performance with other narratives.

Narrative: In this era, the development of environmental technologies and solutions are high. It will result in lower prices for environmentally friendly fuel, like ammonia and hydrogen, as supply and infrastructure continue to be better. The EEDI regulations have to be met within the second epoch. Likewise, IMO ambitions have to satisfied from epoch three. Prices on fossil fuels are assumed to be first cheaper then become more expensive as the production supply is assumed to go down. The era is meant to begin when Johan Castberg opens its production. Therefore, capacity follows the known variables given in Table 7.3. If production is higher than the capacity on the proposed ship design stakeholders values bigger vessels. Equally, if production is low as in the latest epochs, stakeholders value smaller vessels. Furthermore, the following requirements and regulation is essential and is valued before non-compliance options. Table 7.6 shows the development of the era.

Table 7.6: Era 1 - Full Environmental Development

Era 1					
Epoch variable	**E-ID:6838**	**E-ID:6682**	**E-ID:3403**	**E-ID:138**	**E-ID:25**
ULSFO ($\frac{USD}{tonne}$)	425	337.5	425	512.5	600
LNG Price	400	300	200	400	600
Ammonia Price	575	450	325	200	200
Hydrogen Price	1520	1140	1140	760	380
Crude Oil bbl	10	10	10	10	10
EEDI 30 %	0	1	1	1	1
IMO 40 %	0	0	1	1	1
IMO 70 %	0	0	0	0	0
M Sm^3 Available	10	5	2	1	1

ERA 2 - Late Technological Maturity

This era is meant to see which design alternatives that perform well when the technological development for ammonia and hydrogen slowly increase.

Narrative: This era also begins in 2022 when Johan Castberg opens. The only significant difference is the price development. General fluctuations are assumed for ULSFO, while for LNG prices is expected to decrease and remain low due to the expected availability and supply of LNG. Ammonia does not become relatively cheap before the last epoch. Else, production is assumed the same as in Era 1, and the preferred size of vessels also follows the ability to transfer cargo at a high utilisation rate. Environmental regulations are assumed implemented at the same time as in Era 1. Table 7.7 shows the development of the era.

Table 7.7: Era 2 - Late Technological Maturity

Era 2					
Epoch variable	**E-ID:6868**	**E-ID:7362**	**E-ID:4838**	**E-ID:2332**	**E-ID:1558**
ULSFO ($\frac{USD}{tonne}$)	425	337.5	425	337.5	425
LNG Price	500	400	400	300	300
Ammonia Price	700	700	575	575	450
Hydrogen Price	1900	1520	1520	1520	1140
Crude Oil bbl	10	37.5	65	92.5	65
EEDI 30 %	0	1	1	1	1
IMO 40 %	0	0	1	1	1
IMO 70 %	0	0	0	0	0
M Sm^3 Available	10	5	2	1	1

ERA 3 - Speed Reduction, General development

This era is included to see how speed reduction affects the utility and the preferred vessels.

Narrative: In this era regulations or cyclical ”through” times make it more attractive to sail with a lower speed. General development is expected in this era, which causes the price levels to fluctuate randomly. However, trends in price levels are reflecting the development of infrastructure and the increase in supply. Production at Johan Castberg is assumed the same as for the first to eras. Table 7.8 shows the development of Era 3.

Table 7.8: Era 3 - Speed Reduction - General Development

Era 3					
Epoch variable	**E-ID:6862**	**E-ID:7343**	**E-ID:4683**	**E-ID:927**	**E-ID:785**
ULSFO ($\frac{USD}{tonne}$)	337.5	425	425	337.5	600
LNG Price	400	500	300	200	300
Ammonia Price	700	575	450	450	325
Hydrogen Price	1900	1520	1140	1140	760
Crude Oil bbl	10	37.5	65	37.5	37.5
EEDI 30 %	0	1	1	1	1
IMO 40 %	0	0	1	1	1
IMO 70 %	0	0	0	0	0
M Sm^3 Available	10	5	2	1	1

ERA 4 - A 2050 Scenario

This Era is intended as an investigation in how the most demanding environmental ambitions affect value robustness in ship design. This Era is a separate investigation from the other three eras.

Narrative: In this era activity in the Barents sea is assumed to have increased. The start year of this era is around 2040, meaning that within the third epoch the vessel should be compliant with 70 % IMO ambitions. In other words, only ammonia and hydrogen options are valued after 2050. Furthermore, the productions in the area are assumed to be constant throughout the epochs at around 7 million Sm^3. The reason for this is that the activity is high and that new oil fields are continuously developed. Else, the prices are meant to have a moderate fluctuation, and thus it follows the same prices as in Era 2. Table 7.9 shows the development of the era.

Table 7.9: Era 4 - 2050 Scenario

Era 4					
Epoch variable	**E-ID:6868**	**E-ID:7362**	**E-ID:4838**	**E-ID:2332**	**E-ID:1558**
ULSFO ($\frac{USD}{tonne}$)	425	337.5	425	337.5	425
LNG Price	500	400	400	300	300
Ammonia Price	700	700	575	575	450
Hydrogen Price	1900	1520	1520	1520	1140
Crude Oil bbl	10	37.5	65	92.5	65
EEDI 30 %	1	1	1	1	1
IMO 40 %	1	1	1	1	1
IMO 70 %	0	0	1	1	1
M Sm^3 Available	7	7	7	7	7

7.5 A Short Guide to the MATLAB Scrips

Appendix D provides the codes developed in this thesis for calculations and investigations into the tradespace. Each MATLAB-code is in the order they are running in the main script. The script gives the same information as provided earlier in this chapter. Hence, the description under is only recommended to study if a more in-depth knowledge is wanted. Nevertheless, the code is the base for all results and can provide useful insight into the Epoch-Era methodology.

Firstly, code main.m in section D.1 is the main script that connects all the other scripts in the model.

Secondly, code epoch2.m in section D.3 provides the epoch space. It is notable that the selected Eras is constructed manually and that in the code some modifications have to be made manually before shifting between epochs.

Thirdly, code DesignvariablesTest.m in section D.2 provides the design space.

Furthermore, code Capacity.m in section D.4 finds capacity and volume displacement in cubic meters. Additionally lightweight is calculated in tonnes.

Next is code powerKW.m in section D.5 that calculates the required power for each design.

Code sailing.m in section D.6 provides all necessary transport estimations.

Regarding zero emission, code GHG_effect.m in section D.7 establish each vessel GHG reduction potential.

Furthermore, code CAPEXwriteoff.m in section D.8 describes the CAPEX cost. It calculates fist total CAPEX cost, then divide it into required annual write off. Using WACC of 0.124.

The first to include functions based on both epoch and design space is code FuelCost.m in section D.9 which calculates first the fuel cost and then provides total OPEX for each vessel when the fixed cost is added.

Similarly code TotalCostYearly.m in section D.10 uses the combined OPEX And CAPEX calculations to estimate the annual cost

An specially important code is Utility_estimation.m in section D.11 that provides the utility calculations. subsection 7.5.1 provides more information about the decisions made for this code.

In the end, code paretoSet.m in section D.12 calculates the Pareto front. If the fuzzy parameter is preferred, a value in row 57 is crucial to change. The code is based upon code given by (Pettersen, 2019) in TMR 4135 Design Methods 2, NTNU Spring 2019. However, it has some modifications in the last part where some coding lines find the best performing designs.

7.5.1 Calculation of Utility

Stakeholder and market analysis is used to determine some shipping relations that are valued. It was early understandable that this case study would not provide many variables, consequently, because of the few types of equipment and the significant focus on environmental compliance. With Keeney and Raiffa conditions in mind, it was necessary to create non-redundant utilities. Three main stakeholders values were identified;

1. Each vessel had to comply with current environmental regulations, which means that vessels with the right requirement would get the utility of 1. On the contrary, if a vessel did not comply with standards, the utility is set to 0.
2. Secondly, the utility relates to the size of the ship and production at Johan Castberg. If production at Johan Castberg is larger than the annual capacity of the vessel, the bigger designs are valued over smaller ones. The opposite happens when production is lower than the annual capacity, which then supports the smallest vessels with the highest utility.
3. Speed depends on the scenario. It is either valued as low or high.

The first utility is based on a yes/no scenario, which gives 1 or 0. On the other side, the two latter utilities are calculated by a normalisation of the vessel size or speed between 1 and 0. MAU is used to estimate the total utility for each vessel and are the basis of the perceived value for each design.

Chapter 8

Phase 3: Results & Post - Processing

"And someday we may see this as the moment that we finally decided to save our planet."

\- **Barack Obama**, *Remarks on the ratification of the Paris Agreement*

8.1 General Information for Interpreting Results

The first element of phase 3 is to evaluate the tradespace in a single epoch analysis. The five chosen epochs that create the actual era are all visualised in single-epoch plots. These plots are given with a colour reference for each machinery; Blue = ULSFO, Green = LNG, Red = Ammonia and Black = Hydrogen (Table 8.1). Each point represents one distinct alternative design. In each era, a fuzzy Pareto front has also been conducted. If it is beneficial to display the fuzzy Pareto front, it is also shown in a single-epoch plot.

Table 8.1: Colour Reference for Machinery

Colour	Fuel for Machinery
Blue	ULSFO
Green	LNG
Red	Ammonia
Black	Hydrogen

Furthermore, Era 1 is used to find some vessels that are indicated as value robust. These value robust ship designs are highlighted and are analysed further in Era 2 and 3. Era 4 is a separate analysis, and the comparing of vessels from Era 1 is not conducted in Era

4. In other words, ship design meant for Johan Castberg in a 2022-2030 (Era 1, 2 & 3) perspective is not comparable with 2050 designs (Era 4). MAU is used to find the vessels performing overall epochs in Era 1. On the other side, for distinguishing these vessels and differentiate them from each other decision criteria is used.

Remember:

1. Colour Refer to Machinery System.

2. Each Point Represent an Individual Design.

3. Era 4 is a Separate Analysis.

8.2 Era1 - Full Environmental Development

Epoch 1. Looking upon Epoch 1, LNG and ULSFO alternatives gives the best value. The vessels on the top right, providing the most utility are also the most expensive, primarily due to the maximisation of main dimensions for those designs. In this context, EEDI and IMO restrictions are unenacted, increasing the utility of ULSFO designs not compliant with those regulations. The fact that general fuel prices for ULSFO are low in this context gives many ULSFO designs, both low annual OPEX in addition to the already lower CAPEX costs. The three ”groups” along the Pareto front indicates the speed. Since high speed is a perceived value in this era, the designs with 15 knots are on the right, while 12.5 knots in the middle and 10 knots are in the bottom right.

The LNG alternative that provides the highest utility gives an annual expense of around 29 million USD. That gives an annual break-even daily freight rate of approximately 79 000 USD/day. This price scale is located high on the Pareto front, and it is accordingly smart to underline the trade-off between utility and cost. By reducing utility from 1 to around 0.85, a reduction in 2 million USD annual cost is plausible. That reduction is equal to a break-even freight rate of 74 000 USD/day. That is a 5 000 USD/day reduction. However, this trade-off will give smaller vessels and will not maximise the size. Remember, that in this context the production at Johan Castberg is over 10 million cubic crude oil annually. Meaning that it is probably actual for charter to need a larger vessel or order several of the smaller designs.

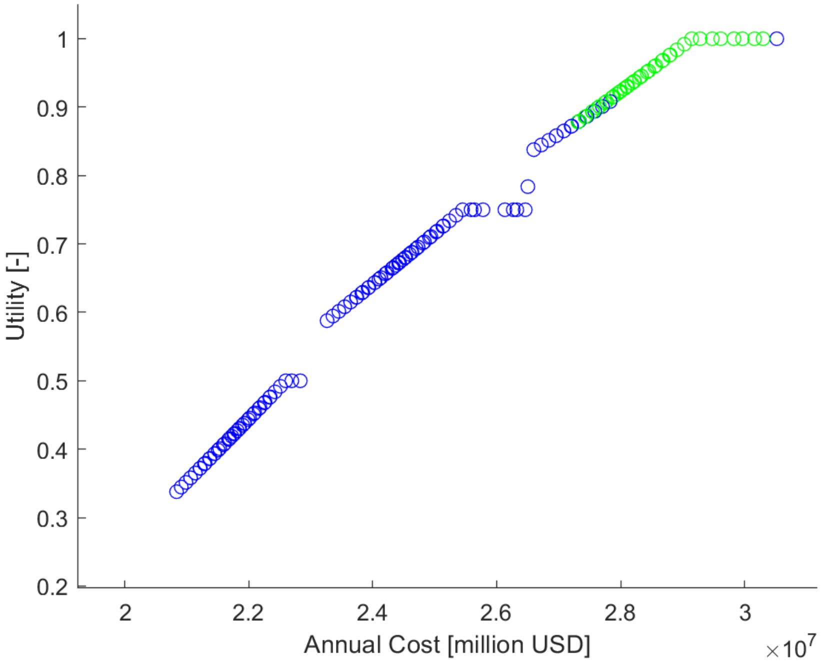


Figure 8.1: Pareto front for Epoch 1 - Era 1. Illustrates a classic Pareto front where increased cost provides more utility. The three clusters represent different speed. LNG and larger vessels is preferred.

Epoch 2. In Epoch 2, the amount of production at Johan Castberg is halved affecting the utility calculations. Now, it is more beneficial for a shipowner to build a smaller vessel to balance the transport supply with the demand generated in the oil field. EEDI requirement of 30 % reduction is another difference, and that affects the results.

At the same time, these design options give the smallest sized vessels. Smaller designs have lower CAPEX costs and OPEX cost resulting in lower expected freight rates. As mentioned in Chapter 7 the code deletes designs that are more expensive than the best design option. This is why Figure 8.2 does not provide the same amount of designs as in Figure 8.1.

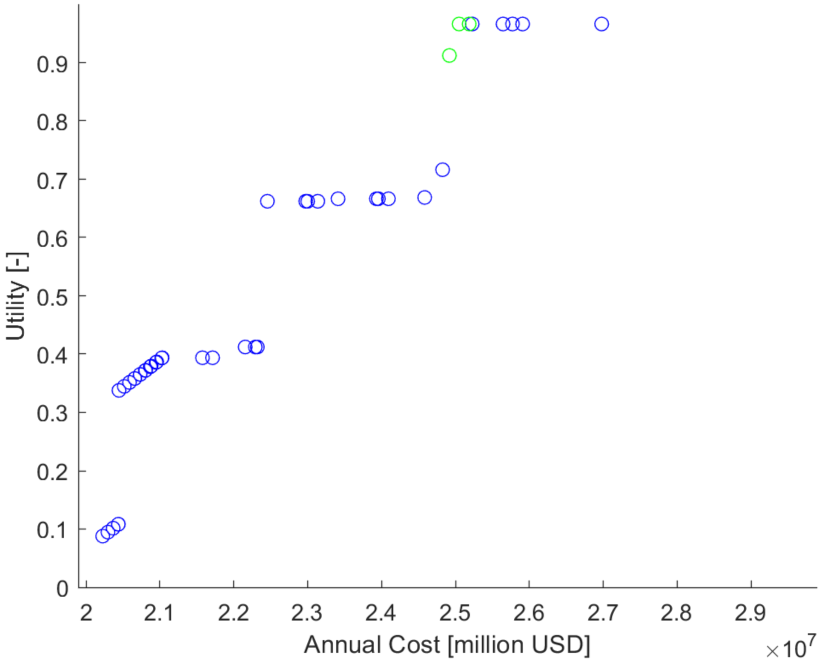


Figure 8.2: Pareto front for Epoch 2- Era 1. Illustrates as production decreases, smaller vessels get valued higher. Three LNG vessels provide the highest utility per cost. Each cluster illustrates the speed, while each plateau shows similar payload capacity. Anyhow, plateau placed vessels have different equipment attached. As an example, the plateau at 0.7 utility, the left design at 2.3 mill USD, have no equipment. The right data point has all equipment included.

Epoch 3. In Epoch 3 context changes a lot. Firstly, IMO ambitions of 40 % GHG reductions are in effect in this context, meaning that the best results have to reduce at least 40 % GHG. Furthermore, the production at Johan Castberg reduces to 2 million Sm^3, meaning that all vessels that provide more volume than that during a year will be forced to transport oil with a utilisation greatly reduced. Requirements increase equipment applied for ULSFO, which increases CAPEX. On the contrary, LNG does only need one extra equipment to reach IMO ambitions. Thus, LNG becomes relatively cheaper and provides together with lower prices much better as displayed in Figure 8.3.

Concerning the GHG emission, the only ULSFO alternative that is feasible is the one with all equipment including (Flettner rotor, battery pack and a flexible engine option). This option is expensive. Additionally, the amount of transported oil will be significantly reduced compared to alternatives given in Epoch 1. At the same time, the ULSFO alternative presents to be much more costly than the LNG alternatives also providing 1 utility. Thus, LNG is a better option in Epoch 3. For LNG designs, the Pareto designs have at least 1 additional equipment. Flettner rotor is the most affordable solution and hence chosen the most times, then battery pack and engine option are selected, in that sequence. LNG is also the cheapest fuel in this context, and this determines the Pareto front.

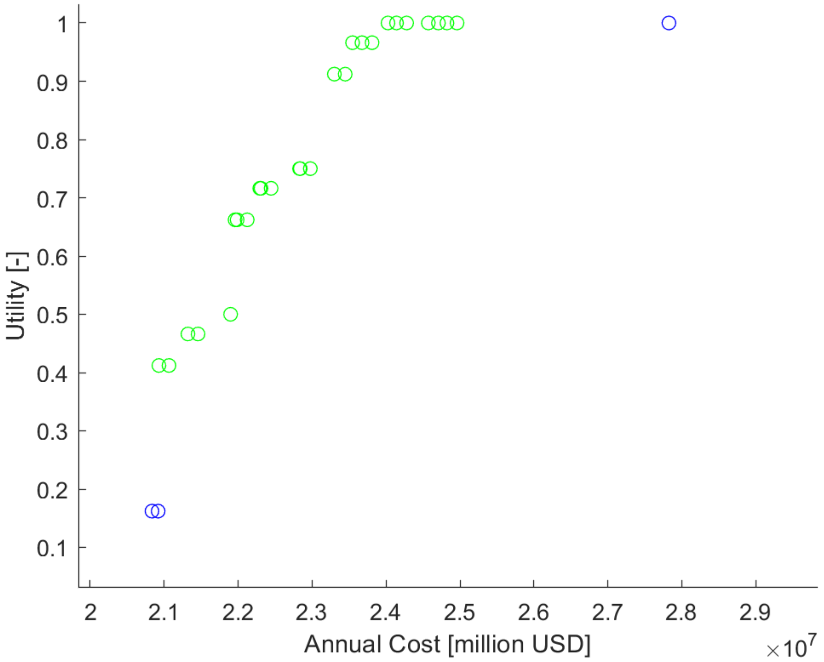


Figure 8.3: Pareto Front for Epoch 3- Era 1. Illustrates the entry of LNG as superior options due to regulations and more competitive fuel prices.

Epoch 4. In epoch 4, ammonia becomes competitive with LNG and ULSFO configurations. Again, small vessels are preferred due to product availability at Johan Castberg. Anyhow, the ammonia options become superior when only looking at the Pareto front. Especially the three designs touching between 0.9-1.0 utility mark around 23 million USD. Fancying ammonia instead of LNG or ULSFO in this context provides a margin of around 8 000 USD/day (from 73 000 to 65 000 USD/day) when speaking of the Pareto front. The other two design resting around 0.7 provides the same size, but with lower design speed (12.5 knots) giving even more reduction in annual cost

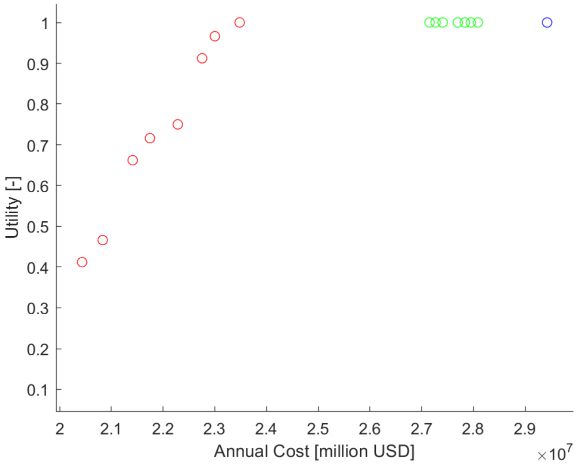


Figure 8.4: The Pareto front for Epoch 4- Era 1. It illustrates a significant change in nature. Ammonia becomes competitive and provides a lower cost than the other machinery options. The clusters illustrate speed. A crucial observation is that only three designs are displayed in each cluster, which is because they are small sizes and provides the lowest CAPEX. Few displayed design is an argument for introducing the fuzzy Pareto front.

Epoch 5. Epoch 5 results give similar results as to Epoch 4 due to the ammonia being the best alternative on price and the production variables stagnation. The only change is that some of the LNG alternatives in top corner shift to the right due to price change in fuel. It is probably more relevant to include some designs from the fuzzy Pareto front.

