Ola Gundersen Skåre

Future-Proofing Cruise Ships by Designing for Flexibility

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

Master's thesis

NTNU
Norwegian University of Science and Technology
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Kunnskap for en bedre verden

Master Thesis in Marine Systems Design

Stud. techn. Ola Gundersen Skåre

"Future-Proofing Cruise Ships by Designing for Flexibility"

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Background

The maritime industry is being pushed to be more environmentally friendly, resulting in new and stricter environmental regulations both on global and local levels. Simultaneously, fuels, technology and market demand are developing rapidly. Shipowners investing in new ships today are therefore disposed to a lot of uncertainty. When designing a new ship, the technology choices and level of system flexibility will thus be crucial to lower the risk of becoming a stranded asset.

Overall aim and focus

The overall aim is to investigate the value of designing cruise ships with flexibility to comply with future environmental requirements, by preparing for technological innovations and alternative fuels.

Scope and main activities

The candidate should presumably cover the following main points:

1. *Literature study on how flexibility can be used to handle future uncertainty in engineering design in general, and more specifically in ship designs.*
2. *Present methods for modelling the future and to estimate the value of flexibility.*
3. *Develop a generic framework that can be used to quantify the value of flexible ship design solutions.*
4. *Provide an overview of the maritime environmental regulatory framework, technologies for power generation and alternative fuels for shipping.*
5. *Apply the generic flexibility analysis framework developed in 3 on a realistic case study of the design of a large cruise ship.*
6. *Discuss and conclude.*

Modus operandi

At NTNU, Professor Stein Ove Erikstad will be the responsible advisor. At DNV GL, Dr. Øyvind Endresen will be co-supervisor.

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

Stein Ove Erikstad
Professor/Responsible Advisor

Abstract

In this thesis, we investigate the value of future-proofing cruise ships by designing for flexibility. Exploring the world by cruise ships has been popular for decades, and in recent years, the cruise industry has been reported as one of the fastest-growing segments in the tourism sector. With the increasing focus on the climate in general, and more awareness about cruise ships emissions is the industry now more than any other shipping segment being pushed to become ”greener” and to reduce emissions. The IMO recently adopted their ambition to drastically reduce GHG emissions from international shipping, but what the specific measures will include are still uncertain. Local emission regimes are also being considered, as in the Norwegian world heritage fjords, where only zero-emission cruise ships are expected to be allowed entrance after 2026. Low- and zero-emission technology for ships are currently tested in pilot projects, and several alternative fuels with the potential of being more environmentally friendly are proposed. However, what will be the preferable technology and fuel of tomorrow for ships is still uncertain.

To value flexibility in the cruise ship designs, a generic flexibility valuation framework which builds on epoch-era analysis and real options analysis with Monte Carlo simulation is proposed in this thesis. This framework applies a structured stepwise approach for valuing flexibility in ship design and includes the following six steps: background description, modelling the future, identify flexibility, design valuation, value flexibility, and sensitivity analysis. The underlying aim of this framework is to facilitate dialogue between maritime experts and technical or non-technical decision makers.

Two different flexible cruise ship designs are analysed in the flexibility valuation framework, an LNG dual fuel cruise ship and an ammonia ready cruise ship. Real options analysis with Monte Carlo simulations is used for estimating the value of flexibility, as this is the preferable method for valuing more complex real options ”in” systems. The epoch-era analysis is used to generate four future scenarios within technology, price and availability of the fuel, and environmental regulations. To value the performance of the cruise ship designs the Net Present Value (NPV) method is used.

Results from the case study show that both of the flexible designs perform better than the baseline design (inflexible design) in each era, except for one. This applies to the ammonia ready design in era 2 (”future scenario 2”), where the baseline design outperforms it. However, when evaluating the flexible cruise ship designs over all eras, both of the flexible designs perform better than the baseline design.

The results from the case study, illustrate that designing future-proof cruise ships by flexibility generally has a high value. However, the results and the sensitivity analysis also shows that flexibility comes with a cost, and if this cost becomes too high, the value of flexibility may be low or even disappear. Additionally, results from the case study show that the value of flexibility is highly dependent on how the future evolves. In the case study, the ammonia ready design performs best in the era we believe is the most likely one, while the LNG dual fuel design performs best when evaluating over all eras. It is,

therefore, difficult to say which of the flexible designs that will be the best investment decision. Thus, which flexible design to invest in is more related to which future the decision maker believes in most.