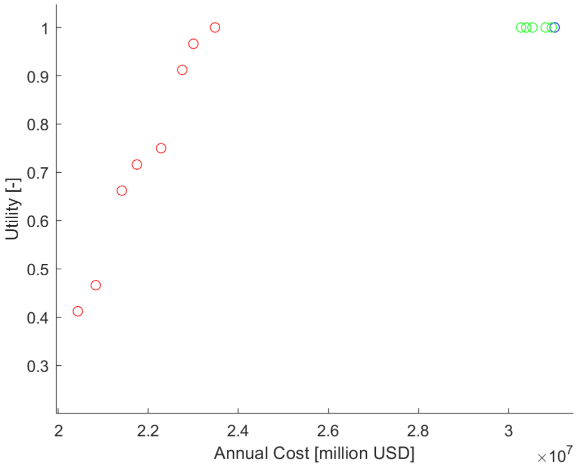


Figure 8.5: The Pareto Front for Epoch 5- Era 1. Illustrates similarities with Epoch 4. The only change is that LNG and ULSFO become more expensive.

The Fuzzy Pareto Front

When including the alternatives that perform within 10 % of the best designs, a fuzzy Pareto front appears. For an illustrating example, Figure 8.6, show the increasing amount of designs that enters the scatter diagram. Similar fuzzy Pareto fronts are conducted for the other epochs within the eras. When the tradespace is expanding from visualising the Pareto front to include the fuzzy Pareto front, the conceived designs are not more beneficial than before. Instead, it expands the options to include designs that might perform good but not the best in each epoch.

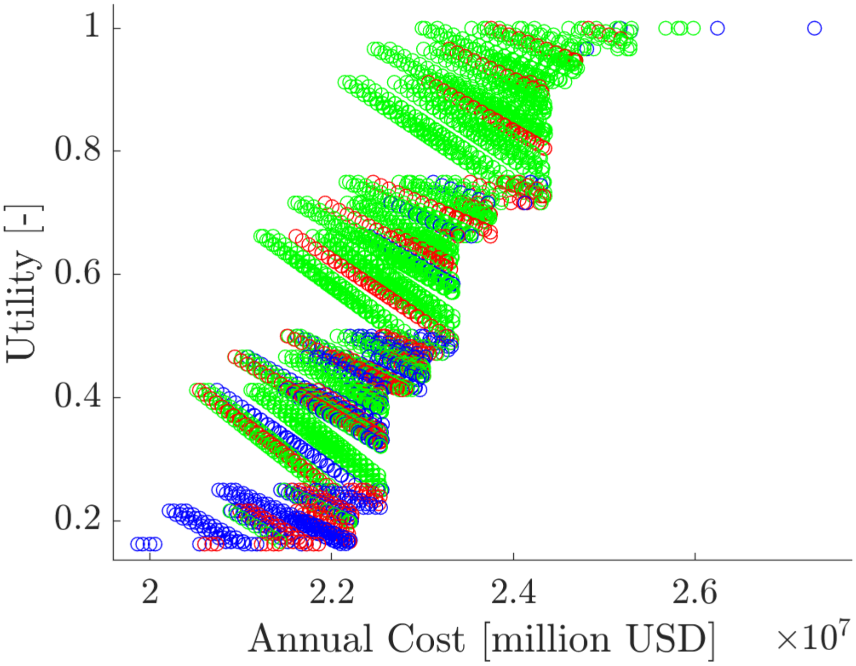


Figure 8.6: An Illustration of Fuzzy Pareto front for Epoch 3- Era 1. With an increase in 10 % of the best designs, many more opportunities are accessible. The fuzzy front illustrated here is used to find the most valued vessel.

After the expansion of tradespace to incorporate the fuzzy Pareto front, 38 designs perform within the fuzzy front of each epoch in this era. The fact that a design is represented in each epoch does not necessarily mean it is within the best performing vessels. Nevertheless, it indicates that the design has potential in enhancing a value robust design. By selecting the designs with the highest overall utility, it is possible to find those designs that perform well throughout an era. Figure 8.7 illustrate a close-up image of the fuzzy Pareto front for Epoch 5 in Era 1. The point highlighted is the Design ID: 36 187, which is the vessel that performs best over Era 1.

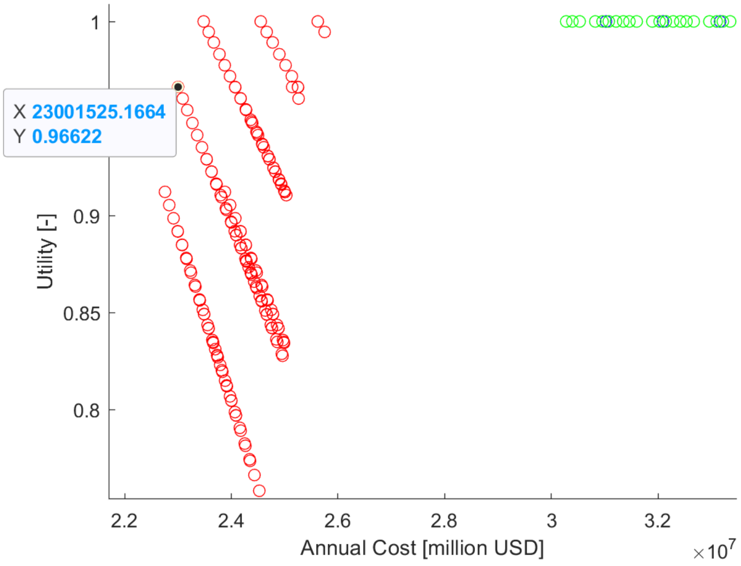


Figure 8.7: Fuzzy Pareto front- Epoch 5- Era 1. Includes Design ID 36187, which the design with the highest total MAU over Era 1. The diagonal lines going down to the right illustrates the increase in capacity for similar designs regarding speed and equipment. PS. Adding equipment to an ammonia vessel is not necessary concerning GHG reduction, so if those options are exercised extensive fuel reduction is the intention.

8.2.1 Life-cycle Performance Era 1

In evaluating life-cycle performance, some individual design ID's have to be found. Since the needs change drastically together with the production offshore for Epoch 1 and the rest, it is no vessels that perform in each original Pareto front. However, for the fuzzy Pareto front, 38 designs were found. The following designs were identified (all designs are small vessels):

- Design ID 787: An ULSFO alternative with all equipment included. Overall utility 0.9.
- Design ID 1966: LNG alternative with all equipment included. Overall utility 0.9.
- Design ID 36187: Ammonia alternative with no equipment. Overall utility 0.9297.

In the first epoch larger vessels performed better, and it can be interesting to see the difference in lifetime performance between the small vessel alternative and the larger vessels. Therefore, separating some vessels in different sizes that also have the demanded reduction of 40 % GHG or more are relevant. Table 8.2 the promising smaller designs are given. Moreover, a larger vessel alternative with high utility is additionally evaluated for each machinery system.

Table 8.2: Designs Attractive for Exploration

Design ID	Machinery	Payload	GHG	Era 1 Total Utility
787	ULSFO	90000	0.4	0.9000
917	ULSFO	156600	0.4	0.8000
1966	LNG	90000	0.6	0.9000
30392	LNG	156600	0.4	0.8000
36187	Ammonia	99000	1.0	0.9297
36287	Ammonia	156600	1.0	0.8000

Figure 8.8 is comparing the chosen designs with each other. The are several interesting aspects to this bar diagram. Firstly, the effect OPEX have on the annual cost is observable as the bar diagram size depends on the epoch fuel price. For example, ammonia is a much cheaper alternative in the last two epochs compared to the first three epochs. Moreover, OPEX follows the price levels and variations in prices can therefore greatly affect which design that is the most competitive. Nonetheless, as seen by the green bar, the smallest ammonia vessel performs better than the large LNG and ULSFO alternatives for the first two epochs despite high fuel prices. As known, a smaller vessel will provide less crude oil to the market compared to the larger vessels, so there is certainly a trade-off evaluation in the picture.

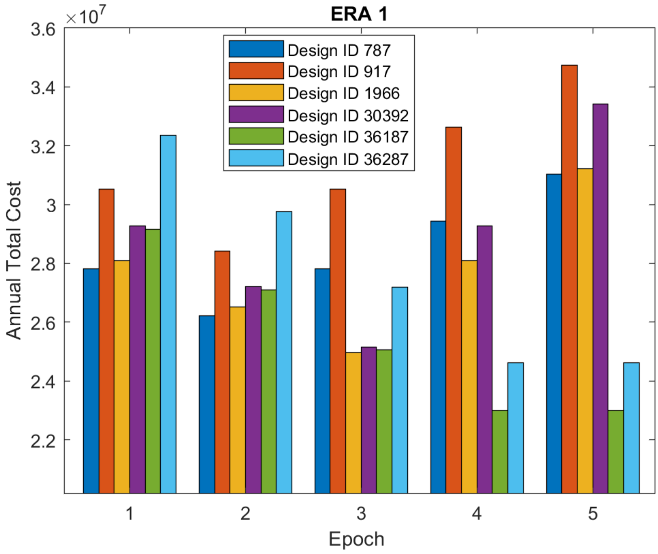


Figure 8.8: Comparison of the six promising designs. Watch how ammonia designs drop in cost for this era as fuel prices decrease. At the same time, in the three first epochs, a shipowner could get a large LNG vessel for the similar small ammonia vessel.

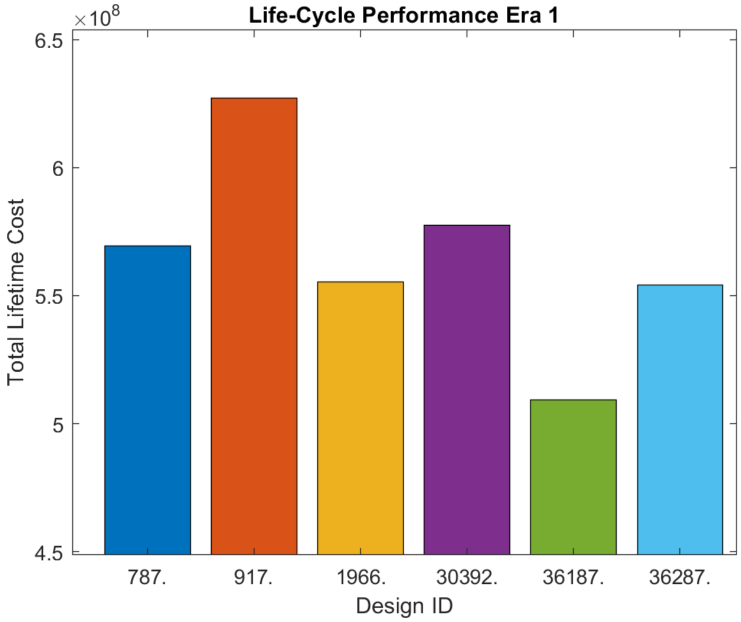


Figure 8.9: Total Cost - Era 1. Illustrates the cumulative cost over a 20 year lifetime for the preferred shuttle tankers. These numbers is the base for freight rate calculations.

The cost difference between the large and the smaller option is for LNG as machinery is lower than the difference between the other options. The reason for that lies in the CAPEX for the small vessel have more equipment than the large LNG ship design. In Epoch 3, the LNG fuel price is so low that the CAPEX becomes as dominating, such as the small vessel becomes more expensive than the large vessel.

Table 8.3: Annual Cost as Required Freight Rates

Annual Total Cost [mill USD]	22	24	26	28	30	32
Daily freight rates [USD/Day]	60 000	66 000	71 000	77 000	82 000	88 000

The required daily freight rates can be derived from Figure 8.9 by dividing the annual total cost on 365 days. Table 8.3 explains that the approximate difference in break-even freight rates ranges from 22 million USD to 32 million USD. Anyhow, when averaging the freight rates for all five epochs, it is possible to understand the required time charter that is required to create positive value across epochs for each design.

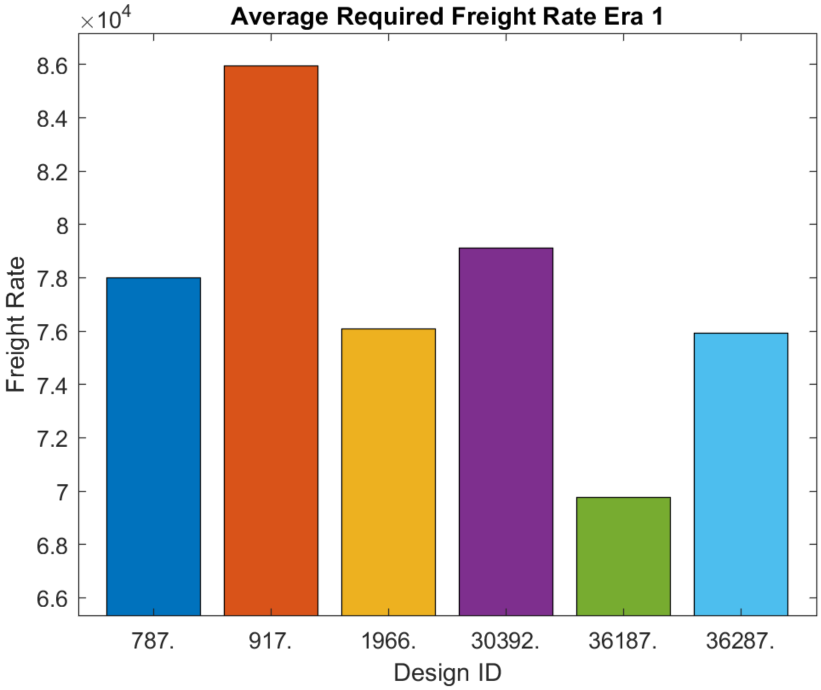


Figure 8.10: Break-even freight rates over the lifetime. This Era clearly favours ammonia based vessels.

8.3 ERA 2 - Late Technological Maturity

Epoch 1 & **Epoch 2**. The first two epochs in Era 2 gives the same performance as in Era 1. The reason for similar results is that the difference in price between eras greater for the other alternatives compared to ULSFO. The low sulphur option accordingly becomes the preferred machinery configuration. In Epoch 1 large vessel dimensions are the most valued alternatives, while for Epoch 2 smaller vessels are appreciated. So the tendency is the same in Era 2 as shown in Era 1.

Epoch 3, **Epoch 4** & **Epoch 5**. As LNG becomes more inexpensive, some smaller vessel designs become more favoured. In the third epoch, the IMO 2030 ambition of 40 % reduction becomes ratified, meaning that only ULSFO with all equipment is compliant. Likewise, LNG needs at least one additional equipment to reach IMO ambitions. The output in these epochs are showing similar results, but the number of LNG alternatives in the Pareto front increases as LNG becomes cheapest. Figure 8.11 illustrates the Pareto front for the fifth epoch.

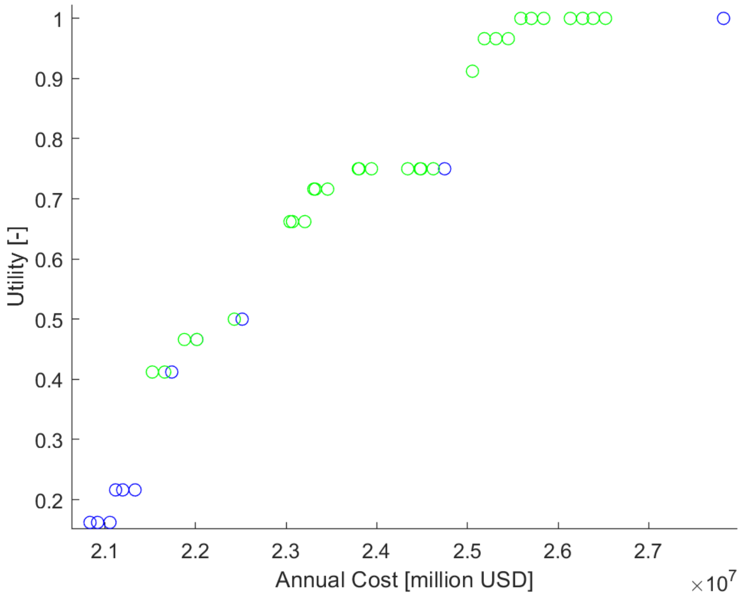


Figure 8.11: Pareto front for Epoch 5 - Era 2. It show the relations of the three last Epochs from Era 2. LNG vessels perform best. For each plateau (same payload capacity), one ULSFO alternative performs well but is more extensive due to extensive equipment configuration.

It is fascinating to observe that when ammonia prices and hydrogen prices are high, they do not perform well enough to be a part of the Pareto front. Therefore, it can be interesting to look at the fuzzy Pareto front. The fuzzy Pareto front for Epoch 3 and 5 include some ammonia designs, but they are never perceived as the best alternatives. Figure 8.12 illustrates that some ammonia (red) points become a part of the results.

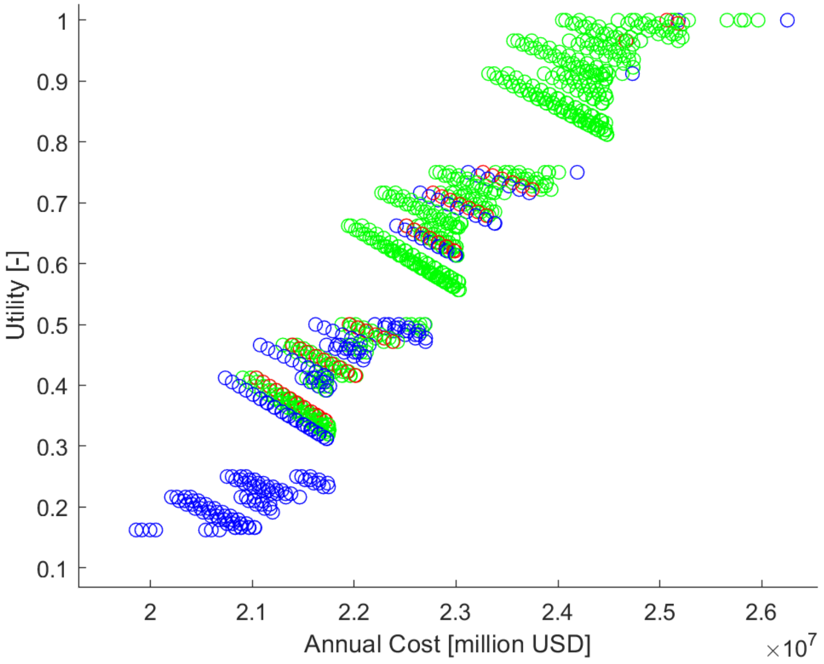


Figure 8.12: Fuzzy Pareto front for Epoch 5 - Era 2. It illustrating that by increasing the solution space, different design types becomes a part of the fuzzy front. There are some ammonia vessels represented in this context, indicating that ammonia machinery system could be a satisfactory solution.

8.3.1 Life-cycle Performance Era 2

The main reason for providing results for another era is to compare the designs in a multi-era analysis. In this subsection, the same methodology of the life cycle is analysed for the chosen six designs from Era 1. Reviewing the same designs provides information that is interesting to highlight. Ammonia designs perform with a substantially higher cost compared with the Era 1 results. It can indicate that the price levels are needed to be either as low or lower than ULSFO/LNG alternatives in order to obtain ammonia as an option with high functionality. The relatively small changes in average prices for ULSFO and LNG in both Era 1 and Era 2 is reflected in the tiny change in average required freight rate.

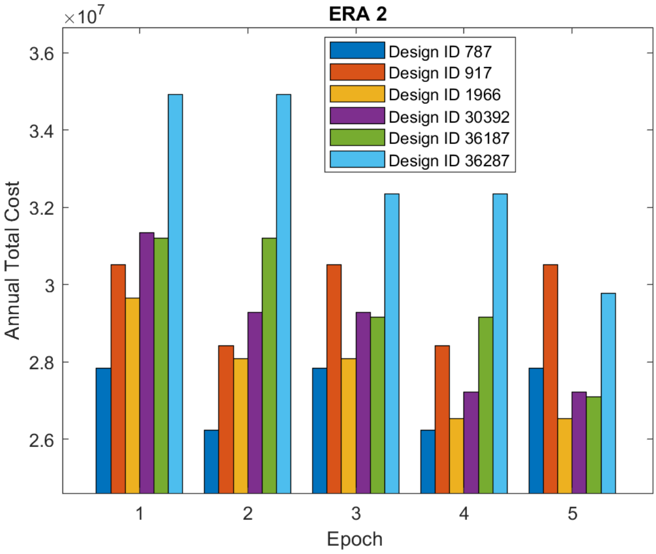


Figure 8.13: Showing annual total cost in Era 2 for the six vessels from Era 1. Ammonia alternatives having a weak performance, while LNG and ULSFO provides consistent performances.