Sammendrag

I denne masteroppgaven undersøker vi verdien av å fremtids forsikre cruise skip ved å designe for fleksibilitet. Utforske verden med cruise skip har vært populært i flere tiår, og i de senere årene har cruise industrien blitt rapportert som en av de kjappest voksende segmentene innenfor turisme sektoren. Med et økende fokus på klimaet generelt og med mere bevissthet om cruise skip sine utslipp er cruise industrien nå mere enn noe annet shipping segment presset til å bli grønnere og til å redusere utslipp. IMO adopterte nylig en ambisjon om å drastisk redusere klimagassutslipp fra internasjonal shipping, men hva de spesifikke tiltakene vil inkludere er fortsatt usikkert. Lokale utslipps regimer er også vurdert, som for eksempel i de norske verdensarvfjordene hvor bare nullutslipps cruise skip er forventet tillatelse til å seile fra 2026. Lav- og nullutslipps teknologi for skip blir for øyeblikket testet i pilot prosjekter, og flere alternative drivstoff med potensialet til å være mere miljøvennlige er foreslått. Men hva som blir den foretrukne teknologien og drivstoffet for morgendagens skip er fortsatt usikkert.

Til å sette en verdi på fleksibilitet i cruise skip design er et generisk rammeverk for verdisetting av fleksibilitet som bygger på epoch-era analyse og real opsjons analyse med Monte Carlo simulering foreslått. Dette rammeverket bruker en strukturert stegvis tilnærming for å sette verdi på fleksibilitet i skips design og inkluderer følgende seks steg: bakgrunn beskrivelse, modellering av fremtiden, identifisere fleksibilitet, sette verdi på design, sette verdi på fleksibilitet og sensitivitets analyse. Det underliggende målet til dette rammeverket er å legge til rette for dialog mellom maritime eksperter og tekniske eller ikke-tekniske beslutningstakere.

To ulike fleksible cruise skip design er analysert i det generiske rammeverket for verdsetting av fleksibilitet, et LNG dual fuel cruise skip og et ammoniakk klart cruise skip. Real opsjons analyse med Monte Carlo simulering er brukt for å estimere verdien av fleksibilitet, ettersom dette er den foretrekkende metoden for å sette verdi på mere komplekse real opsjoner. Epoch-era analyse er brukt for å generere fire fremtidige scenarioer innen teknologi, pris og tilgjengelighet av drivstoff og miljøreguleringer. Til å verdsette ytelsen til cruise skip designene er netto nåverdi metoden brukt.

Resultatene fra case studien viser at begge de fleksible designene yter bedre enn baseline designet (det ikke-fleksible designet) i hver era, med unntak av ett. Dette gjelder det ammoniakk klare cruise skipet i era 2 (fremtids scenario 2), hvor baseline designet yter bedre. Likevel, når vi evaluerer de fleksible cruise skip designene over alle eraene yter begge de fleksible designene bedre enn baseline designet.

Resultatene fra case studien illustrerer at å fremtids forsikre cruise skip ved å designe for fleksibilitet generelt har en høy verdi. Når det er sagt viser resultatene og sensitivitets analysen også at fleksibilitet kommer med en kostnad, og hvis denne kostanden blir for stor vil verdien av fleksibilitet enten bli veldig lav eller forsvinne totalt. I tillegg viser resultatene fra case studien av verdien av fleksibilitet er høyt avhengig av hvordan fremtiden

blir. I case studien yter det ammoniakk klare skipet best i baseline eraen, som på mange måter er den eraen vi har mest troen på at skal forekomme, mens LNG dual fuel skipet yter best når vi evaluerer over alle eraene. Det er derfor vanskelig å si hvilket av de fleksible designene som vil bli den beste investeringen. Hvilket av de fleksible designene som er mest fortrukket vil derfor relatere seg til hvilken fremtid beslutningstakeren har mest troen på.

Preface

This thesis is the final part of my Master of Science degree with specialisation in Marine Systems Design at the Department of Marine Technology at the Norwegian University of Science and Technology (NTNU). The thesis was written in its entirety during the spring of 2020, and the workload is equivalent to 30 ECTS.