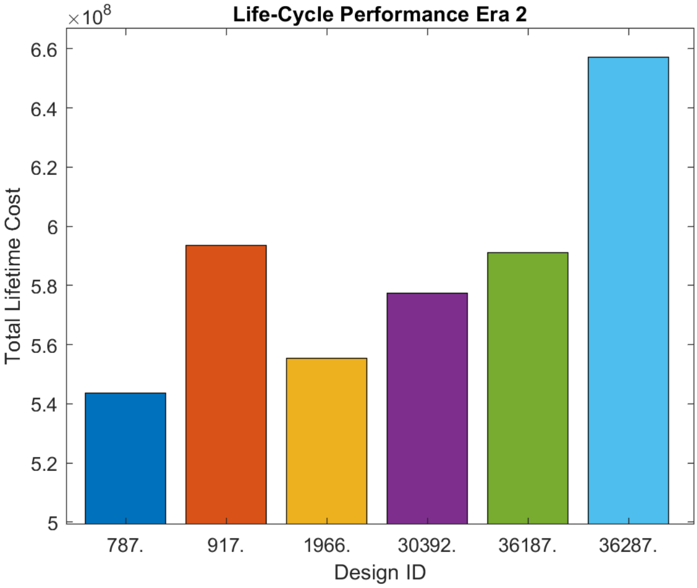


Figure 8.14: Total Cost for Era 2. Illustrating ULSFO as the best performing option. A small ammonia vessel will cost as much as the large alternatives in Era 2.

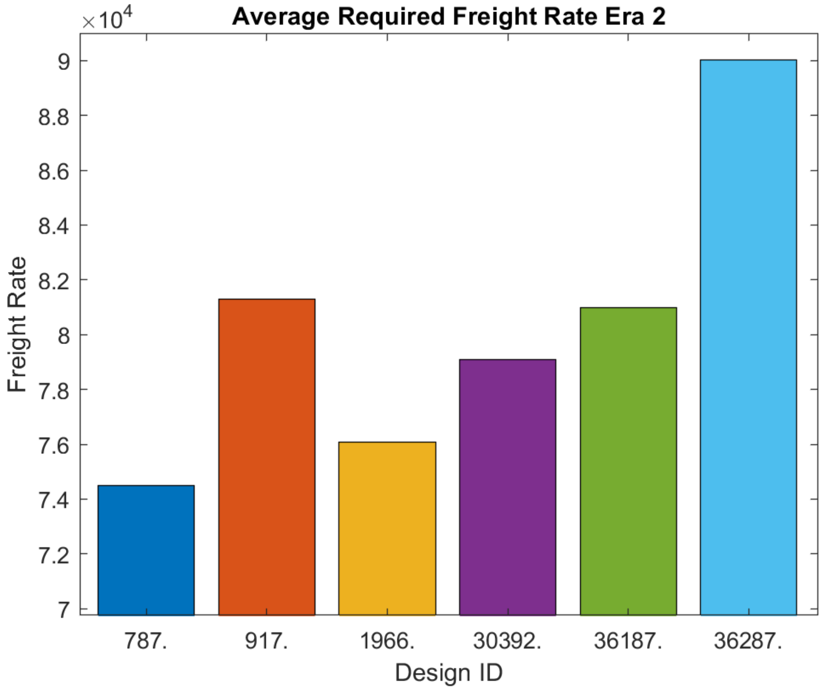


Figure 8.15: Break-Even Freight rates - Era 2. Showing that the low performance of Ammonia is as much as 5 000 -10 000 USD/day more costly than the other alternatives.

8.4 ERA 3 - Speed Reduction Scenario

In this era, the speed reduction is valued, meaning that the time aspects of the delivery of crude oil are not that important for the charterer. Since a vessel with low design speed will provide lower OPEX cost, it is to be expected that only a few points will be along the Pareto front. Therefore, the results are shown with a 5 % extended Pareto front. The results provide some interesting observations, and they are, therefore, all included in this chapter. Notably, all plots in this era are zoomed in on the top of the utility axis. In other words, the designs that are displayed with a high utility will also be the most cost-effective alternatives.

Epoch 1. This epoch shows much of the dynamics for the utility calculation in this epoch. By following the Pareto front (or one of the other ”lines”), it is possible to see that an increase in capacity will also increase the cost. At the same time utility goes up. The four points aligning next to each other on the same utility level are the different alternatives of equipment applied to any vessel. The second line cluster that performs with a higher cost indicated that engine options are one of the applied equipment. Another view on this plot is the relatively small change in cost. The difference is from approximately 4000 USD/day to 2000 USD/day. Meaning that trade-off is marginal in decision making and it becomes evident that in this epoch other criteria than utility and cost might be better decision-makers.

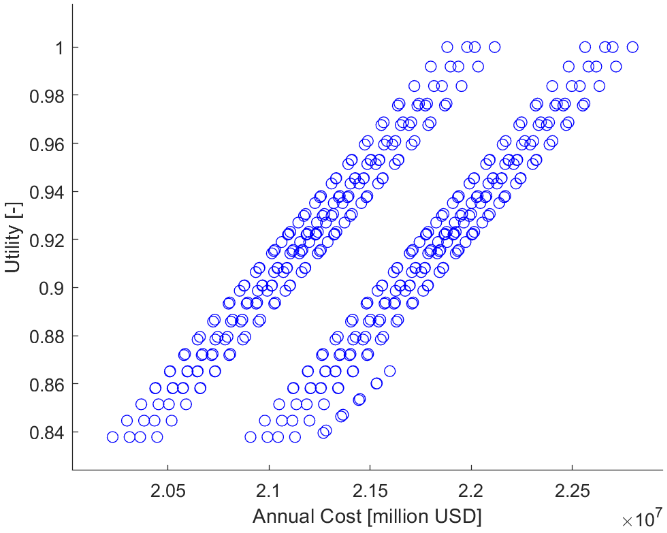


Figure 8.16: Fuzzy Pareto front for Epoch 1 - Era 3. Each plateau represents a specific payload capacity. The eight designs along the plateau are simply the different combinations of equipment. In the four right points (following the diagonal lines) engine Option is included, while in the left EO is excluded. All vessels in this figure have 10 knots as design speed.

Epoch 2. In this epoch, the alternatives that are selected for visualisation is affected by the production rate at Johan Castberg. A vessel with a payload capacity of approximately 130 000 m^3 is the most valued. The vertical line around 0.9 utility reveals them. Remembering that EEDI requirement is ratified in this epoch, the designs that preform below 0.65 utility does not have the required reduction of GHG. In between the design, one row of design goes in the opposite diagonal, which indicates that for this single representation of vessel property, cost increase when utility sinks. Evidently, this is not a preferred situation when other designs have the opposite state of nature. The reason for this circumstance is that the utility related to production level at Johan Castberg change if the vessel provides more capacity than production offshore.

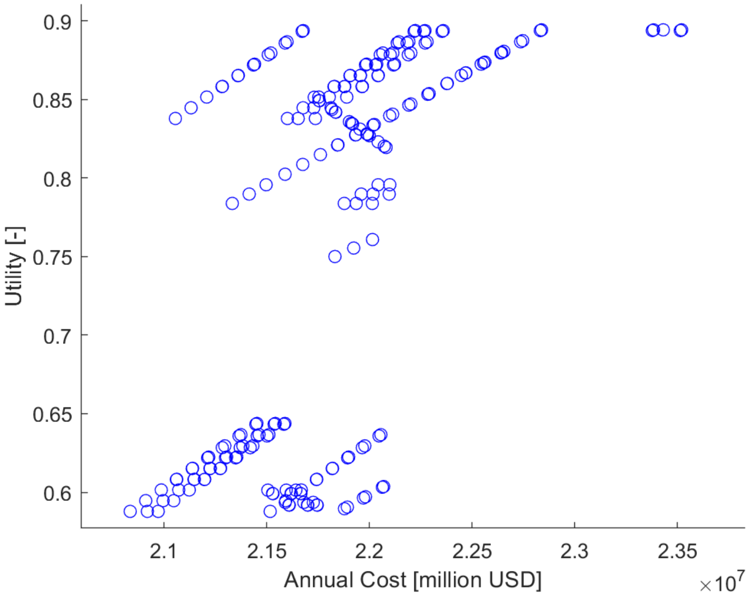


Figure 8.17: Fuzzy Pareto Front Epoch 2 - Era 3. In this epoch, observe that utility capturing capacity is changing and displayed by contrary aligned diagonals.

Epoch 3 & **Epoch 4**. These epochs are interesting because they illustrate what would happen if only the Pareto front designs are included. In that case, multiple designs would have disappeared from the visualised solution. Both epochs are showing similar results; hence only Epoch 4 is shown here (Figure 8.18).

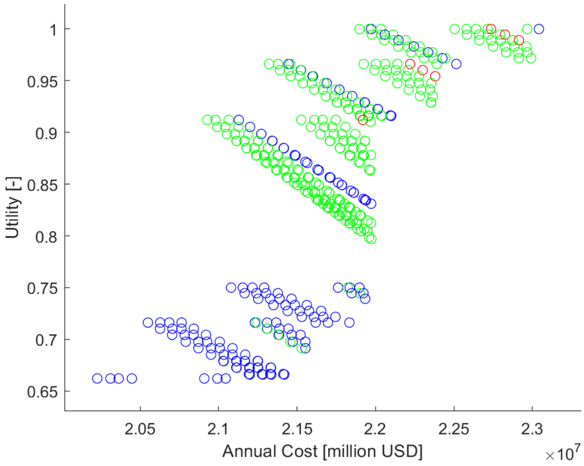


Figure 8.18: Fuzzy Pareto Front for Epoch 4 - Era 3. Illustrates the importance of including a fuzzy front, since if not displayed only a few designs would have been highlighted along the Pareto front.

Epoch 5. This epoch (Figure 8.19 illustrates that when emission requirements are high, the ability to comply with regulations become important. The blue ULSFO alternatives are all with the maximise equipment. When ULSFO needs all that equipment, some ammonia and LNG alternatives become cheaper and therefore more valued. In this case, the Pareto front would prefer ammonia vessel designs (three left outermost designs). However, the high utility performance can be an argument for that the difference is not too significant for any of the displayed vessels.

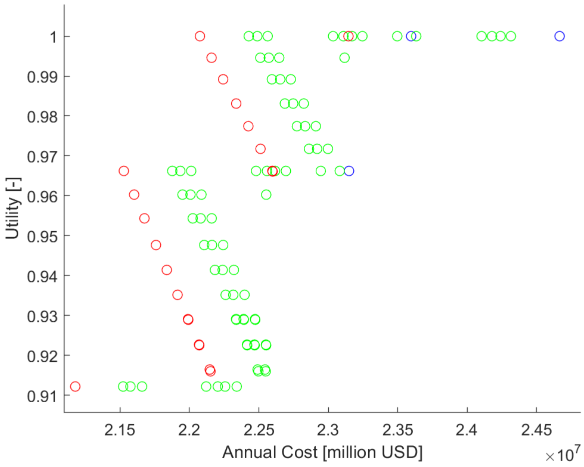


Figure 8.19: Epoch 5 - Era 3 - Fuzzy Pareto Front

8.4.1 Life-cycle Performance Era 3

By comparing the six high-performance vessels from era 1 with this speed reduction era, the main difference lies in the utility perceived by stakeholders which are reduced to around 0.3-0.4. This utility would be enough to exclude those designs in this era. Vessels with speed reduction near 10 knots would be preferable. Anyhow, the same comparing is done in this era for the designs found valuable in Era 1, which means that cost illustrated in Figure 8.20, Figure 8.21 and Figure 8.22 is not depended on speed. An investigation into income would probably show that these vessels performing best in Era 1 would struggle with their higher break-even cost if stakeholders would prefer slow-steaming vessels.

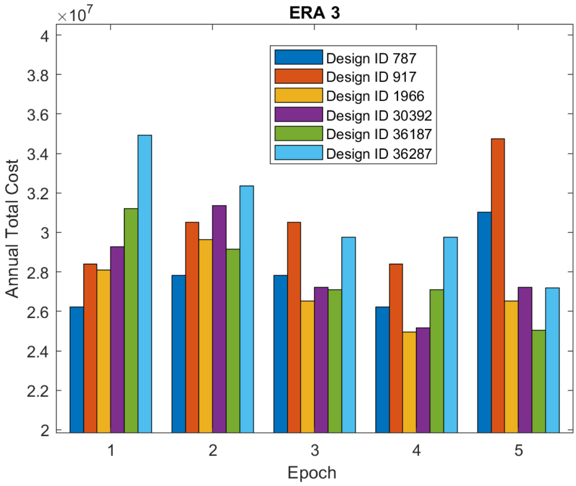


Figure 8.20: Annual Cost for Era 3. This figure does not display any relation with

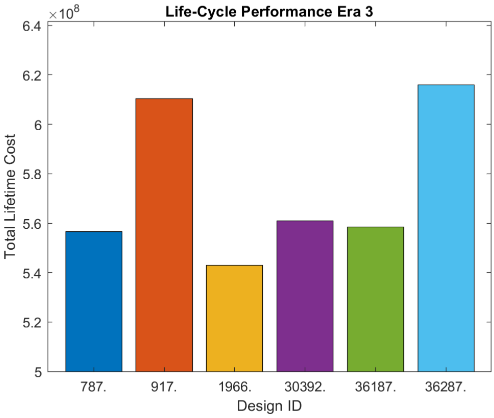


Figure 8.21: Life cycle performance for Era 3.

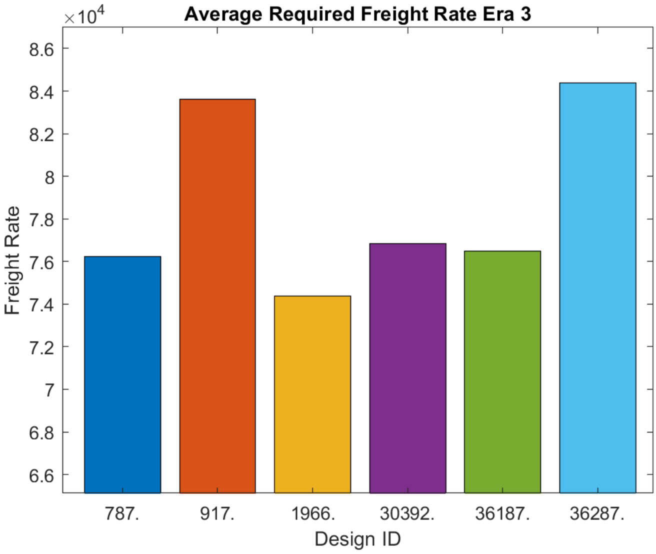


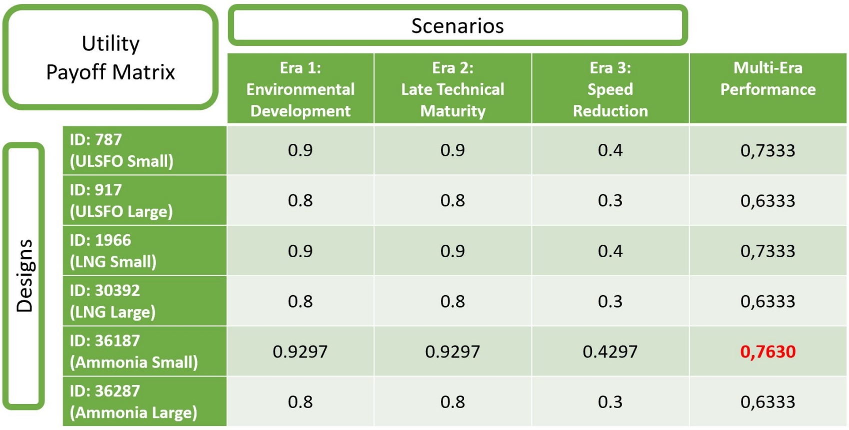
Figure 8.22: Required break-even freight rates for Era 3

8.5 Deciding the Most Value Robust Design

The six different vessels are all identified with a value robustness profile. Which of them that actually would provide the most revenue in the future is difficult to decide. Remembering from section 5.8, that several decision criteria can be exercised. The result is presented for each methodology.

The first method to use is the multi-attribute utility (MAU) criteria. MAU is already the basis for choosing those appealing ship design that has been compared in this section. The total utility for each vessel differs from era to era. Therefore it is most favourable to look on the multi-era utility. Meaning that adding the utility for each epoch provides the average utility value. Figure 8.23 shows the utility results. Contemplating upon the utility for each era, the small ammonia vessel is the best MAU alternative concerning each era. It is therefore foreseeable that the design with highest MAU over a multi-era analysis also is the small ammonia design. The red value in the Figure 8.23 is the numerical value for the overall utility.

The fact that one design is better than the others in the MAU measure is a solid reason for choosing that vessel. It is value robust and will satisfy the stakeholders' needs for the best average cost. Nonetheless, the utility measure in this project is based only three variables (speed, payload and GHG requirements), so there are some limitations. For example, the utility does not change between era 1 and 2, since the only change lies in the price levels in the epoch variable. Consequently, the other decision criteria can be useful to exercise as well.

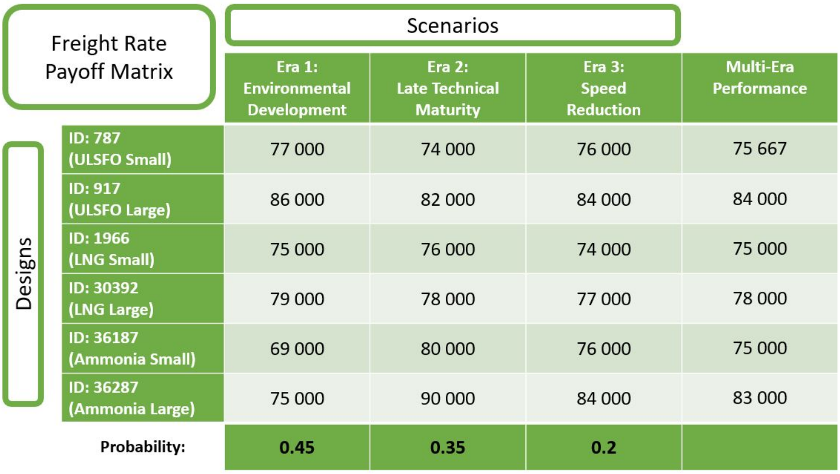


	Utility Payoff Matrix	Scenarios			
		Era 1: Environmental Development	Era 2: Late Technical Maturity	Era 3: Speed Reduction	Multi-Era Performance
Designs	ID: 787 (ULSFO Small)	0.9	0.9	0.4	0,7333
	ID: 917 (ULSFO Large)	0.8	0.8	0.3	0,6333
	ID: 1966 (LNG Small)	0.9	0.9	0.4	0,7333
	ID: 30392 (LNG Large)	0.8	0.8	0.3	0,6333
	ID: 36187 (Ammonia Small)	0.9297	0.9297	0.4297	**0,7630**
	ID: 36287 (Ammonia Large)	0.8	0.8	0.3	0,6333

Figure 8.23: Utility Matrix

8.5.1 Freight Rate Payoff Matrix

In Figure 8.24 the freight rate payoff matrix is shown. Each number indicates the cost, in USD/day, required to sustain a positive bottom line for the shipowner. They are rounded to the nearest thousand. It is important to remember that these are costs, and therefore the lowest value is favourable. The figure also includes a probability of the likelihood of the scenario to be unfolding. These probabilities are based on a thought likelihood, where Era 1 is rated somewhat more likely compared to Era2. Era 3 of low-speed reduction is not valued as imaginable as the other two eras.



	Freight Rate Payoff Matrix	Scenarios			
		Era 1: Environmental Development	Era 2: Late Technical Maturity	Era 3: Speed Reduction	Multi-Era Performance
Designs	ID: 787 (ULSFO Small)	77 000	74 000	76 000	75 667
	ID: 917 (ULSFO Large)	86 000	82 000	84 000	84 000
	ID: 1966 (LNG Small)	75 000	76 000	74 000	75 000
	ID: 30392 (LNG Large)	79 000	78 000	77 000	78 000
	ID: 36187 (Ammonia Small)	69 000	80 000	76 000	75 000
	ID: 36287 (Ammonia Large)	75 000	90 000	84 000	83 000
	Probability:	**0.45**	**0.35**	**0.2**	

Figure 8.24: Payoff Matrix for Freight Rates

Min Cost Criteria. From an optimisation perspective, min cost is the straight forward decision method. Regarding min-cost decision Table 8.4 shows the result as modified from the payoff matrix.

Table 8.4: Min Cost Results

Scenario	Alternative	Min Cost
Era 1	Ammonia Small	69 000
Era 2	ULSFO Small	74 000
Era 3	LNG Small	74 000
Multi - Era	LNG/Ammonia Small	**75 000**

Maximum Likelihood Criteria. From the matrix the and the min-cost investigation, it is easy to make a maximum likelihood decision. Era 1 is considered the most probable scenario, and for that reason, the small ammonia vessel is also the best alternative in that regard.

Table 8.5: Maximum Likelihood Result

Scenario	Alternative	Maximum Likelihood
Era 1	Ammonia Small	69 000

Maximin payoff criteria. In this situation, the shipowner first wants to find the minimum payoff, which is shown in Table 8.6. The small LNG alternative provides the best performance (remember that cost and not profit or revenue is the criteria). If a larger vessel is to be chosen regardless of the performing small vessels, the LNG alternative also provides the best results with the maximin criteria (with 79 000 USD/day).

Table 8.6: Maximin Results

Alternative	Maximin payoff
ID: 787 (ULSFO Small)	77 000
ID: 917 (ULSFO Large)	86 000
ID: 1966 (LNG Small)	**76 000**
ID: 30392 (LNG Large)	79 000
ID: 36187 (Ammonia Small)	80 000
ID: 36287 (Ammonia Large)	90 000

Bayes Decision Rule Criteria. This criterion takes possibilities into account, so there are, as mentioned earlier, some imperfections associated with this decision method. However, the calculations were conducted, and the results are shown in Table 8.7. The small ammonia alternative is marginally better than both ULSFO and LNG. For the larger vessels, the

LNG option has the lowest anticipated cost.

Table 8.7: Bayes Decision Rule Criteria

Alternative	Expected cost
ID: 787 (ULSFO Small)	75750
ID: 917 (ULSFO Large)	84200
ID: 1966 (LNG Small)	75150
ID: 30392 (LNG Large)	78250
ID: 36187 (Ammonia Small)	**74250**
ID: 36287 (Ammonia Large)	82050

Minimum Regret Criteria. The first thing to do is to establish a ”regret table”, seen in Table 8.8 as the values beneath the different eras. It is important to keep in mind that the evaluation of cost means that the regret for each era will be the actual option minus the best alternative. The second thing to do is creating minimum regret values. That is the highest value for each design across eras. The small LNG and ammonia vessels perform best when it comes to minimum regret. The large LNG vessel performs best between the larger vessel options.

Table 8.8: Regret Table

Alternative	Era 1	Era 2	Era 3	Minimum Regret
ID: 787 (ULSFO Small)	8 000	0	2 000	8 000
ID: 917 (ULSFO Large)	17 000	8 000	10 000	17 000
ID: 1966 (LNG Small)	6 000	2 000	0	**6 000**
ID: 30392 (LNG Large)	10 000	4 000	3 000	10 000
ID: 36187 (Ammonia Small)	0	6 000	2 000	**6 000**
ID: 36287 (Ammonia Large)	6 000	16 000	10 000	16 000

8.5.2 The Value Robust Vessels

Comparing all vessels, the designs with smaller capacity showed the most value robustness across all three eras (High utility, Low Cost). There was only a marginal difference between the LNG and Ammonia options. LNG will provide a lower risk than the other options due to the performance in both maximin and minimum regret decision criteria. Moreover, LNG becomes a risk-averse option. On the other side, Ammonia can provide the most upside (lowest required cost) and perform better when the assumed probability is included. As seen in results for Era 2, the variations in performance are higher for the ammonia, and the downside could be more substantial.

The final choice of vessel design depends on details in the charterparty. In the scenario of only supplying Johan Castberg, the small vessel of 115 000 m^3 can travel a total amount of 5.7 million m^3 a year, meaning that in the first few years of production it would not be sufficient shuttle tanker supply (yearly average production of 10 million m^3 first four years). Therefore, it would require at least one more vessel of this size. As known from the operator side, providing redundancy to the system is fundamental. Therefore, three or even a fourth vessel should be needed. Furthermore, the decisions will depend on new oil fields and continuous production. Hence, charterparty will most likely bend towards three small vessels if no more activity is anticipated.

The large LNG design can provide an annual amount of 9.2 million m^3 crude oil from Johan Castberg, which means that even by choosing this vessel, two ships is needed in the beginning. For redundancy, a third vessel could be necessary for the operator. Hence, the total cost will be more significant with three large vessels compared to three smaller vessels.

A relevant proposition for the charter parties is to have one large vessel and two smaller vessels. That could provide redundancy for the first years of production and at the same time give a higher utilisation in the proceeding years after production drops. However, all these decisions highly depend on the opening of new oil fields.

The specifications of the vessels providing the most valuable results are given in the following subsections.

Design ID 36187 - The Small Ammonia Option

The small ammonia vessel properties are shown in the Table 8.9, while Figure 8.25 shows the important information for stakeholders.

Table 8.9: Specifications Design ID 36187

Design Specification	Numerical Value	Unit
Length	250	m
Breadth	40	m
Depth	22	m
Draft	15	m
Design Speed	15	knots
Machinery	Ammonia	[-]
Payload Capacity	99000	m^3
Displacement	127 500	m^3
Lightweight	45 700	tonnes
Power	19 000	kW
GHG reduction	100%	[-]

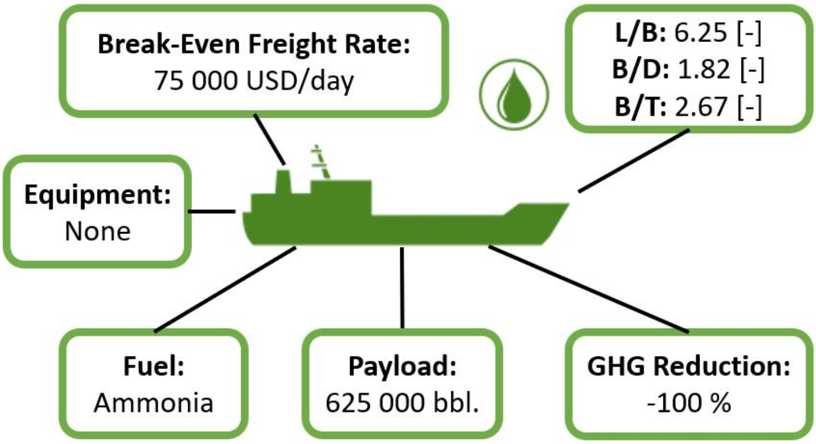


Figure 8.25: The Small Ammonia Option

Design ID 1966 - The Small LNG Option

The small LNG vessel properties are shown in the Table 8.10, while Figure 8.26 shows the important information for stakeholders.

Table 8.10: Specifications Design ID 1966

Design Specification	Numerical Value	Unit
Length	250	m
Breadth	40	m
Depth	20	m
Draft	15	m
Design Speed	15	knots
Machinery	LNG	[-]
Payload Capacity	90 000	m^3
Displacement	127 500	m^3
Lightweight	53 500	tonnes
Power	18 500	kW
GHG reduction	60%	[-]

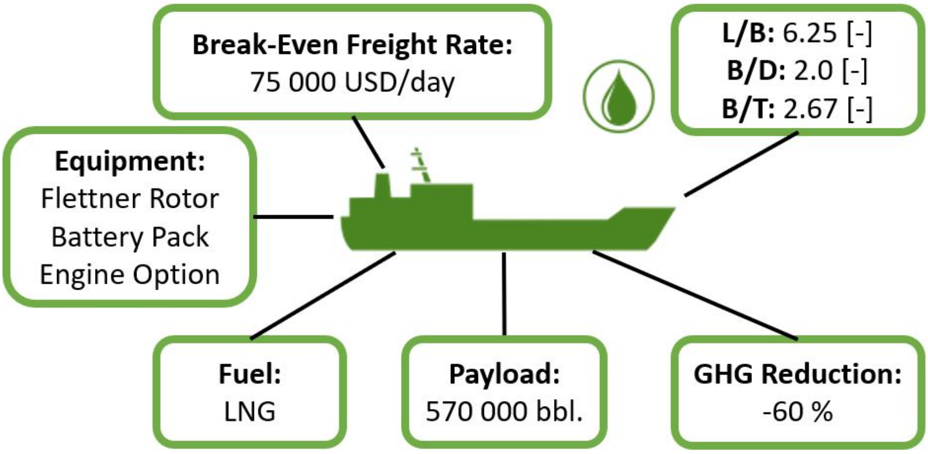


Figure 8.26: The Small LNG Option

Design ID 30392 - The Large LNG Option

The small LNG vessel properties are shown in the Table 8.11, while Figure 8.27 shows the important information for stakeholders.

Table 8.11: Specifications Design ID 30392

Design Specification	Numerical Value	Unit
Length	290	m
Breadth	50	m
Depth	24	m
Draft	15	m
Design Speed	15	knots
Machinery	LNG	[-]
Payload Capacity	156 000	m^3
Displacement	184 000	m^3
Lightweight	55 000	tonnes
Power	24 000	kW
GHG reduction	40%	[-]

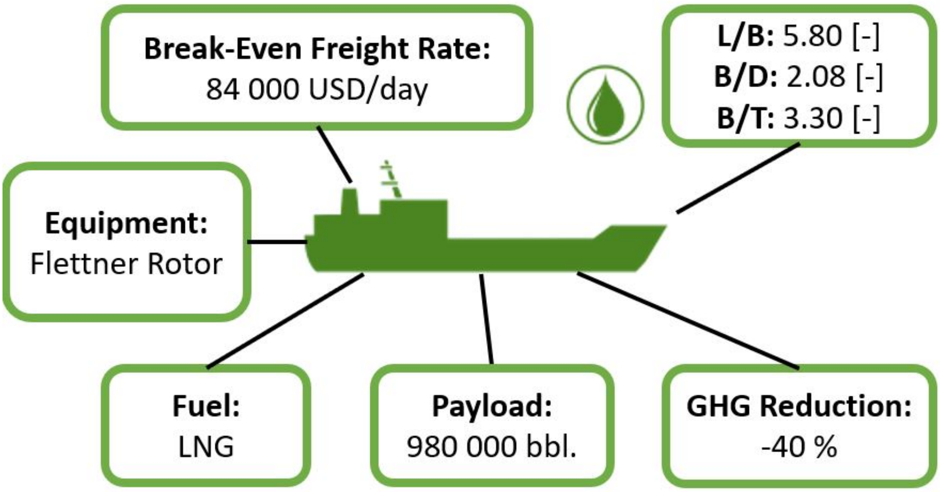


Figure 8.27: The Large LNG Option

8.6 ERA 4 - A 2050 Scenario

The results for the 2050 scenario can be divided into the design that satisfies a 2030 perspective (40% GHG reduction) and those that are 2050 compliant (70% GHG reduction). The first two epochs have the same characteristics; hence Epoch 1 is the only visualised. Looking at the designs seen in Figure 8.28 the "levels" in the graph represents the design speed. Reducing speed can give a lower break-even cost. The same evaluation regards the payload capacity of the vessel. All vessels above 0.67 utility are 2030 compliant designs, and since it is ULSFO alternatives, they all have full equipment.

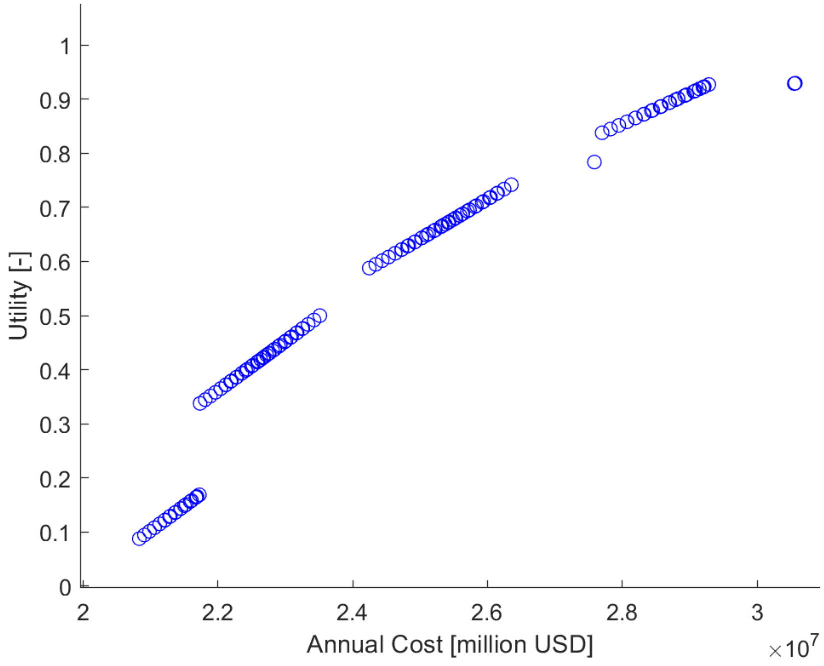


Figure 8.28: Epoch 1 - Pareto Front

The analysis is also done with a fuzzy Pareto front in order to see if there are more results than ULSFO that appears close to the best alternatives. The fuzzy Pareto front includes the 5 % more costly designs. The results (Figure 8.29) indicates that many designs for both LNG and ULSFO are performing well in IMO 2030 scenarios with relatively few changes in prices. No vessels achieve 1 utility, meaning that large vessels are appreciated, but maximising the main dimensions does not give the highest value. Hence, the largest payload capacity will provide larger annual transport capacity compared to the production in the Barents sea.

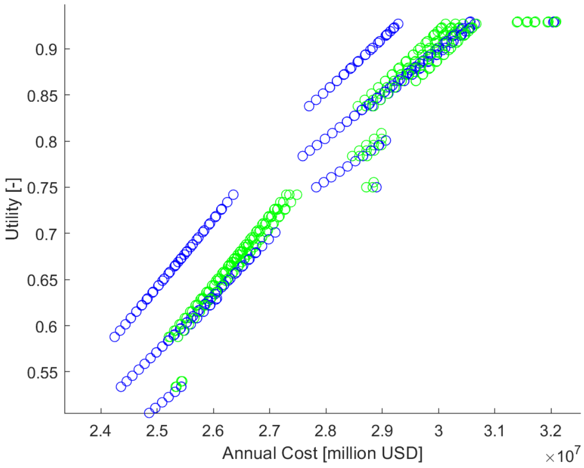


Figure 8.29: Epoch 1 - Fuzzy Pareto Front

Looking on the IMO 2050 epochs (3,4 and 5) ammonia and hydrogen is the only feasible alternatives in providing full GHG reduction. The huge difference in CAPEX between those two makes ammonia much more valuable and consequently, also the preferred machinery solution. Figure 8.30 illustrates this for Epoch 5. Ammonia solutions in the top left line will provide the best results. The next best designs are also ammonia fuelled ship designs, meaning that hydrogen is too expensive. Hydrogen's low performance is either related to the much higher CAPEX cost, or the price level influencing high OPEX resulting cost.

.

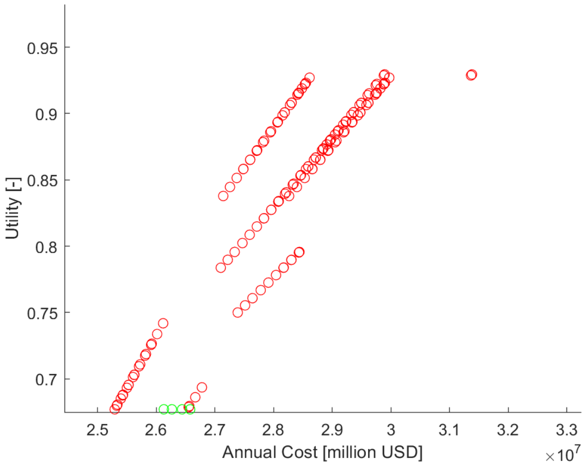


Figure 8.30: Epoch 5 - Fuzzy Pareto Front

Life-Cycle for some Ammonia designs for 2050 Scenario

Furthermore, in Figure 8.30, the designs that provide the most value are related to the ability to maximise utility. As many as 25 different designs create utility over 0.9. However, there is one common factor that is extra visible. All of the best designs provide around 130 000 - 140 000 tonnes of payload. That equals to around 820 000 - 880 000 bbl. All these vessels are sailing with a design speed of 15 knots. The figure is cut at 0.67 utility to illustrate that the non-compliant designs cannot get higher than that. Here represented by the LNG designs that provide max value in speed and payload, but does not perform in GHG requirements.

Picking, the right vessel of 25 designs, might be challenging. Comparing the designs on the cost could be one way to determine. Other methods rely on more evaluation, like hydrodynamics and construction properties. section C.1 shows the different main specifications for the 25 highest performing vessels. Table 8.12 displays the four highest utility valued design from the appendix. The four designs perform well in utility and seem alike in value. Despite this, there are aspects of properties that can make those design differ from each other. For example, looking at the break-even cost can make expenditures to be reduced by almost 5 000 USD/day (see: Figure 8.31).

Table 8.12: Four Ammonia designs

Design ID	L	B	Dr	Payload	Era Total Utility
36227	290	48	22	137808	0.9295
36235	278	50	22	137610	0.9287
36278	254	50	24	137160	0.9270
36261	274	46	24	136123	0.9231

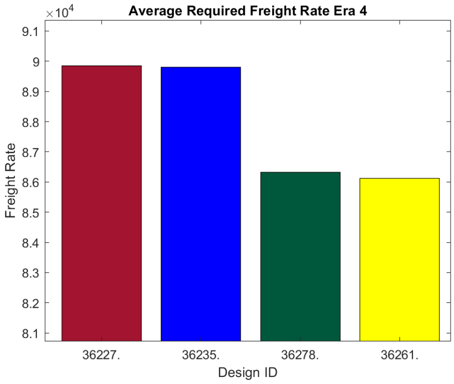


Figure 8.31: Required Break-Even Freight Rates for the four best performing ammonia vessels in 2050 scenario.

Chapter 9

Discussions

9.1 About Technologies

The technologies for fuelling the future shuttle tanker depends on the context we talk about. In a 2030 perspective with a reduction ambition of 40 % decrease of GHG, we think about transition fuels. LNG and ULSFO were used in the further examinations and modelling of the later case of Johan Castberg. They both represent the most likely alternatives that the industry valuates and are exceptionally exciting and realistic fuel options. Nevertheless, LPG, MGO and methanol could all be relevant to have investigated because of their properties and reduction capabilities. Especially LPG is worth discussing since it has similar properties to ammonia and could, therefore, be a considerable transition fuel for ammonia. However, flexibility and real option pricing are not included in the scope of this model. Thus, LPG was not chosen to be investigated further since LNG is a more realistic alternative for providing a transition alternative in the model. Likewise, biofuels could also offer flexibility as a transition fuel. However, biofuels were excluded from the model because of the availability of the fuel and the properties of usage. It is central to be aware of both LPG and Biofuels as industry-relevant options for flexibility. Still, in a perspective of value robustness, they do not add more value than LNG.

Battery and wind are exciting possibilities for the future of maritime propulsion. For that reason, they were included as additional equipment in this model. Wind as propulsion could have been analysed solely as a zero-emission solution, but the technology does not support a vessel size of a shuttle tanker alone anyway. Batteries provide three hybrid methods for machinery effectiveness, and they were further included in the modelling as a possibility of 10 % reduction. This could be a little unorthodox conclusion and are most likely not precisely correct. However, the cost of battery reduction of 10 %, were directly connected to 10 % of the required power(kW).

Hydrogen had some initial promising properties that were seen as a possibility. Hence, it was further examined, but it had some distinct worrying aspects such as density properties, infrastructure and cost perspectives. This leads us to the investigation of infrastructure.

9.2 About Infrastructure

Realising the importance of ship sizes and speed relations to estimating mass required for propulsion regarding hydrogen based infrastructure is essential. The concept of reducing speed, to need less engine power resulting in less fuel consumed is available information. Although it is not necessarily talked much about or performed in the maritime industry. Machinery optimality is not included in the investigation of required mass. Nonetheless, optimality would depend on the engine and auxiliary systems and cannot be given an accurate evaluation without thorough research. That would be scope for a more detailed approach of engines for future fuels, but in our case, it is fascinating to see that reduction in speed can decrease power significantly.

The investigation of the amount of mass needed to sail a specific distance become vital in analysing where the infrastructure around hydrogen based infrastructure should be built. In section 4.1 an example was made with special consideration of hydrogen as fuel. Since continuously refuelling was assumed in that shortest path problem, a distance of max 300 nm was constructed between each node. The distance mark is not meant to illustrate how long a shuttle tanker could travel, but rather a realistic distance that could cover several ship segments. It is reasonably not an option for any shipowner to go with hydrogen if they have to refill three or four times per voyage.

The results provide information that could be of help for any ship segment and further investigation of synergies with the construction of hydrogen infrastructure. In the distance between Johan Castberg and Mongstad, the main barriers in building hydrogen infrastructure are the number of nautical miles that have to be travelled along a coastline with low population density. Some issues that have to be discussed further by governing decision-makers are cost, constraints in ports or production facilities. In that regard, Aasta Hansteen was included as an alternative node. The choice of Aasta Hansteen is unusual and spikes an unspoken aspect of this project. Perhaps old offshore platforms can be used for hydrogen production and storage, or as a refuelling station, in the future?

9.3 About The Three Phases of RSC

The three phases summarising the RSC method is a simplification of the process to customise the methodology to fit ship design of a value robust shuttle tanker. In this part, we want to answer the advantages and constraints of applying the RSC model to ship design. In what degree do the ship design that we have found meet the criteria for what a value robust vessel is and our definition of value.

About Market Analysis

The toolbox provided for the market analysis in this thesis is practical for any stakeholder in ship design. However, by the time this master has been written, it can clearly be seen that some of the market analysis are momentary analysis. The extreme shift in the global markets (Early 2020) become a real-life example for the essentials and principal issues that value robustness under uncertainty means. In the case of the shuttle tanker market analysis for this thesis, some observations changed during the months of writing. Especially the part of the macro analysis like the PEST method become somewhat absolute from the original text first written in January. In other words, some of the considerations explained in the market thesis have evolved within these months.

Nonetheless, the dynamics between stakeholders and general tendencies is unaffected by volatile markets. Likewise, the plans to develop the Johan Castberg field and production is also unchanged, despite the profitability might be lowered with the fall in oil price. The market analysis is, therefore, still relevant in understanding to read the stakeholder's needs and how they can be visualised. The MAU estimation is exclusively based on the subjective interpretation of value as related to stakeholders needs and market analysis. For a shipowner or other design offices, an in-depth comparison MAU method might be more useful for identifying utility because that could cover even more aspects. Anyhow, identifying some utility as some value-based parameters have been sufficient to displaying different interpretations and effects of varying the utility across epochs and eras.