Trondheim, Norway, June 2020

Ola G. Skåre

Ola Gundersen Skåre

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Abbreviations

AR	Autoregressive
ARMA	Autoregressive Moving Average
CAPEX	Capital Expenditures
CCS	Carbon Capturing and Storage
CI	Compression Ignition
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ENPV	Expected Net Present Value
EPI	Environmental Port Index
ETS	Emission Trading System
GBM	Geometrical Brownian Motion
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
HT-PEMFC	High Temperature Proton Exchange Membrane Fuel Cell
HVO	Hydrogenated Vegetable Oil
ICE	Internal Combustion Engine
IMO	International Maritime Organisation
LBG	Liquefied Biogas
LCA	Life Cycle Analysis
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MDO	Marine Diesel Oil
MEPC	Marine Environmental Protection Committee
NO_x	Nitrogen Oxide
NPV	Net Present Value
OPEX	Operational Expenditures
OU	Ornstein-Uhlenbeck

PEMFC	Proton Exchange Membrane Fuel Cell
PM	Particulate Matter
SEEMP	Ship Energy Efficiency Management Plan
SI	Spark Ignition
SOFC	Solid Oxide Fuel Cell
SO_x	Sulphur Oxide
VOYEX	Voyage Expenditures

Chapter 1

Introduction

This chapter starts by introducing the background for the master thesis. The main objective and the approach for answering the objective in this thesis are then presented. The chapter ends with an overview of the structure of this thesis.

1.1 Background

International shipping is on the threshold of the largest change in recent time. For the first time in history have the world's nations now agreed on dramatically to reduce Greenhouse Gas (GHG) emissions from ships. In April 2018, the International Maritime Organisation (IMO) adopted an ambition to reduce GHG emissions from international shipping by at least 50 per cent by 2050 based on a 2008 baseline. Furthermore, with a strong emphasis on reducing GHG emissions by 100% as quickly as possible.

Today, the IMO is working on translating its GHG ambition into specific requirements for ships. However, what these requirements will include, both in the short-term and in the long-term are yet highly uncertain. Besides, introducing new regulations in the IMO usually take some time, and its member states are expected to be impatient after introducing GHG regulations. Thus, it is not unthinkable that GHG measures will be implemented in some local or regional areas in the meantime (e.g. in the EU or the Norwegian world heritage fjords).

To comply with the future GHG emission requirements from the IMO and others, new technology and alternative fuels will have to be taken into use. Currently, many pilot projects, testing different technologies and fuels for ”greener” shipping operations are underway, however, considerable testing is still needed for most of them to become commercially available. Thus, nobody knows yet what will be the technology and the fuels of tomorrow, and in the future.

> *Without a doubt, today's shipowners face more change in the near future than at any time in recent memory. We cannot assume that the regulatory and technology landscape will remain stationary, and we need to examine the questions of what is next, how can we plan for the future, and what are the factors we need to take into account.* Magnus Eide, Principal Consultant, DNV GL Maritime Advisory (DNV GL, 2019d).

One of the shipping segments currently being pushed more than any others to become ”greener”, and to operate more environmentally friendly, is the cruise industry. Cruise ships operate all over the world and are therefore required to comply with both local and global environmental regulations. It is also to expect that the cruise passengers will have an increasing awareness of cruise ships emissions in the coming years and that they potentially will select cruise ships based on their environmental performance. A cruise ship able to withstand not only stormy weather but also to comply with radical environmental requirements will thus be indispensable in the years to come.

The question is then: How can a decision maker investing in a new cruise ship design best handle uncertainty related to future environmental requirements, technological innovations and alternative fuels?

> *Shipowners must avoid investing in ships that are ”locked” to existing technology. Most ships have a lifetime of 20-30 years, and many above that. All ships being launched the coming years should therefore be designed and built so that they can be converted from fossil fuels to zero-emission solutions when the technology is available.* Harald Solberg, CEO, Norwegian Shipowners' Association (Energi og Klima, 2020).

This thesis, therefore, focuses on how one can handle future uncertainty associated with environmental requirements for cruise ships, by introducing flexibility. The future is inherently uncertain, and having a ship that is prepared for the future, or often characterised as ”future-proof” can potentially create high value. Having a ”future-proof” ship design means that it is both optimised for the current and more certain near-future scenarios, whereas constructed with enough flexibility to handle also more uncertain long-term scenarios. Introducing flexibility in cruise ship design permits the shipowner to take a proactive approach against future uncertainty, by both mitigating its downside risk, and exploiting its opportunities.

1.2 Objective

The objective of this thesis is to investigate the value of designing cruise ships with flexibility to comply with future environmental requirements, by preparing for technological innovations and alternative fuels.

To investigate the value of flexibility in cruise ship designs, the following points are going to be covered in this thesis:

1. Literature study on how flexibility can be used to handle future uncertainty in engineering design in general, and more specifically in ship designs.
2. Present methods for modelling the future and to estimate the value of flexibility.
3. Develop a generic framework that can be used to quantify the value of flexible ship design solutions.
4. Provide an overview of the maritime environmental regulatory framework, technologies for power generation and alternative fuels for shipping.
5. Apply the generic flexibility analysis framework developed in 3 on a realistic case study of the design of a large cruise ship.
6. Discuss and conclude.