About Epoch-Era Methodology

Phase 2 includes the development of the tradespace that consist of both design space and epoch space. Epoch-Era as an exercise requires a vast amount of computational capacity, and the main constraints in the model lie within this area. For the design space, 57 000 designs are created with the levels related to the range for design variables. The number of designs increases exponentially with more extensive levels. Ideally, we would have wished to evaluate ship designs for every meter in length and breadth. Still, since the computational time would increase drastically, we had to limit it to every second meter. To illustrate, an every meter analysis would create around 200 000 designs. SEAWEB was used to find the relevant information about the shuttle tankers. The data set is limited to the previous designs developed, meaning that the range for the main dimensions especially is bounded by earlier built vessels. It could have been relevant to include a broader range between min and max so that unthinkable designs becomes apart of the tradespace. Anyhow that would again spike the number of designs to an infeasible computable amount.

For the epoch variables, the same constraints apply, however, for these variables is different in nature. Price levels are fluctuating numbers in continuous time, but in this model, it is limited to illustrate five levels of performance (from very low, low, medium, high and very high). This reduction to five levels is effective in capturing the basics of the changing prices. Furthermore, since the Eras is constructed through the storytelling approach, the amount of Epochs is not that important. However, it is vital that developed narratives can be found in the epoch space.

The decisions around excluding STL, BLS and DP are vital to discuss. They all provide significant relevance to the design of a shuttle tanker. If they were a part of the solution, it probably would have interfered the utility objectives provided by stakeholders. Nevertheless, it was decided in the early phase of the coding to exclude them, since they did not offer much difference in vessel configuration. In other words, the upside of including that information in the model, would not replace the downside of increased computational time. Other variables, like equipment providing GHG reduction, was more vital for the intended solutions.

Oil price was an epoch variable meant to provide the variation in production rate offshore. However, information around the estimated production for the lifetime of Johan Castberg appeared later in the project. Therefore, the oil price variable becomes absolute in the case study. Nevertheless, it stayed in the model, since it would not affect any computational time. The reason for that was because eras was selected manually through the storytelling approach. Nonetheless, this development in information became a real practice of how uncertainty in the early marine system design can affect decision-making. It is arguably a ”lack of knowledge” uncertainty, which is fascinating in retrospect.

The narratives creating each era are unique scenarios based on a valuation of epoch variables and how they could describe the future. This is done to cope with uncertainty, but there are, of course, risk related to only applying a few scenarios. The most ideal methodology would be to implement a Multi-Era analysis with a sufficient number of eras, including as many of the 12 000 epochs. On the contrary, this would require an enormous amount of computational power and is not necessary to get primary indications.

The methodology described in Chapter 7 for establishing the tradespace needs different numerical values. A lot of these values are approximate numbers rounded to the million (USD). The information is gathered from reference vessels of Aurora Spirit (Teekay) and new Knutsen and AET vessels provided by shipbroker Galbraith’s Oslo office. As a part of the iterative process of ship design, the cost of different equipment would depend on the size and speed of the vessel. For example, engine prices are given for one engine and related storage systems. In a final design, a shipowner might wish for two main engines or additional auxiliary systems, which would increase costs. For illustration, one extra 12 million USD engine would provide an added annual CAPEX write off 1.4 million USD if the same WACC is used. Speaking of WACC and CAPEX estimation, the financial scenario is a realistic thought situation. The fact that the same financial pricing model is used for all designs will provide some misguidance from any final designs. Financing of the vessel will depend on bank, shipowner, main dimensions and other factors. However, the WACC calculate provides a reasonable first estimation for calculating required freight rates.

About Results

The tendency of small vessels is well supported through the amount of production at Johan Castberg. Even after one epoch, the small vessels become preferred in the model, since the production levels drop by a relatively high amount. In that scenario, we exclude known unknowns that relates to the opening of more oil fields in the Barents Sea. There is a considerable chance that more oil fields and more production will affect any decision-maker in the shuttle tanker market. The separate 2050 scenario has an estimated annual production of 7 million Sm^3 and indicate that some larger vessels would be preferred when the output is higher.

This leads to a weakness that is worth discussing within the utility estimations. In the MATLAB code, only three utility criteria are used to produce the MAU relating to each vessel. These are GHG reductions, vessel payload capacity and speed—the two former only changes with regulations that are ratified and the production at Johan Castberg, respectively. Therefore the difference in utility does not differ when solely price levels for fuel are changed. An interpretation of this aspect of the coding is that it provides little information about the stakeholder's needs and value. However, the construction of these utility calculations is based on the Keeney and Raiffa conditions to keep it simple and complete. Moreover, the non-redundant criteria have been valued the most in this model. The reason lies in the problem of counting attributes twice since there are such a low amount of variables. If a design attribute had been counted twice, it would change the model to provide a utility that is unrepresentative to the market analyse conducted.

The machinery systems that is selected is highly dependent on the OPEX costs meaning that the price levels dictate the results. CAPEX is, of course, relevant when it comes to sizes of the vessels, but the difference between the ships with the same payload capacity (or size) exist mainly in the equipment. Resulting in only small variations in cost calculations. Hence, OPEX becomes the contrasting variable between designs.

Break-even freight rates calculated imitates real values, but several factors could make the required freight rate either go up and down. First of all, the calculation of CAPEX is not exact, and an increase in CAPEX (equipment, storage, etc.) would increase the break-even price. Secondly, there is no rest value assumed at the end of the ship lifetime. Usually, a shipowner would estimate some rest value and writing off the vessel down to zero at the end of the lifetime is not a common practice. The ship can have a longer lifetime, or it could trade in other waters (markets, e.g. Brazil), that would also affect the daily write-off cost. Thirdly, real options are often used in the charterparty between shipowner and charterer. Those options will depend on contract and agreement in the charterparty. Therefore, the freight rates would also vary between contract periods.

The investigations into the six best performing vessels from Era 1 and the comparison with Era 2 and 3 indicates that the small ammonia vessel is the best alternative. The small ammonia shuttle tanker performs best with MAU, Maximum likelihood, Bayes and minimum regret criteria. The high overall performance confirms the feasibility for ammonia as a future fuel. If the technology becomes accessible on a large commercial scale, it could really become the favoured solution. The drawbacks are that within the scenario (Era 2) where ammonia is an expensive fuel, the OPEX cost gets affected, and it becomes a lesser valued option in terms of cost. The price levels for ammonia in this model is using current valuation. The current ammonia market consists of mostly gas-based production. If the production of ”green” ammonia is expected, the price levels would most likely increase due to infrastructure and production cost of hydrogen.

Hydrogen was included in the model as an ”underdog” option, and it is fair to say that hydrogen did not perform well enough. The barriers of having hydrogen as a fuel for a larger shuttle tanker is substantial. Speaking of space and mass required to the energy efficiency. Hydrogen CAPEX, including engine and fuel cells, give the highest cost and becomes absolute to the other alternatives. OPEX cost was also affected by the fact that even the lowest estimations become non-competitive to the varying fuels.

For the more massive vessels LNG becomes the most favourable option. The reason for that may rely on the CAPEX difference since the large vessel does not have more than one equipment. The small LNG shuttle tanker did have all equipment included. It might not have been an entirely fair comparing between LNG and the other small vessels, but the indication of MAU would still prefer this ship designs before others.

About Final Designs

The final propose of the vessel will depend on charterparty specifications and particular interests of stakeholders. This affects the conclusions on how many vessels and which sizes that can provide the most value robust designs. Anyhow, the small ammonia and LNG shuttle tanker will alone give the most value as shown in the result of this model.

Often would shipyards prefer to build several of the same type and dimensions. This is an aspect that tends to favour conservative decision making. Hence, it probably would be more actual to order a charterparty consisting of LNG vessels. Additionally, if ammonia vessels were to be chosen, the combinations of large and small ships would be even less attractive for a risk-averse decision-maker due to the downside a high ammonia fuel price can provide. Likewise, the non-existing infrastructure would also provide barriers that affect the feasibility of ammonia.

It has to be acknowledged that the data around the development of the Norwegian continental shelf is affecting any decision regarding the Barents Sea. This is information and knowledge that could have been included in the model as shifting variables, but that would expand the case from supplying Johan Castberg to providing the whole activity platforms in the Barents Sea. Furthermore, this aspect shows the difficulties by handle uncertainty. Known unknowns are, as in this case, seldom established before later in the design phase and is, therefore, challenging to predict in current time.

Era 4 was modelling meant to try to capture some of the known uncertainties. The constant production level (7 million Sm^3) in the Barents Sea given to the epochs meant that vessels with the payload capacity of intermediate numerical values provided better results. These intermediate results (around 137 000 m^3) are comparable to the comparison-vessels of Teekay and AET, which is exciting. It can anticipate that when established companies order new vessels, they have indications or expectations that crude oil production will be on a relatively stable intermediate level.

Chapter 10

Conclusion

The main objective of this thesis is to investigate how we can design a value robust shuttle tanker under uncertainty. Especially with a focus upon new environmental regulations and technical innovations. About which technologies that are the most favourable, ammonia performs as the best feasible zero-emission option for deep-sea shipping. Hydrogen is also a promising zero-emission alternative, but it is more suited for short sea shipping. Batteries and wind technology together with engine performance optimisation was concluded good options as supporting technologies for transition fuels such as LNG and ULSFO.

Hydrogen was through the relations of power, ship size and speed excluded as a top-performing fuel option. The infrastructure research highlighted the differences in mass required for hydrogen and ammonia. Furthermore, the investigations into possible locations for hydrogen infrastructure concluded that Tromsø, Stavanger, Kristiansund are all suitable locations. The Johan Castberg case study also verified that hydrogen did not perform well enough to be competitive for shuttle tankers, but for other ship segments, hydrogen can be vital in achieving IMO goals.

The three phases applied in this thesis as a simplification of the Responsive Systems Comparison method (RSC) is a framework that can identify value across uncertain changing contexts. As an example of set-based design, RSC, most importantly focus on the needs of the stakeholders and uses market analysis, strategies, and maritime knowledge to evaluate perceived value. Multi-attribute utility (MAU) is a measure of this value. Value robust designs have a high MAU performance across contextual and temporal aspects of ship design complexity.

The results of RSC indicates that a small shuttle tanker between 570 000 bbl (for LNG) - 625 000 bbl (for ammonia) creates the most value robustness in the case of supplying Johan Castberg from 2022 and into the future 20 years. The machinery systems should either be LNG or Ammonia. Ammonia performs best when analysing it from a straightforward perspective, such as minimum cost and with a probability given in the decision criteria. LNG achieve the best results when conservative measures are conducted. Hence, it is a low-risk option.

Concerning environmental regulations LNG is a suitable option meeting 2030 criteria. However, it only provides reduction of GHG and not a complete abandonment. On the contrary, ammonia brings a zero GHG profile to any ship design and is also 2050 compliant. Therefore, ammonia is an excellent alternative for a zero-emission solution into a 2050 perspective. Anyhow, when it comes to the reduction of GHG, the sooner solutions are available, the better it is. This thesis shows that ammonia can be competitive and in some cases, the best perceived value robust solution. Maritime decision-makers will first look at the break-even freight rates. However, decisions including corporate environmental responsibility should then come secondly.

10.1 Further Work

As indicated in the discussion, the methodology used in this project is a useful tool to cope with uncertainty. However, the number of solutions that are a part of the research has been affected by the computer capacity. For companies using the RSC to identifying value robustness might want to evaluate more vessels and analyse them in more than three/four eras. Hence, one of the suggested further work is how to apply the methodology for a multi-Era analysis. Such analyses will require much higher computing power. Anyhow, the codes in the appendix can be a good base for further work towards even more detailed analysis.

The results in this project provides discrete solutions that are based on only a few numerical values. The iterative process of ship design demonstrates that real values will change. Adding analysis relating to flexibility, the ability to modify jobs not included initially. That could be options on shuttle tanker contracts, options on retrofitting or similar aspects.

The regulations are very likely to become more strict as time goes. Thus, it is going to be essential to keep track of possibilities, innovations and feasible solutions. Ammonia looks promising now, and detailed analysis is necessary to evaluate this fuel opportunity. That could be analysis around machinery configuration, optimisation of fuel systems or similar engineering approaches. Vessels that will sail in 2050 should be built already in 2030, meaning that an enormous transformation and development of the shipping industry have to occur in the next ten years. In conclusion, all contributions toward zero-emission solutions are encouraged.

Bibliography

AET Tankers Pte Ltd, 2020. Cleanest Twin DPSTs Make Maiden Voyages. URL: https://www.aet-tankers.com/media-centre/cleanest-twin-dpsts-make-maiden-voyages/.

Amdahl, J., Endal, A., Fuglerud, G., Hultgreen, L.R., Minsaas, K., Rasmussen, M., Sillerud, B., Sortland, B., Steen, S., Valland, H., 2015. TMR4105 - Marin Teknikk Grunnlag.

Anderson, J.C., Narus, J.A., 2017. Business Marketing: Understand What Customers Value Harvard Business Review. Technical Report.

ASKO, 2017. I front med hydrogen. URL: https://asko.no/nyhetsarkiv/i-front-med-hydrogen/.

Blanchard, O., Amighini, A., Giavazzi, F., 2017. Macroeconomics - Third Edition.

Bøhlerengen, M., 2019. Workshop on liquid hydrogen safety Liquid Hydrogen Bunker Vessel LH2 Bunker Vessel. Technical Report.

Bunker, S.., 2019. ULFSO Rotterdam Bunker Prices. URL: https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#ULSFO.

Christensen, C.M., Hall, T., Dillon, K., Duncan, D.S., 2016. Know Your Customers' "Jobs to Be Done" Is innovation inherently a hit-or-miss endeavor? Not if you understand why customers make the choices they do. Technical Report.

DNV-GL, 2017a. DNV GL NOx Tier III Update. Technical Report.

DNV-GL, 2017b. Shuttle Tankers - Vessels built to be fit for purpose - providing safe flexible and efficent operations. Technical Report.

DNV-GL, 2019a. Forecast to 2050 - Energy transition outlook 2019. Technical Report.

DNV-GL, 2019b. SYNTESERAPPORT OM PRODUKSJON OG BRUK AV HYDROGEN I NORGE PRODUKSJON OG BRUK

AV HYDROGEN I NORGE Klima-og miljødepartementet og Olje-og energidepartementet URL: https://www.regjeringen.no/contentassets/0762c0682ad04e6abd66a9555e7468df/hydrogen-i-norge---synteserapport.pdf.

DNV-GL, 2020. Alternative Fuels Insight. URL: https://afi.dnvgl.com/.

E24, 2017. Her vil de lage hydrogen fra vind. URL: https://e24.no/energi/i/oRgy1R/her-vil-de-lage-hydrogen-fra-vind.

E24, 2019. Equinor dropper oljeterminalen på Veidnes i Finnmark. URL: https://e24.no/energi/i/BR2JJG/equinor-dropper-oljeterminalen-paa-veidnes-i-finnmark.

Energifakta, 2019. Electricity production. URL: https://energifaktanorge.no/en/norsk-energiforsyning/kraftproduksjon/#hydropower.

Equinor, 2017. Johan Castberg - konsekvensutredning. (PL532.). URL: https://www.equinor.com/no/how-and-why/impact-assessments/johan-castberg.html.

Equinor, 2019. Johan Castberg - felt i Barentshavet. URL: https://www.equinor.com/no/what-we-do/new-field-developments/johan-castberg.html.

Erikstad, S.O., 2017. Design Methods for Ocean Engineering. Technical Report. doi:10.1111/j.1559-3584.1970.tb04361.x.

Evans, J., 1959. Basic Design Concepts.

Gaspar, H.M., Rhodes, D.H., Ross, A.M., Erikstad, S.O., 2012. Addressing Complexity Aspects in Conceptual Ship Design: A Systems engineering Approach .

Gauci-Maistre, J.P., 2009. The Maritime Commons: Digital Repository of the World Maritime University Shipping strategies in dry bulk and tanker markets : specialisation versus diversification. Technical Report. URL: http://commons.wmu.se/all_dissertationshttp://commons.wmu.se/all_dissertations/115.

Hollensen, S., 2012. Essentials of Global Marketing. Second edi ed.

IMO, 2019a. Energy Efficiency Measures. URL: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx.

IMO, 2019b. GHG Emissions. URL: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/GHG-Emissions.aspx.

Kahneman, D., Tversky’, A., 1979. PROSPECT THEORY: AN ANALYSIS OF DECISION UNDER RISK. Technical Report.

Keeney, R.L., Raiffa, H., 1993. Decisions with Multiple Objectives:Preferences and Value Tradeoffs.

Larsen, K., 2019. TMR4225 Marine Operations Lecture. Technical Report.

Levander, K., 2012. System Based Ship Design.

Lundgren, J., Rönnqvist, M., Värbrand, P., 2010. Optimization.

MacGregor, 2019. Bow loading system. URL: `https://www.macgregor.com/Products/products/offshore-loading-systems/pusnes-bow-loading-system/`.

MAN, 2019. Batteries on board ocean-going vessels. Technical Report.

Market Risk Premia, 2019. Norway Market Risk Premia. URL: `http://www.market-risk-premia.com/no.html`.

Mcmanus, H., Hastings, D., 2005. A Framework for Understanding Uncertainty and its Mitigation and Exploitation in Complex Systems. Technical Report.

Niels de Vries, 2019. REPORT (THESIS) Safe and effective application of ammonia as a marine fuel. Technical Report. URL: `https://repository.tudelft.nl/`.

Norsepower, 2019. Flettner Rotor — Technology — Norsepower. URL: `https://www.norsepower.com/technology`.

Olsen, M.B., 2019. Pre-Thesis: Zero Emission Solutions for North Sea Shuttle Tanker Market. Ph.D. thesis.

Pahl, G., Beitz, W., Feldhusen, J., Grote, K.H., 1977. Engineering Design: A Systematic Approach.

Pettersen, S., 2019. Pareto Set - TMR4135 Design Methods 2.

PWC, 2019. Norway - Taxes on corporate income. URL: `http://taxsummaries.pwc.com/ID/Norway-Corporate-Taxes-on-corporate-income`.

Ross, A.M., Mcmanus, H.L., Rhodes, D.H., Hastings, D.E., Long, A., 2009. Responsive Systems Comparison Method: Dynamic Insights into Designing a Satellite Radar System. Technical Report.

Rutkowski, G., 2019. A Comparison Between DP Offshore Loading Operation on Submerged Turret Loading System STL, Submerged Single Anchor Loading System SAL and Offshore Loading System OLS Considering the Hydro-meteorological Condition Limits for the Safe Ship's Operation Offsh. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation 13, 175–185. doi:`10.12716/1001.13.01.18`.

Singer, D.J., Doerry, N., Buckley, M.E., 2009. What Is Set-Based Design? doi:`10.1111/j.1559-3584.2009.00226.x`.

Skipsrevyen.no, 2020. ≪Viking Energy≫ blir første skip på ammoniakk. URL: https://www.skipsrevyen.no/article/viking-energy-blir-foerste-skip-paa-ammoniakk/.

Stopford, M., 2009. Maritime Economics 3e. URL: https://ebookcentral.proquest.com/lib/ntnu/reader.action?docID=371028.

WinGD, 2019a. Diesel Engine WinGD Engines. URL: https://www.wingd.com/en/engines/engine-types/diesel/x62/.

WinGD, 2019b. Dual Fuel WinGD Engines. URL: https://www.wingd.com/en/engines/engine-types/x-df-dual-fuel/x62df/.

Woud, H.K., Stapersma, D., 2017. Design of Propulsion and Electric Power Generatiomn System.

Appendices

Appendix A

A.1 Dijkstra's Algorithm

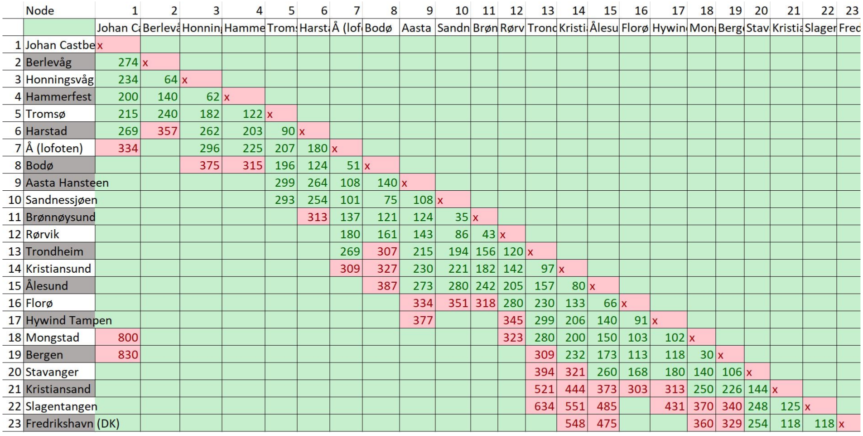
The Algorithm is presented as in (Lundgren et al., 2010).

"The following algorithm determines the shortest path from node n_s to node n_t in a network defined by sets of nodes N and arcs B.

- **Step 0**. Divide the set of nodes in subset A = searched = Ø and D = non-searched = N.
  Let node n_s have label (p_s, y_s) = predecessor,node price) = (-,0), which means that the node has no predecessor and the node price is y_s = 0.
  All other nodes are given the initial node price of y_j = ∞
- **Step 1**. Identify node i $\in$ D with minimum node price y_i = $\min\limits_{k \in D} y_k$
- Step 2. Search node n_i, i.e check all arcs (i,j)$\in$ B starting from node n_i. If $(y_i + c_ij) < y_j$, then we have found a shorter path from n_s to n_j passing node n_i.
  Let node n_j have the new label (p_j, y_j) = $(i, y_i + c_ij)$.
  (*) If $n_j \in A$ move node n_j from set A to set D.
- **Step 3**. Move node n_i from the set D to the set A.
- **Step 4**. Stop when all nodes are searched, i.e when A = N. Otherwise, go to Step 1.

We find the shortest path using the final nodes labels" (Lundgren et al., 2010).
MATLAB have a embedded function, shortestpath, that does this algorithm for us.

A.2 Distance Matrix



	Node	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
		Johan C	Berlevå	Honnin	Hamme	Troms	Harst	Å (lof	Bodø	Aasta	Sandn	Brøn	Rørv	Trond	Kristi	Ålesu	Florø	Hywin	Mon	Berg	Stav	Kristi	Slager	Fred
1	Johan Castbe	x																						
2	Berlevåg	274	x																					
3	Honningsvåg	234	64	x																				
4	Hammerfest	200	140	62	x																			
5	Tromsø	215	240	182	122	x																		
6	Harstad	269	357	262	203	90	x																	
7	Å (lofoten)	334		296	225	207	180	x																
8	Bodø			375	315	196	124	51	x															
9	Aasta Hansteen					299	264	108	140	x														
10	Sandnessjøen					293	254	101	75	108	x													
11	Brønnøysund						313	137	121	124	35	x												
12	Rørvik							180	161	143	86	43	x											
13	Trondheim							269	307	215	194	156	120	x										
14	Kristiansund							309	327	230	221	182	142	97	x									
15	Ålesund								387	273	280	242	205	157	80	x								
16	Florø									334	351	318	280	230	133	66	x							
17	Hywind Tampen									377			345	299	206	140	91	x						
18	Mongstad	800											323	280	200	150	103	102	x					
19	Bergen	830												309	232	173	113	118	30	x				
20	Stavanger													394	321	260	168	180	140	106	x			
21	Kristiansand													521	444	373	303	313	250	226	144	x		
22	Slagentangen													634	551	485		431	370	340	248	125	x	
23	Fredrikshavn (DK)														548	475			360	329	254	118	118	x

A.3 Important Relations

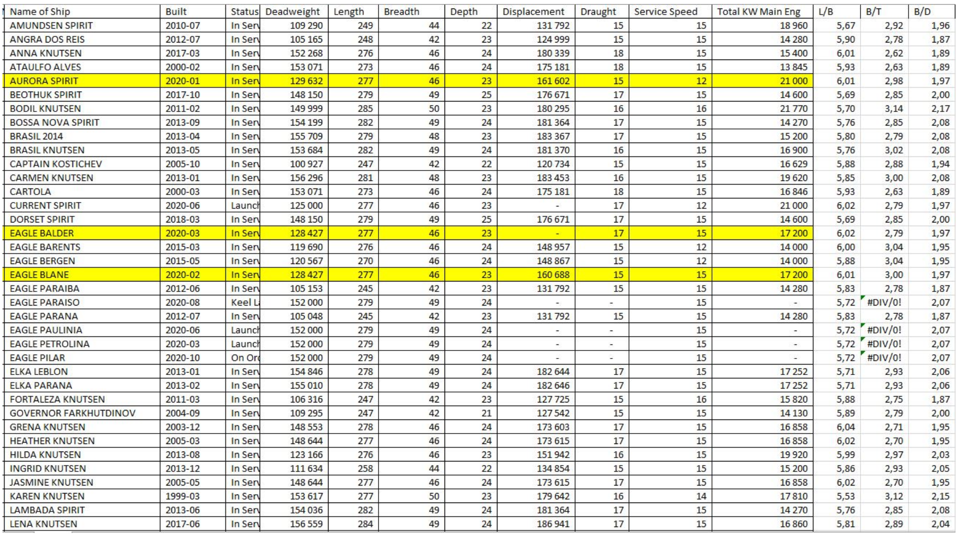
Oil equivalents

$$1\ \mathrm{S}m^3 = 6.3\ \mathrm{bbl} = 0.858\ \mathrm{tonne}$$
$$1\ \mathrm{tonne} = 7.33\ \mathrm{bbl} = 1.166\ \mathrm{S}m^3$$
$$1\ \mathrm{bbl} = 0.159\ \mathrm{S}m^3 = 0.136\ \mathrm{tonne}$$

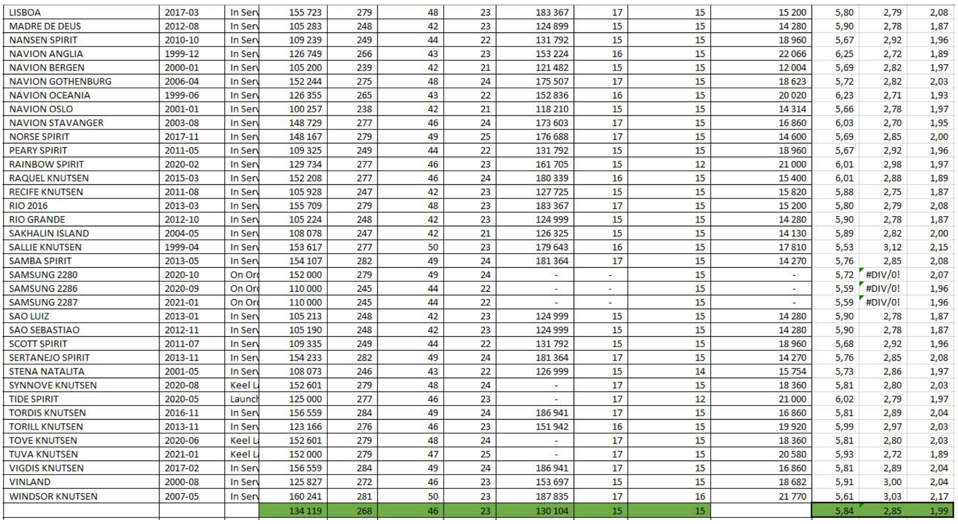
Appendix B

B.1 Data Used for Design Space

Data is gathered from the database SEAWEB. Yellow highlighted is vessels used for comparison in the project. The bottom green line are average values calculated from the data. The bottom figure is of AET's Eagle Balder (AET Tankers Pte Ltd, 2020).



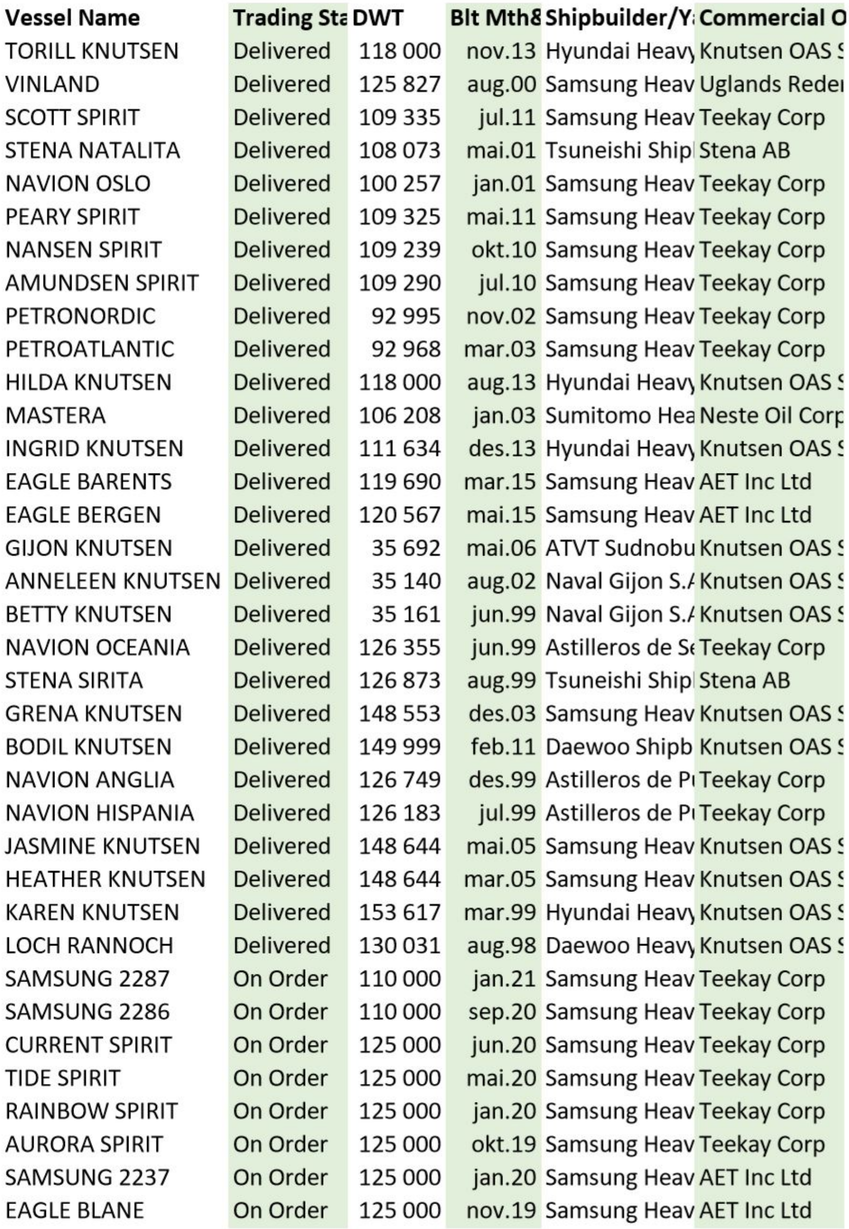
Name of Ship	Built	Status	Deadweight	Length	Breadth	Depth	Displacement	Draught	Service Speed	Total KW Main Eng	L/B	B/T	B/D
AMUNDSEN SPIRIT	2010-07	In Serv	109 290	249	44	22	131 792	15	15	18 960	5,67	2,92	1,96
ANGRA DOS REIS	2012-07	In Serv	105 165	248	42	23	124 999	15	15	14 280	5,90	2,78	1,87
ANNA KNUTSEN	2017-03	In Serv	152 268	276	46	24	180 339	18	15	15 400	6,01	2,62	1,89
ATAULFO ALVES	2000-02	In Serv	153 071	273	46	24	175 181	18	15	13 845	5,93	2,63	1,89
AURORA SPIRIT	2020-01	In Serv	129 632	277	46	23	161 602	15	12	21 000	6,01	2,98	1,97
BEOTHUK SPIRIT	2017-10	In Serv	148 150	279	49	25	176 671	17	15	14 600	5,69	2,85	2,00
BODIL KNUTSEN	2011-02	In Serv	149 999	285	50	23	180 295	16	16	21 770	5,70	3,14	2,17
BOSSA NOVA SPIRIT	2013-09	In Serv	154 199	282	49	24	181 364	17	15	14 270	5,76	2,85	2,08
BRASIL 2014	2013-04	In Serv	155 709	279	48	23	183 367	17	15	15 200	5,80	2,79	2,08
BRASIL KNUTSEN	2013-05	In Serv	153 684	282	49	24	181 370	16	15	16 900	5,76	3,02	2,08
CAPTAIN KOSTICHEV	2005-10	In Serv	100 927	247	42	22	120 734	15	15	16 629	5,88	2,88	1,94
CARMEN KNUTSEN	2013-01	In Serv	156 296	281	48	23	183 453	16	15	19 620	5,85	3,00	2,08
CARTOLA	2000-03	In Serv	153 071	273	46	24	175 181	18	15	16 846	5,93	2,63	1,89
CURRENT SPIRIT	2020-06	Launch	125 000	277	46	23	-	17	12	21 000	6,02	2,79	1,97
DORSET SPIRIT	2018-03	In Serv	148 150	279	49	25	176 671	17	15	14 600	5,69	2,85	2,00
EAGLE BALDER	2020-03	In Serv	128 427	277	46	23	-	17	15	17 200	6,02	2,79	1,97
EAGLE BARENTS	2015-03	In Serv	119 690	276	46	24	148 957	15	12	14 000	6,00	3,04	1,95
EAGLE BERGEN	2015-05	In Serv	120 567	270	46	24	148 867	15	12	14 000	5,88	3,04	1,95
EAGLE BLANE	2020-02	In Serv	128 427	277	46	23	160 688	15	15	17 200	6,01	3,00	1,97
EAGLE PARAIBA	2012-06	In Serv	105 153	245	42	23	131 792	15	15	14 280	5,83	2,78	1,87
EAGLE PARAISO	2020-08	Keel L	152 000	279	49	24	-	-	15	-	5,72	#DIV/0!	2,07
EAGLE PARANA	2012-07	In Serv	105 048	245	42	23	131 792	15	15	14 280	5,83	2,78	1,87
EAGLE PAULINIA	2020-06	Launch	152 000	279	49	24	-	-	15	-	5,72	#DIV/0!	2,07
EAGLE PETROLINA	2020-03	Launch	152 000	279	49	24	-	-	15	-	5,72	#DIV/0!	2,07
EAGLE PILAR	2020-10	On Ord	152 000	279	49	24	-	-	15	-	5,72	#DIV/0!	2,07
ELKA LEBLON	2013-01	In Serv	154 846	278	49	24	182 644	17	15	17 252	5,71	2,93	2,06
ELKA PARANA	2013-02	In Serv	155 010	278	49	24	182 646	17	15	17 252	5,71	2,93	2,06
FORTALEZA KNUTSEN	2011-03	In Serv	106 316	247	42	23	127 725	15	16	15 820	5,88	2,75	1,87
GOVERNOR FARKHUTDINOV	2004-09	In Serv	109 295	247	42	21	127 542	15	15	14 130	5,89	2,79	2,00
GRENA KNUTSEN	2003-12	In Serv	148 553	278	46	24	173 603	17	15	16 858	6,04	2,71	1,95
HEATHER KNUTSEN	2005-03	In Serv	148 644	277	46	24	173 615	17	15	16 858	6,02	2,70	1,95
HILDA KNUTSEN	2013-08	In Serv	123 166	276	46	23	151 942	16	15	19 920	5,99	2,97	2,03
INGRID KNUTSEN	2013-12	In Serv	111 634	258	44	22	134 854	15	15	15 200	5,86	2,93	2,05
JASMINE KNUTSEN	2005-05	In Serv	148 644	277	46	24	173 615	17	15	16 858	6,02	2,70	1,95
KAREN KNUTSEN	1999-03	In Serv	153 617	277	50	23	179 642	16	14	17 810	5,53	3,12	2,15
LAMBADA SPIRIT	2013-06	In Serv	154 036	282	49	24	181 364	17	15	14 270	5,76	2,85	2,08
LENA KNUTSEN	2017-06	In Serv	156 559	284	49	24	186 941	17	15	16 860	5,81	2,89	2,04



LISBOA	2017-03	In Ser	155 723	279	48	23	183 367	17	15	15 200	5,80	2,79	2,08
MADRE DE DEUS	2012-08	In Ser	105 283	248	42	23	124 899	15	15	14 280	5,90	2,78	1,87
NANSEN SPIRIT	2010-10	In Ser	109 239	249	44	22	131 792	15	15	18 960	5,67	2,92	1,96
NAVION ANGLIA	1999-12	In Ser	126 749	266	43	23	153 224	16	15	22 066	6,25	2,72	1,89
NAVION BERGEN	2000-01	In Ser	105 200	239	42	21	121 482	15	15	12 004	5,69	2,82	1,97
NAVION GOTHENBURG	2006-04	In Ser	152 244	275	48	24	175 507	17	15	18 623	5,72	2,82	2,03
NAVION OCEANIA	1999-06	In Ser	126 355	265	43	22	152 836	16	15	20 020	6,23	2,71	1,93
NAVION OSLO	2001-01	In Ser	100 257	238	42	21	118 210	15	15	14 314	5,66	2,78	1,97
NAVION STAVANGER	2003-08	In Ser	148 729	277	46	24	173 603	17	15	16 860	6,03	2,70	1,95
NORSE SPIRIT	2017-11	In Ser	148 167	279	49	25	176 688	17	15	14 600	5,69	2,85	2,00
PEARY SPIRIT	2011-05	In Ser	109 325	249	44	22	131 792	15	15	18 960	5,67	2,92	1,96
RAINBOW SPIRIT	2020-02	In Ser	129 734	277	46	23	161 705	15	12	21 000	6,01	2,98	1,97
RAQUEL KNUTSEN	2015-03	In Ser	152 208	277	46	24	180 339	16	15	15 400	6,01	2,88	1,89
RECIFE KNUTSEN	2011-08	In Ser	105 928	247	42	23	127 725	15	15	15 820	5,88	2,75	1,87
RIO 2016	2013-03	In Ser	155 709	279	48	23	183 367	17	15	15 200	5,80	2,79	2,08
RIO GRANDE	2012-10	In Ser	105 224	248	42	23	124 999	15	15	14 280	5,90	2,78	1,87
SAKHALIN ISLAND	2004-05	In Ser	108 078	247	42	21	126 325	15	15	14 130	5,89	2,82	2,00
SALLIE KNUTSEN	1999-04	In Ser	153 617	277	50	23	179 643	16	15	17 810	5,53	3,12	2,15
SAMBA SPIRIT	2013-05	In Ser	154 107	282	49	24	181 364	17	15	14 270	5,76	2,85	2,08
SAMSUNG 2280	2020-10	On Or	152 000	279	49	24	-	-	15	-	5,72	#DIV/0!	2,07
SAMSUNG 2286	2020-09	On Or	110 000	245	44	22	-	-	15	-	5,59	#DIV/0!	1,96
SAMSUNG 2287	2021-01	On Or	110 000	245	44	22	-	-	15	-	5,59	#DIV/0!	1,96
SAO LUIZ	2013-01	In Ser	105 213	248	42	23	124 999	15	15	14 280	5,90	2,78	1,87
SAO SEBASTIAO	2012-11	In Ser	105 190	248	42	23	124 999	15	15	14 280	5,90	2,78	1,87
SCOTT SPIRIT	2011-07	In Ser	109 335	249	44	22	131 792	15	15	18 960	5,68	2,92	1,96
SERTANEJO SPIRIT	2013-11	In Ser	154 233	282	49	24	181 364	17	15	14 270	5,76	2,85	2,08
STENA NATALITA	2001-05	In Ser	108 073	246	43	22	126 999	15	14	15 754	5,73	2,86	1,97
SYNNOVE KNUTSEN	2020-08	Keel L	152 601	279	48	24	-	17	15	18 360	5,81	2,80	2,03
TIDE SPIRIT	2020-05	Launch	125 000	277	46	23	-	17	12	21 000	6,02	2,79	1,97
TORDIS KNUTSEN	2016-11	In Ser	156 559	284	49	24	186 941	17	15	16 860	5,81	2,89	2,04
TORILL KNUTSEN	2013-11	In Ser	123 166	276	46	23	151 942	16	15	19 920	5,99	2,97	2,03
TOVE KNUTSEN	2020-06	Keel L	152 601	279	48	24	-	17	15	18 360	5,81	2,80	2,03
TUVA KNUTSEN	2021-01	Keel L	152 000	279	47	25	-	17	15	20 580	5,93	2,72	1,89
VIGDIS KNUTSEN	2017-02	In Ser	156 559	284	49	24	186 941	17	15	16 860	5,81	2,89	2,04
VINLAND	2000-08	In Ser	125 827	272	46	23	153 697	15	15	18 682	5,91	3,00	2,04
WINDSOR KNUTSEN	2007-05	In Ser	160 241	281	50	23	187 835	17	16	21 770	5,61	3,03	2,17
			134 119	268	46	23	130 104	15	15		5,84	2,85	1,99

B.2 Used for Market Analysis

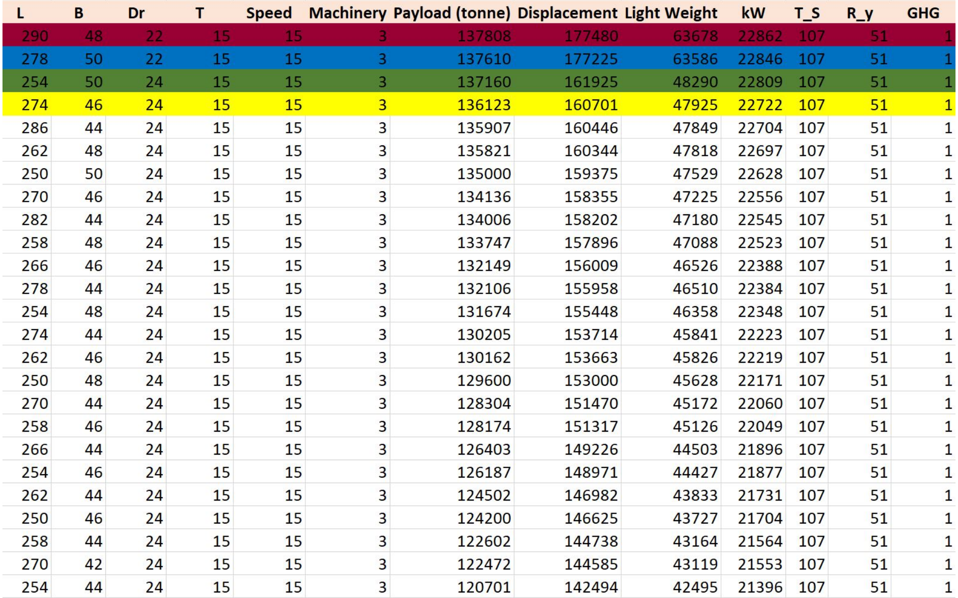
The following vessels are operating or in order for the North Sea as of January 2020. Provided by Galbraith's Oslo office.