1.3 Approach

The approach taken in this thesis for investigating the value of flexibility in cruise ship design can be divided into two parts. First, a generic framework for valuing flexibility in cruise ship design is proposed. Secondly, using the flexibility valuation framework for investigating the value of designing cruise ships with flexibility.

The flexibility valuation framework proposed in this thesis strives to be as generic as possible and has the potential of being used on all types of shipping segments. Furthermore, the framework aims to facilitate communication between a maritime expert and a decision maker and intends to be used for example, by a maritime consultant in DNV GL Maritime Advisory.

1.4 Structure of the Report

The structure of this thesis is as follows:

- **Chapter 2** describes how flexibility can be used to handle uncertainty, followed by an introduction to real options analysis as a methodology for quantifying the value of flexibility. The chapter ends with a short introduction to the process of identifying flexibility.
- **Chapter 3** presents approaches for modelling the future, with a particular focus on the epoch-era analysis as a structured method for creating scenarios. Stochastic processes are also introduced in this chapter.
- **Chapter 4** presents real options analysis as a tool for valuing flexibility, and describes the most used methods for valuing real options: Black and Scholes formula, binomial lattice method and Monte Carlo simulations.
- **Chapter 5** presents a generic framework building epoch-era analysis and real options analysis with Monte Carlo simulation for analysing the value of flexibility in ship design.
- **Chapter 6** gives a general introduction to environmental regulations in shipping, and describes regulations for GHG, SO_x, NO_x and PM emissions both globally and locally in more detail.
- **Chapter 7** provides an overview of a selection of maritime energy converters and alternative fuels with the potential of being low- and zero-emission solutions for deep-sea shipping in general, and cruise ships more specifically.
- **Chapter 8** presents a realistic case study where the value of flexibility in cruise ship designs for complying with future environmental requirements is investigated.
- **Chapter 9** presents the results from the case study. A sensitivity analysis is also presented in this chapter.
- **Chapter 10** provides a discussion of the results from the cruise ship case study.
- **Chapter 11** presents the conclusions of the thesis, and proposes further work.

Chapter 2

Handling Uncertainty by Flexibility

This chapter describes how flexibility can be used to handle uncertainty. First, uncertainty and flexibility as two terms are described. Secondly, an introduction to how flexibility can be used to reduce risk from uncertainty, and instead exploit upside potential in engineering design are provided. Thirdly, real options analysis, inspired by finance, as a methodology for quantifying the value of flexibility in engineering design, is described. Finally, a brief introduction to methods for identifying flexibility in engineering design is given.

The underlying aim of this chapter is to present central literature on the subject of using flexibility to handle uncertainty in engineering design in general, and more specifically in ship design. This literature was found by using keywords such as ”flexibility in engineering design” and ”real options analysis in engineering design”, or combinations of these words in search engines like *Scopus*, *IEEE Xplore*, and *Engineering Village*. The literature included in this chapter, includes journals, conference papers and books etc. from a selection of disciplines both economic and engineering.

2.1 Understanding Uncertainty

McManus and Hastings (2005) describes uncertainty as: *Uncertainty are things that are not known, or known only imprecisely.* Richard de Neufville and Stefan Scholtes precise that the future is inevitably uncertain (de Neufville and Scholtes, 2011). As a direct result of this, experiences shows again and again that it is impossible to predict exactly what the future will bring in the long term. A general rule is, therefore, that the forecast of the future is ”always wrong” (de Neufville, Hodota, et al., 2008). Something important to be aware of when designing large capital-intensive and long-lived engineering systems.

In Table 2.1, examples of uncertainties in marine systems design are outlined.

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

Field	**Example**
Economic	Fuel price, oil price, supply/demand, freight rates, and interest rates etc.
Technology	Technological development, new types of fuels, energy efficiency etc.
Regulatory	Global and local emission restrictions and ballast water treatment etc.
Physical	Extreme weather, sea ice, port & canal restrictions etc.