Vessel Name	Trading Sta	DWT	Blt Mth8	Shipbuilder/Y	Commercial O
TORILL KNUTSEN	Delivered	118 000	nov.13	Hyundai Heavy	Knutsen OAS
VINLAND	Delivered	125 827	aug.00	Samsung Heav	Uglands Rede
SCOTT SPIRIT	Delivered	109 335	jul.11	Samsung Heav	Teekay Corp
STENA NATALITA	Delivered	108 073	mai.01	Tsuneishi Ship	Stena AB
NAVION OSLO	Delivered	100 257	jan.01	Samsung Heav	Teekay Corp
PEARY SPIRIT	Delivered	109 325	mai.11	Samsung Heav	Teekay Corp
NANSEN SPIRIT	Delivered	109 239	okt.10	Samsung Heav	Teekay Corp
AMUNDSEN SPIRIT	Delivered	109 290	jul.10	Samsung Heav	Teekay Corp
PETRONORDIC	Delivered	92 995	nov.02	Samsung Heav	Teekay Corp
PETROATLANTIC	Delivered	92 968	mar.03	Samsung Heav	Teekay Corp
HILDA KNUTSEN	Delivered	118 000	aug.13	Hyundai Heavy	Knutsen OAS
MASTERA	Delivered	106 208	jan.03	Sumitomo Hea	Neste Oil Corp
INGRID KNUTSEN	Delivered	111 634	des.13	Hyundai Heavy	Knutsen OAS
EAGLE BARENTS	Delivered	119 690	mar.15	Samsung Heav	AET Inc Ltd
EAGLE BERGEN	Delivered	120 567	mai.15	Samsung Heav	AET Inc Ltd
GIJON KNUTSEN	Delivered	35 692	mai.06	ATVT Sudnobu	Knutsen OAS
ANNELEEN KNUTSEN	Delivered	35 140	aug.02	Naval Gijon S.A	Knutsen OAS
BETTY KNUTSEN	Delivered	35 161	jun.99	Naval Gijon S.A	Knutsen OAS
NAVION OCEANIA	Delivered	126 355	jun.99	Astilleros de S	Teekay Corp
STENA SIRITA	Delivered	126 873	aug.99	Tsuneishi Ship	Stena AB
GRENA KNUTSEN	Delivered	148 553	des.03	Samsung Heav	Knutsen OAS
BODIL KNUTSEN	Delivered	149 999	feb.11	Daewoo Shipb	Knutsen OAS
NAVION ANGLIA	Delivered	126 749	des.99	Astilleros de P	Teekay Corp
NAVION HISPANIA	Delivered	126 183	jul.99	Astilleros de P	Teekay Corp
JASMINE KNUTSEN	Delivered	148 644	mai.05	Samsung Heav	Knutsen OAS
HEATHER KNUTSEN	Delivered	148 644	mar.05	Samsung Heav	Knutsen OAS
KAREN KNUTSEN	Delivered	153 617	mar.99	Hyundai Heavy	Knutsen OAS
LOCH RANNOCH	Delivered	130 031	aug.98	Daewoo Heavy	Knutsen OAS
SAMSUNG 2287	On Order	110 000	jan.21	Samsung Heav	Teekay Corp
SAMSUNG 2286	On Order	110 000	sep.20	Samsung Heav	Teekay Corp
CURRENT SPIRIT	On Order	125 000	jun.20	Samsung Heav	Teekay Corp
TIDE SPIRIT	On Order	125 000	mai.20	Samsung Heav	Teekay Corp
RAINBOW SPIRIT	On Order	125 000	jan.20	Samsung Heav	Teekay Corp
AURORA SPIRIT	On Order	125 000	okt.19	Samsung Heav	Teekay Corp
SAMSUNG 2237	On Order	125 000	jan.20	Samsung Heav	AET Inc Ltd
EAGLE BLANE	On Order	125 000	nov.19	Samsung Heav	AET Inc Ltd

Appendix C

C.1 Ammonia Designs for 2050 - Era 4 Results



L	B	Dr	T	Speed	Machinery	Payload (tonne)	Displacement	Light Weight	kW	T_S	R_y	GHG
290	48	22	15	15	3	137808	177480	63678	22862	107	51	1
278	50	22	15	15	3	137610	177225	63586	22846	107	51	1
254	50	24	15	15	3	137160	161925	48290	22809	107	51	1
274	46	24	15	15	3	136123	160701	47925	22722	107	51	1
286	44	24	15	15	3	135907	160446	47849	22704	107	51	1
262	48	24	15	15	3	135821	160344	47818	22697	107	51	1
250	50	24	15	15	3	135000	159375	47529	22628	107	51	1
270	46	24	15	15	3	134136	158355	47225	22556	107	51	1
282	44	24	15	15	3	134006	158202	47180	22545	107	51	1
258	48	24	15	15	3	133747	157896	47088	22523	107	51	1
266	46	24	15	15	3	132149	156009	46526	22388	107	51	1
278	44	24	15	15	3	132106	155958	46510	22384	107	51	1
254	48	24	15	15	3	131674	155448	46358	22348	107	51	1
274	44	24	15	15	3	130205	153714	45841	22223	107	51	1
262	46	24	15	15	3	130162	153663	45826	22219	107	51	1
250	48	24	15	15	3	129600	153000	45628	22171	107	51	1
270	44	24	15	15	3	128304	151470	45172	22060	107	51	1
258	46	24	15	15	3	128174	151317	45126	22049	107	51	1
266	44	24	15	15	3	126403	149226	44503	21896	107	51	1
254	46	24	15	15	3	126187	148971	44427	21877	107	51	1
262	44	24	15	15	3	124502	146982	43833	21731	107	51	1
250	46	24	15	15	3	124200	146625	43727	21704	107	51	1
258	44	24	15	15	3	122602	144738	43164	21564	107	51	1
270	42	24	15	15	3	122472	144585	43119	21553	107	51	1
254	44	24	15	15	3	120701	142494	42495	21396	107	51	1

Appendix D

MATLAB Codes - Epoch - Era

D.1 Main File

```
%% Main. Tradespace evaluation

%% Epoch Space
[EpochSpaceERA] = epoch2();
%% Design Variables
[shipsFeasible] = DesignvariablesTest();

%Capacity,volumedisplacement, Lightweight
[tradespaceCapacity] = Capacity(shipsFeasible);

%Power to engine
[tradespacePowerKW] = powerKW(tradespaceCapacity);

%include sailingtime
[TradespaceFinal] = sailing(tradespacePowerKW);

% include GHG reduction
[TradespaceFinalGHG] = GHG_Effect(TradespaceFinal);

%% Cost Functions
%Opex
[OPEX] = FuelCost(TradespaceFinal,EpochSpaceERA);

%Capex
[CAPEX] = CAPEXwriteoff(TradespaceFinal,EpochSpaceERA);


```

```

%Total Cost
[TotalCost] = TotalCostYearly(OPEX,CAPEX);

%% Utility
[Utility] = Utility_estimation2(TradespaceFinal,
    EpochSpaceERA);

%% Pareto
[paretoUtility, paretoCost,paretoFront,paretoDesignEpoch1,
    ...
   paretoDesignEpoch2,paretoDesignEpoch3,paretoDesignEpoch4
    ,paretoDesignEpoch5, ...
   DesignOverAll, OverAllDesignProperties, OverAllUtility,
    ...
   OverAllUtilitySum ,maxvalue,Index] = paretoSet(Utility,
    TotalCost);
```

D.2 Establishing Design Space

```
function [shipsFeasible] = DesignvariablesTest()

%% Design variable, design criteria

%Main dimentions ranges
L_range = linspace(250,290,11); %(min,max,number of steps)
B_range = linspace(40,50,6);
Dr_range = linspace(20,24,3);
T_range = linspace(15,18,3);

%Speed Range
speed_range = linspace(10,15,3);

%Machinery
machinery = linspace(1,4,4);
%#1 =HFO #2=LNG Dual fuel #3=Ammonia #4 = Hydrogen.


%Equipment yes/no options
Flettner_rotor = [1,0];
battery_pack = [1,0];
Engine_option = [1,0];


```

```
%Generating Design space (also infeasable)

DesVariables = {L_range,B_range,Dr_range,T_range, speed_range,...
     machinery,Flettner_rotor,battery_pack, Engine_option};

%Enumerating all possible designs
[a b c d e f g h i] = ndgrid(DesVariables{:});

Design_Space_inf = [a(:) b(:) c(:) d(:) e(:) f(:) g(:) h(:) i(:)];


%Create arrays representing each design
L_inf = Design_Space_inf(:,1);
B_inf = Design_Space_inf(:,2);
Dr_inf = Design_Space_inf(:,3);
T_inf = Design_Space_inf(:,4);
speed_range_inf = Design_Space_inf(:,5);
machinery_inf = Design_Space_inf(:,6);
Flettner_rotor_inf = Design_Space_inf(:,7);
battery_pack_inf = Design_Space_inf(:,8);
Engine_option_inf = Design_Space_inf(:,9);


%Remove all infeasible designs from the design %space.

ships = [L_inf, B_inf, Dr_inf, T_inf, speed_range_inf, machinery_inf,...
           Flettner_rotor_inf, battery_pack_inf, Engine_option_inf ];

shipsFeasible =[];

for i = 1:size(ships,1) % check for every ship design

    %L/B have to be between 5-6.5
    %B/Dr have to between 1.7 -2.3

    %kan ikke ha flettner rotor and hydrogen and ammonia
%     if  ((ships(i,6) == 3) && (ships(i,7) == 1)) % Flettner and ammonia
%     elseif ((ships(i,6) == 4) && (ships(i,7) == 1)) % Flettner and hydrogen
```

```
    if(ships(i,1) / ships(i,2) > 6.5) && (ships(i,1)/ships(i,2) > 5.0) %L/B
    elseif(ships(i,1) / ships(i,2) < 6.5) && (ships(i,1)/ships(i,2) < 5.0)
    elseif(ships(i,2)/ships(i,3) > 2.3) && ((ships(i,2)/ships(i,3) > 1.7)) %B/Dr
    elseif (ships(i,2)/ships(i,3) < 2.3) && ((ships(i,2)/ships(i,3) < 1.7))

    shipsFeasible = [shipsFeasible];
    else
        shipsFeasible = [shipsFeasible; ships(i,:)];
    end

end


end
```

D.3 Create Epoch Space

```
function [EpochSpaceERA] = epoch2()

%% Establish epoch space

%Epoch variables
ULSFO_prices = linspace(250,600,5); %USD/tonne
LNG_prices = linspace(200,600,5); %USD/tonne
Ammonia_prices = linspace(200,700,5); %USD/tonne
Hydrogen_prices = linspace(380,1900,5); %USD/tonne
Crude_oil_spot = linspace(10,120,5); %USD/bbl

% Yes/no variables
EEDIphase3_2025 = [1,0];
IMO2030 = [1,0];
IMO2050 = [1,0];

%Generating Epoch variables
epochVariables = {ULSFO_prices, LNG_prices ,Ammonia_prices, Hydrogen_prices,...
    Crude_oil_spot, EEDIphase3_2025, IMO2030, IMO2050};

%Enumerating all possible designs
[a b c d e f g h] = ndgrid(epochVariables{:});
```

```

epochSpace_inf = [a(:) b(:) c(:) d(:) e(:) f(:) g(:) h(:)];


%Create arrays representing each epoch
ULSFO_prices_inf = epochSpace_inf(:,1);
LNG_prices_inf = epochSpace_inf(:,2);
Ammonia_inf = epochSpace_inf(:,3);
Hydrogen_inf = epochSpace_inf(:,4);
Crude_inf = epochSpace_inf(:,5);
EEDIphase3_2025_inf = epochSpace_inf(:,6);
IMO2030_inf = epochSpace_inf(:,7);
IMO2050_inf = epochSpace_inf(:,8);


%Remove all infeasible designs from the epoch space

Epoch_space = [ULSFO_prices_inf, LNG_prices_inf, Ammonia_inf, ...
    Hydrogen_inf, Crude_inf , EEDIphase3_2025_inf, IMO2030_inf, IMO2050_inf];


EpochSpaceFeasible =[];

for i = 1:size(Epoch_space,1) % check for every epoch space
   %2030 can only happen when EEDI have happend
    if  ((Epoch_space(i,6) == 0) && (Epoch_space(i,7) == 1) )...

    EpochSpaceFeasible = [EpochSpaceFeasible];
    else
        EpochSpaceFeasible = [EpochSpaceFeasible; Epoch_space(i,:)];
    end
end

%Era 1 - Full environmental development
Epoch1 = find(ismember(EpochSpaceFeasible, [425 400 575 1520 10 0 0 0],'rows'));
Epoch2 = find(ismember(EpochSpaceFeasible, [337.5 300 450 1140 10 1 0 0],'rows'));
Epoch3 = find(ismember(EpochSpaceFeasible, [425 200 325 1140 10 1 1 0],'rows'));
```

```
Epoch4 = find(ismember(EpochSpaceFeasible, [512.5 400 200 760 10 1 1 0],'rows'));
Epoch5 = find(ismember(EpochSpaceFeasible, [600 600 200 380 10 1 1 0],'rows'));

% Era 2 - Late Technical Maturity
% Epoch1 = find(ismember(EpochSpaceFeasible, [425 500 700 1900 10 0 0 0],'rows'));
% Epoch2 = find(ismember(EpochSpaceFeasible, [337.5 400 700 1520 37.5 1 0 0],'rows'));
% Epoch3 = find(ismember(EpochSpaceFeasible, [425 400 575 1520 65 1 1 0],'rows'));
% Epoch4 = find(ismember(EpochSpaceFeasible, [337.5 300 575 1520 92.5 1 1 0],'rows'));
% Epoch5 = find(ismember(EpochSpaceFeasible, [425 300 450 1140 65 1 1 0],'rows'));

% Era 3 - Speed Reduction & General Expected Development
% Epoch1 = find(ismember(EpochSpaceFeasible, [337.5 400 700 1900 10 0 0 0],'rows'));
% Epoch2 = find(ismember(EpochSpaceFeasible, [425 500 575 1520 37.5 1 0 0],'rows'));
% Epoch3 = find(ismember(EpochSpaceFeasible, [425 300 450 1140 65 1 1 0],'rows'));
% Epoch4 = find(ismember(EpochSpaceFeasible, [337.5 200 450 1140 37.5 1 1 0],'rows'));
% Epoch5 = find(ismember(EpochSpaceFeasible, [600 300 325 760 37.5 1 1 0],'rows'));

% Era 4 - 2050 Perspective
% Epoch1 = find(ismember(EpochSpaceFeasible, [425 500 700 1900 10 1 1 0],'rows'));
% Epoch2 = find(ismember(EpochSpaceFeasible, [337.5 400 700 1520 37.5 1 1 0],'rows'));
% Epoch3 = find(ismember(EpochSpaceFeasible, [425 400 575 1520 65 1 1 1],'rows'));
% Epoch4 = find(ismember(EpochSpaceFeasible, [337.5 300 575 1520 92.5 1 1 1],'rows'));
% Epoch5 = find(ismember(EpochSpaceFeasible, [425 300 450 1140 65 1 1 1],'rows'));

%Chooseing 5 epochs
EpochSpaceERA_Initial = EpochSpaceFeasible([Epoch1,Epoch2,Epoch3,Epoch4,Epoch5] , :); %

```

```
%Include Production, which is the same for all 5 epochs
Production_Johan_Castberg = [10*10^6, 5*10^6, 2*10^6, 1*10^6, 1*10^6]'; %Column: '
%Production_Johan_Castberg = [7*10^6, 7*10^6, 7*10^6, 7*10^6, 7*10^6]'; %Column: ' %2050 alternative


%Create a Era including 5 epochs from
EpochSpaceERA = [EpochSpaceERA_Initial Production_Johan_Castberg];

end
```

D.4 Tradespace Exploration - Find Capacities

```
function [tradespaceCapacity] = Capacity(shipsFeasible)

[shipsFeasible] = DesignvariablesTest();

%Initialize
q = zeros(length(shipsFeasible),1);
Lightweight = zeros(length(shipsFeasible),1);
VolumeDisplacement = zeros(length(shipsFeasible),1);

%Constants
rho = 1.025; %Sea water density %tonne/m^3
C_b = 0.85; %Block Coeffsient

for i =1:length(shipsFeasible)

    %0.45 is how much of a "Cubic" that is payload shuttle tanker.
    q(i) = 0.45 * shipsFeasible(i,1) * shipsFeasible(i,2) * shipsFeasible(i,3); %Capacity payload for each vessel in Sm^3


    VolumeDisplacement(i) = C_b * shipsFeasible(i,1) * shipsFeasible(i,2)*shipsFeasible(i,4); %Volum displacement in Sm^3

    Lightweight(i) =  (VolumeDisplacement(i)*rho) - (q(i) * 0.858); %Lightweight in tonne. 1 Sm^3 = 0.858
```

```

end

%Include in Tradespace
tradespaceCapacity = [shipsFeasible q VolumeDisplacement
    Lightweight];


end
```

D.5 Tradespace Exploration - Find Power (kW)

```
function [tradespacePowerKW] = powerKW(tradespaceCapacity)

[shipsFeasible] = DesignvariablesTest();
[tradespaceCapacity] = Capacity(shipsFeasible);

%Initialize
kW = zeros(length(tradespaceCapacity),1);

for i =1:length(tradespaceCapacity)

     %Power. %0.0197 is an estimated costant representing
    shuttle tankers.
    % q in tonne
    % 1Sm^3 = 0.858 tonne
     kW(i) = (0.0197)*( ( (tradespaceCapacity(i,10)) *0.858)
    ^(0.5))*((tradespaceCapacity(i,5))^(3));

end

%Add Power to Tradespace
tradespacePowerKW = [tradespaceCapacity kW];


end
```

D.6 Tradespace Exploration - Transport Properties

```
function [TradespaceFinal] = sailing(tradespacePowerKW)


```

```
[shipsFeasible] = DesignvariablesTest();
[tradespaceCapacity] = Capacity(shipsFeasible);
[tradespacePowerKW] = powerKW(tradespaceCapacity);

nm = 800; %Distance
T_p = 24; %Time in port
T_o = 40; %waiting time + operation time
OH = 4; %Off hire

%Initialize
T_s = zeros(length(tradespacePowerKW),1);
Roundtrip_y = zeros(length(tradespacePowerKW),1);

for i=1:length(tradespacePowerKW)

    T_s(i) = 2*(nm/tradespacePowerKW(i,5)); %Sailing time
   at sea
    Roundtrip_y (i) = ((365-OH)*24)/(T_s(i)+T_p + T_o); %
   Annual Roundtrips

end

%Add Sailing time and annual roundtrips to tradespace
TradespaceFinal = [tradespacePowerKW T_s Roundtrip_y];

end
```

D.7 Tradespace Exploration - GHG Estimation

```
function [TradespaceFinalGHG] = GHG_Effect(TradespaceFinal)


[shipsFeasible] = DesignvariablesTest();
[tradespaceCapacity] = Capacity(shipsFeasible);
[tradespacePowerKW] = powerKW(tradespaceCapacity);
[TradespaceFinal] = sailing(tradespacePowerKW);

%Initialize
 GHG_Effect = zeros(length(TradespaceFinal),1); %

for j=1:length(TradespaceFinal)

    if  TradespaceFinal(j,6) == 1
            GHG_reduction(j) = 0; %ULFSO do not reduce GHG
```

```
        elseif TradespaceFinal(j,6) == 2
            GHG_reduction(j) = 0.2; %LNG reduces GHG by 20
   %
        elseif TradespaceFinal(j,6) == 3
            GHG_reduction(j) = 1; %Ammonia reduce GHG by
   100 %
        elseif TradespaceFinal(j,6) == 4
           GHG_reduction(j) = 1; %Hydrogen reduce GHG by
   100 %
    end

    %Estimate total GHG reduction effect for each design.
   First 0.1 is the
    %VOC system.
    GHG_Effect(j) = 0.1 + GHG_reduction(j) + (0.1 *
   TradespaceFinal(j,7)) ...
         + (0.1 * TradespaceFinal(j,8))+ (0.1 *
   TradespaceFinal(j,9));

end

%Add GHG_Effect to Tradespace.
TradespaceFinalGHG = [TradespaceFinal GHG_Effect];

end
```

D.8 CAPEX & Write Off

```
function [CAPEX] = CAPEXwriteoff(TradespaceFinal,
   EpochSpaceERA)

[EpochSpaceERA] = epoch2();

[shipsFeasible] = DesignvariablesTest();
[tradespaceCapacity] = Capacity(shipsFeasible);
[tradespacePowerKW] = powerKW(tradespaceCapacity);

[TradespaceFinal] = sailing(tradespacePowerKW);
[TradespaceFinalGHG] = GHG_Effect(TradespaceFinal);

%initializing
CAPEXtotal = zeros(length(TradespaceFinal),1);
CAPEXyearly = zeros(length(TradespaceFinal),1);
Hull = zeros(length(TradespaceFinal),1);
```

```
SCR = zeros(length(TradespaceFinal),1);
Engine_CAPEX = zeros(length(TradespaceFinal),1);
costFlettner= zeros(length(TradespaceFinal),1);
costBattery= zeros(length(TradespaceFinal),1);
costEngineOption = zeros(length(TradespaceFinal),1);

for i = 1: length(TradespaceFinal)
   costSteel = 600; %USD/tonne

   Hull(i) = (TradespaceFinal(i,12)*costSteel); % Lightweight * Steel Price

        if  TradespaceFinal(i,6) == 1
            Engine_CAPEX(i) = 12*10^6; %if ULFSO maachinery then ULFSO machine price
            SCR(i) = 1*10^6;
        elseif TradespaceFinal(i,6) == 2
            Engine_CAPEX(i) = 25*10^6 ; %if LNG maachinery then LNG machine price
            SCR(i) = 1*10^6;
        elseif TradespaceFinal(i,6) == 3
            Engine_CAPEX(i) = 22*10^6; %if NH3 maachinery then Ammonia machine price
            SCR(i) = 1*10^6; %NH
        elseif TradespaceFinal(i,6) == 4
            Engine_CAPEX(i) = 27*10^6  ; %if H2 maachinery then Hydrogen fuel cell price and engine price
            SCR(i) = 0; %Hydrogen does not emitt NOx
        end

        %Flettner rotor
        if TradespaceFinal(i,7) == 1
            costFlettner(i) = 1*10^6;
        else
            costFlettner(i) = 0;
        end

        %Battery (peak shaving)
        if TradespaceFinal(i,8) == 1
            costBattery(i) = 2*( 500 * (TradespaceFinal(i,13) * 0.1)) ;  % 500 USD/kWh 10% of Power %*2 since fuel cells have to be changed. %1 hour max
        else
            costBattery(i) = 0;
        end
```

```

         if TradespaceFinal(i,9) == 1
            costEngineOption(i) = 5*10^6; % General price for new engine for a shuttle tanker
        else
            costEngineOption(i) = 0;
         end

         %VOC system
        VOC(i) = 15 * 10^6;

        %shipyard share
        Workinghours(i) = 25 * 10^6;
        Shipyardmargin (i) = 10 * 10^6;


    CAPEXtotal(i) = Hull(i) + Engine_CAPEX(i) + SCR(i) + costFlettner(i)+ ...
        costBattery(i) + costEngineOption(i) + Workinghours (i)...
        + VOC(i) + Shipyardmargin (i);

    WACC = 0.124;
CAPEXyearly(i) = CAPEXtotal(i)* WACC;
end


CAPEX = [CAPEXtotal CAPEXyearly];




end
```

D.9 OPEX - Fuel Cost

```
function [OPEX] = FuelCost(TradespaceFinal,EpochSpaceERA)

[EpochSpaceERA] = epoch2();

[shipsFeasible] = DesignvariablesTest();
[tradespaceCapacity] = Capacity(shipsFeasible);
[tradespacePowerKW] = powerKW(tradespaceCapacity);

```

```
[TradespaceFinal] = sailing(tradespacePowerKW);
[TradespaceFinalGHG] = GHG_Effect(TradespaceFinal);

%Fixed operational cost in the North Sea
FixedCost = 15000*365 ; % USD/year

%Initializing
YearlyFuelCost = zeros(length(TradespaceFinal),size(EpochSpaceERA,1));
Price_fuel = zeros(length(TradespaceFinal),size(EpochSpaceERA,1));
sfc = zeros(length(TradespaceFinal),size(EpochSpaceERA,1));
OPEX = zeros(length(TradespaceFinal),size(EpochSpaceERA,1));

for i = 1:size(EpochSpaceERA,1)
    for j = 1: length(TradespaceFinal)

        if  TradespaceFinal(j,6) == 1
            Price_fuel(j) = EpochSpaceERA(i,1); %If ULFSO maachinery then ulfso price
            sfc(j) = 0.000166;
        elseif TradespaceFinal(j,6) == 2
            Price_fuel(j) = EpochSpaceERA(i,2); %If LNG machinery then lng price
            sfc(j) = 0.000142;
        elseif TradespaceFinal(j,6) == 3
            Price_fuel(j) = EpochSpaceERA(i,3); %If NH3 maachinery then ammonia price
            sfc(j) = 0.000142;
        elseif TradespaceFinal(j,6) == 4
            Price_fuel(j) = EpochSpaceERA(i,4); %If H2 maachinery then hydrogen price
            sfc(j) = 0.000142;
        end

    YearlyFuelCost(j,i) = Price_fuel(j) * sfc(j) * TradespaceFinal(j,13)...
        * TradespaceFinal(j,14) * TradespaceFinal(j,15); % Price fuel * sfc * P * T_s *R_y

    OPEX(j,i) =  YearlyFuelCost(j,i) + FixedCost ;
    end

end
```

```


end
```

D.10 Annual Cost Estimation

```
function [TotalCost] = TotalCostYearly(OPEX,CAPEX)

[EpochSpaceERA] = epoch2();

[shipsFeasible] = DesignvariablesTest();
[tradespaceCapacity] = Capacity(shipsFeasible);
[tradespacePowerKW] = powerKW(tradespaceCapacity);

[TradespaceFinal] = sailing(tradespacePowerKW);
[TradespaceFinalGHG] = GHG_Effect(TradespaceFinal);


[OPEX] = FuelCost(TradespaceFinal,EpochSpaceERA);
[CAPEX] = CAPEXwriteoff(TradespaceFinal,EpochSpaceERA);

%Initialize
TotalCost = zeros(length(TradespaceFinal),size(
    EpochSpaceERA,1));

for i = 1: size(EpochSpaceERA,1)
    for j = 1: length(TradespaceFinal)

    Margin = 1.1; %Shipowners required estimated margin, 10
     %
     %TotalCost is the yearly required payment, total cost
    must not exceed
     %fright rate for creating positive cash flow.
     TotalCost(j,i) = (OPEX(j,i) + CAPEX(j,2))* Margin;
     end

end

end
```

D.11 Utility Estimation

```
function [Utility] = Utility_estimation(TradespaceFinalGHG,
    EpochSpaceERA)

[EpochSpaceERA] = epoch2();

[shipsFeasible] = DesignvariablesTest();
[tradespaceCapacity] = Capacity(shipsFeasible);
[tradespacePowerKW] = powerKW(tradespaceCapacity);

[TradespaceFinal] = sailing(tradespacePowerKW);

[TradespaceFinalGHG] = GHG_Effect(TradespaceFinal);


[OPEX] = FuelCost(TradespaceFinal,EpochSpaceERA);
[CAPEX] = CAPEXwriteoff(TradespaceFinal,EpochSpaceERA);

%[TotalCost] = TotalCost(OPEX,CAPEX);

%Initialize
Utility = zeros(length(TradespaceFinal),size(EpochSpaceERA
    ,1));

%Collects values before normalizing
Speed = TradespaceFinal(:,5);
Machinery  = TradespaceFinal(:,6);
Flettner_Rotor  = TradespaceFinal(:,7);
Battery_Pack  = TradespaceFinal(:,8);
Engine_Option  = TradespaceFinal(:,9);
Payload  = TradespaceFinal(:,10);
%Roundtrip = TradespaceFinal(:,15);

%Utility is normalized. 1 means 100% utility, 0 %means 0%
    utility.

%Method for Yes/No decision
% U_Flettner_Rotor  = Flettner_Rotor ;
% U_Battery_Pack  = Battery_Pack ;
% U_Engine_Option  = Engine_Option ;

%More is better. Normalized, 0 is lowest value, 1 is
    highest value
%More payload is better
U_PayloadMore = (Payload -min(Payload ))/(max(Payload )-min
    (Payload ));
```

```

%Higher speed is better
U_Speed  = ((Speed -min(Speed ))/(max(Speed )-min(Speed )))
    ; % more is better

%Less Payload is preferred
U_PayloadLess  = 1- (Payload -min(Payload ))/(max(Payload )
    -min(Payload )); %less is better

%Lower speed is better
%U_Speed  = 1 - ((Speed -min(Speed ))/(max(Speed )-min(
    Speed )));


%Utility for fixed functions %(1/x) changes with x as
    number of fixed
%utilities
UtilityFixed  = (1/1)*( U_Speed ); %U_Payload +
%U_Flettner_Rotor  + U_Battery_Pack + U_Engine_Option  +

%Initialize
U_GHG = zeros(length(TradespaceFinalGHG),size(EpochSpaceERA
    ,1));
U_Availability = zeros(length(TradespaceFinalGHG),size(
    EpochSpaceERA,1));
UtilityChanged = zeros(length(TradespaceFinalGHG),size(
    EpochSpaceERA,1));
Utility = zeros(length(TradespaceFinalGHG),size(
    EpochSpaceERA,1));

for i = 1: size(EpochSpaceERA,1)
    for j = 1: length(TradespaceFinalGHG)

        %If GHG reduction measures are higher than 1 it is
    0 utility
        if TradespaceFinalGHG(j,16) > 1.01
            U_GHG(j,i)  = 0;
            %Ship has to require EEDI 2025
        elseif TradespaceFinalGHG(j,16) < 0.29 &&
    EpochSpaceERA(i,6) == 1
            U_GHG(j,i)  = 0;
            %Ship has to require IMO 2030
        elseif TradespaceFinalGHG(j,16) < 0.39 &&
    EpochSpaceERA(i,7) == 1
            U_GHG(j,i)  = 0;
```

```
            %Ship has to require IMO 2050
        elseif TradespaceFinalGHG(j,16) < 0.69 &&
   EpochSpaceERA(i,8) == 1
            U_GHG(j,i) = 0;
        else
            U_GHG(j,i) = 1;
        end

        %Payload utility depends on the vessels possibility
    to travel in
        %full laden mode
        if  EpochSpaceERA(i,9) > (TradespaceFinalGHG(j,10)
   * TradespaceFinalGHG(j,15))
            U_Availability (j,i) = U_PayloadMore(j);
        else
            U_Availability (j,i) = U_PayloadLess(j); %less
   is better
        end

%Calculating utility for dependent variables
UtilityChanged (j,i) = (1/2)*(U_GHG(j,i) + U_Availability (
   j,i));

%Total utility
Utility (j,i) = (1/2) *(UtilityChanged(j,i)+ UtilityFixed(j
   ));

    end
end


end
```

D.12 Pareto Front

```
function [paretoUtility, paretoCost,paretoFront,
   paretoDesignEpoch1,...
   paretoDesignEpoch2,paretoDesignEpoch3,paretoDesignEpoch4
   ,paretoDesignEpoch5, ...
   DesignOverAll, OverAllDesignProperties, OverAllUtility,
   ...
   OverAllUtilitySum ,maxvalue,Index] = paretoSet(Utility,
   TotalCost)

```

```
[EpochSpaceERA] = epoch2();
[shipsFeasible] = DesignvariablesTest();
[tradespaceCapacity] = Capacity(shipsFeasible);
[tradespacePowerKW] = powerKW(tradespaceCapacity);
[TradespaceFinal] = sailing(tradespacePowerKW);
[TradespaceFinalGHG] = GHG_Effect(TradespaceFinal);


[OPEX] = FuelCost(TradespaceFinal,EpochSpaceERA);
[CAPEX] = CAPEXwriteoff(TradespaceFinal,EpochSpaceERA);

[TotalCost] = TotalCostYearly(OPEX,CAPEX);
[Utility] = Utility_estimation2(TradespaceFinalGHG,
    EpochSpaceERA);

%%Code is based on paper given by S.Pettersen in TMR4135
    Design Methods 2
%Spring 2019. Some modifications have been made.

% 1. Check utility for all designs

% 2. Select all design that maximize utility

% 3. Add the one design of these that minimizes costs, to
    an array
%       for Pareto optimal designs.
% 4. Set the utility of all designs that are more expensive
    , or equally
%       expensive (including the one added to the array for
     Pareto front),
%       to zero.
% 5. Repeat the procedure, until all designs have been
    checked,
%       ie. stop when the lowest cost is reached.

[nDesigns,nEpochs] = size(Utility);
utilityOriginal = Utility;



for e = 1:nEpochs
    %Condition for while loop:
    condition = 0;
    %The first element in the Pareto array:
    k = 1;
```

```
    while condition == 0
        %Finding the maximum utility ship.
        [maxUtility,designID] = max(Utility(:,e));
        %Adding utility point to Pareto array.
        paretoFront(k,e) = designID;
        paretoUtility(k,e) = utilityOriginal(designID,e);
        paretoCost(k,e)    = TotalCost(designID,e);

        %Setting current utility to -1 to avoid rechecking.
        Utility(designID,e) = -1;
        %Setting utility of all elements with a larger cost to -1.
        for j = 1:nDesigns
            if TotalCost(j,e) >= TotalCost(designID,e)*1.05 %Multiply with desired percentage included
                Utility(j,e) = -1;
            end
        end

        %Exiting while loop when the lowest cost is reached or the max
        %utility is 0.
        if (TotalCost(designID,e) == min(TotalCost(:,e))) || (max(Utility(:,e)) == 0)
            condition = 1;
        end
        %For finding next element in Pareto array.
        k = k+1;
    end
end

%Initialize
paretoFront1 = nonzeros(paretoFront(:,1));
paretoFront2 = nonzeros(paretoFront(:,2));
paretoFront3 = nonzeros(paretoFront(:,3));
paretoFront4 = nonzeros(paretoFront(:,4));
paretoFront5 = nonzeros(paretoFront(:,5));


%Find the values corresponding to pareto designs
paretoDesignEpoch1 = TradespaceFinalGHG(paretoFront1(:,1),:);
paretoDesignEpoch2 = TradespaceFinalGHG(paretoFront2(:,1),:);
```

```
paretoDesignEpoch3 = TradespaceFinalGHG(paretoFront3(:,1),:);
paretoDesignEpoch4 = TradespaceFinalGHG(paretoFront4(:,1),:);
paretoDesignEpoch5 = TradespaceFinalGHG(paretoFront5(:,1),:);

%Check if any design appears in each fuzzy epoch pareto front
A = intersect(paretoFront(:,1),paretoFront(:,2));
B = intersect(A,paretoFront(:,3));
C = intersect(B,paretoFront(:,4));
DesignOverAll = intersect(C,paretoFront(:,5));

G = intersect(paretoFront(:,3),paretoFront(:,4));
%DesignOverAll = intersect(G,paretoFront(:,5));

%initialize
%OverAllFront = nonzeros(A(:,1));
OverAllFront = nonzeros(DesignOverAll(:,1));

%FInd corresponidng values
OverAllDesignProperties = TradespaceFinalGHG(OverAllFront(:,1),:);
OverAllUtility = utilityOriginal(OverAllFront(:,1),:);



%initialize
OverAllUtilitySum = zeros(length(DesignOverAll),1);

%fint the designs that have the highest utility over epochs.
for i = 1:length(OverAllUtilitySum)
OverAllUtilitySum(i) = (1/5) * sum(OverAllUtility((i),:)) ;
end

[maxvalue,Index] = maxk(OverAllUtilitySum,5);

end
```

Appendix E

Infrastructure Calculations

E.1 Ship Size and Speed

```
classdef SSS

    methods (Static) ;


        % KW - antall kW som funksjon av cargo og speed

        function KW = KW(q,v)
            KW = 0.0197*(q.^(0.5)).*(v.^(3));
        end


     %mass
         function mass = mass(power2,hours_at_sea)

             eff=0.5;
             density= 120 ; % 18.6 ammonia. %120 hydrogen

            mass = ((power2 * 3600 * hours_at_sea)/(eff*density*1000)) *0.001 ;
            %0.015 forholdstall mellom kg og kubikkmeter for hydrogen
            %0.00162 for ammonia
            %To get tonnes * 0.001
         end
    end
end
```

```

v = 8:0.5:18; %Speed in knots
q = 40000:10000:160000; %Capasity in 1000 tonnes

KW = zeros(length(v),length(q));

for i = 1:length(q)
for j = 1:length(v)
    KW(j,i)=SSS.KW(q(i),v(j));
    end
end

[X,Y] = meshgrid(q,v);

kw_levels = 0:1000:30000;

figure(1)
[Q,V] = contour(X,Y,KW,kw_levels) ;% kw_levels);
title('Isoquants Vessel Power [kW]');
xlabel('q - Vessel Capacity [tonnes]');
ylabel('V - Vessel Speed [knots]');
set(V,'ShowText','on')


power2 = 7000:500:24000;
hours_at_sea = 0:10:500;

mass = zeros(size(hours_at_sea,2),size(power2,2));

for i = 1:size(power2,2)
for j = 1:size(hours_at_sea,2)
    mass(j,i)= SSS.mass(power2(i),hours_at_sea(j));
    end
end

figure(2)
[X2,Y2] = meshgrid(power2,hours_at_sea);


%mass_levels = 0:400:12600; %hydrogen cubic
mass_levels = 0:50:75000; %mass hydrogen
%mass_levels = 0:250:40000; %mass ammonia
%mass_levels = 0:400:12600; %cubic Ammonia

```

```
[Q,V] = contour(X2,Y2,mass,mass_levels) ;% kw_levels);
title('Isoquants Required Mass of Hydrogen [tonnes]'); %
xlabel('Vessel Power [kW]');
ylabel('Time at Sea [hours]');
set(V,'ShowText','on')
```

E.2 Shortest Path

```


G = graph([1 1 1 1 1 2 2 2 3 3 3 3 4 4 4 5 5 5 5 5 6 6 6 6 7 7 7 7 7 7 8 8 8 8 9 9 9 9 9 9 ...
    10 10 10 10 10 11 11 11 11 12 12 12 12 13 13 13 13 13 14 14 14 14 14 15 15 15 15 15 ...
    16 16 16 16 17 17 17 18 18 18 19 19 20 20 20 21 21 22], ...
[2 3 4 5 6 3 4 5 4 5 6 7 5 6 7 6 7 8 9 10 7 8 9 10 8 9 10 11 12 13 9 10 11 12 13 14 10 11 12 13 ...
    11 12 13 14 15 12 13 14 15 13 14 15 16 14 15 16 17 18 15 16 17 18 19 16 17 18 19 20 ...
    17 18 19 20 18 19 20 19 20 21 20 21 21 22 23 22 23 23], ...
[17 19 20 19 17 27 24 20 28 23 20 18 15 12 11 12 8 8 4 4 26 28 22 23 36 34 34 33 31 27 25 28 26 25 ...
     29 28 27 24 24 22 42 40 35 34 32 36 32 31 28 33 32 30 27 20 18 15 12 13 23 21 18 18 17 23 20 20 19 16 ...
     20 20 19 17 28 27 25 21 16 12 24 19 12 8 8 13 13 15]);

% [274 234 200 215 269 64 140 240 62 182 262 296 122 203 225 90 ...
%     207 196 299 293 180 124 264 254 51 108 101 137 180 269 140 75 121 161 ...
%     108 124 143 215 230 273 35  86 194 221 280 43 156 182 242 120 142 205 280 97 ...
%     157 230 299 280 80 133 206 200 232 66 ...
%     140 150 173 260 91 103 113  168 102 118 180 30  140 250 106 226 144 248 254 125 118 118]);


p = plot(G,'EdgeLabel',G.Edges.Weight);

%[P1,d,edgepath1] = shortestpath(G,1,22)
[P2,d,edgepath2] = shortestpath(G,1,18)

```

```
%highlight(p,P1,'EdgeColor','r')
highlight(p,P2,'EdgeColor','g')

%highlight(p,'Edges',edgepath1)
highlight(p,'Edges',edgepath2)




%Distanse

% [274 234 200 215 269 64 140 240 62 182 262 296 122 203 225 90 ...
%     207 196 299 293 180 124 264 254 51 108 101 137 180 269 140 75 121 161 ...
%     108 124 143 215 230 273 35  86 194 221 280 43 156 182 242 120 142 205 280 97 ...
%     157 230 299 280 80 133 206 200 232 66 ...
%     140 150 173 260 91 103 113  168 102 118 180 30  140 250 106 226 144 248 254 125 118 118]);


% Weighted value
% [17 19 20 19 17 27 24 20 28 23 20 18 15 12 11 12 8 8 4 4 26 28 22 23 36 34 34 33 31 27 25 28 26 25 ...
%      29 28 27 24 24 22 42 40 35 34 32 36 32 31 28 33 32 30 27 20 18 15 12 13 23 21 18 18 17 23 20 20 19 16 ...
%      20 20 19 17 28 27 25 21 16 12 24 19 12 8 8 13 13 15];
```

Matias Bøe Olsen

Designing a Value Robust Shuttle Tanker to Handle Environmental and Technical Uncertainty

NTNU
Norwegian University of
Science and Technology