Types of Uncertainty

Uncertainty comes in different forms, where some can be actively managed through design and others not. Lin et al. (2013) classify uncertainty into three different categories according to how they can be influenced:

- *Endogenous uncertainty* can be actively handled by decision makers and depends on the systems design and project plans. An example is the actual maximum speed of a ship after it is being built. This uncertainty can, for example, often be reduced by introducing better computational models (Rehn, 2018).
- *Exogenous uncertainty* is external and outside the control of the decision maker. For example market rates, fuel prices or demand for a ship in the market.
- *Hybrid uncertainty* can be partly influenced by decision makers. For example, the chance of a vessel to win a contract, which is partially dependent on the design.

The contextual variables addressed in this thesis are mainly exogenous.

Complexity in Systems

Complexity is a system characteristic that is frequently mentioned in the literature related to handling uncertainty (Rehn, 2015). There exists an apparent reason for this, as complexity and uncertainty are positively correlated. As introducing more complexity to the system will increase the uncertainty, while reducing complexity, will in most cases, reduce uncertainty (Rehn, 2018). Generally, as a result of this relationship, it is desirable to reduce the complexity as much as possible within the limits of the functional requirements of the system (Suh, 1990).

By Rhodes and Ross (2010), it is proposed to decompose complexities of engineering designs into five aspects: structural, behavioural, contextual, temporal and perceptual. In Gaspar et al. (2012), these five aspects are discussed related to conceptual ship design. Figure 2.1, which is adopted from Gaspar et al. (2012), describes the different aspects of complexity related to ship design in more detail.

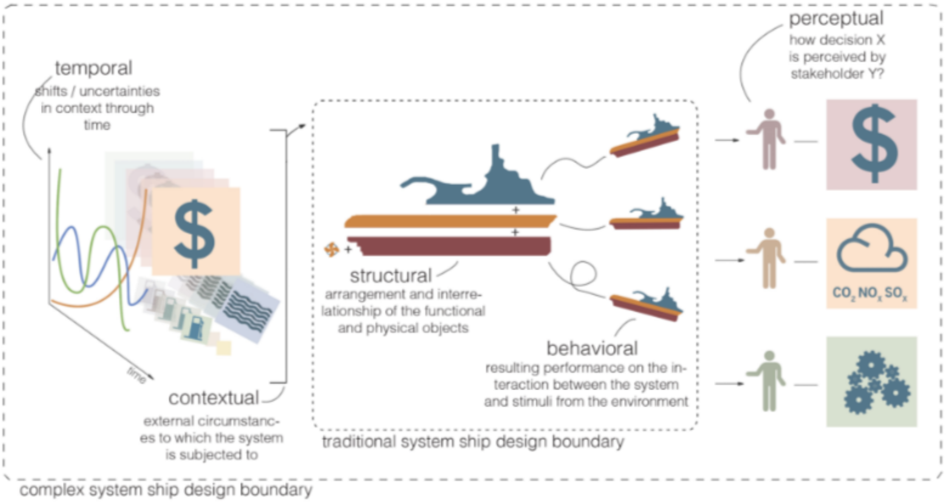


Figure 2.1: The five aspects of complexity in ship design (adopted from (Gaspar et al., 2012))

In this thesis, the primary focus is on the temporal aspect of complexity, which is related to uncertainties in the contextual variables over time. The epoch-era analysis later introduced in this thesis is a decomposition-based approach for handling temporal complexity (Gaspar, 2013).

”The Flaw of Averages”

When calculating the average value of a project or design, it may be tempting to use average conditions, as for example, using future contextual parameters by the mean value, or the most likely scenario. However, using average conditions is a dangerous approach and may quickly lead into *the flaw of averages* (Savage, 2002). The flaw of averages can mathematically be described by Jensen’s Inequality (de Neufville and Scholtes, 2011):

$$f(E[x]) \leq E[f(x)] \tag{2.1.1}$$

Where x is a vector of input variables. In more simple words, Jensen’s Inequality describes that average inputs may not produce the average value of the project or design. Thus, Jensen’s Inequality greatly illustrates the non-linear influence of uncertainty on the value of a project or design. The reason behind this non-linear behaviour is that the effects of the upside and downside values of the input variables on the performance of a project or design, not generally cancel each other out. For example, consider a case with an oil tanker, its capacity may be increased to a limit degree if the market is good, while have to take the whole downside if the market collapses. Thus, not considering the existence of Jensen’s Inequality may lead to bad decisions.

Another example, where wrong decisions can be made if only the most-likely scenario is used, is when valuing the flexibility of having a dual fuel engine installed on board a ship.

This valuation process will greatly depend on the difference in fuel price between, e.g. HFO and LNG, and wrong conclusions may potentially be made if only average values are used. Figure 2.2 depicts this, and only the graph on the right-hand side will be able to value the switching option for a dual fuel engine.

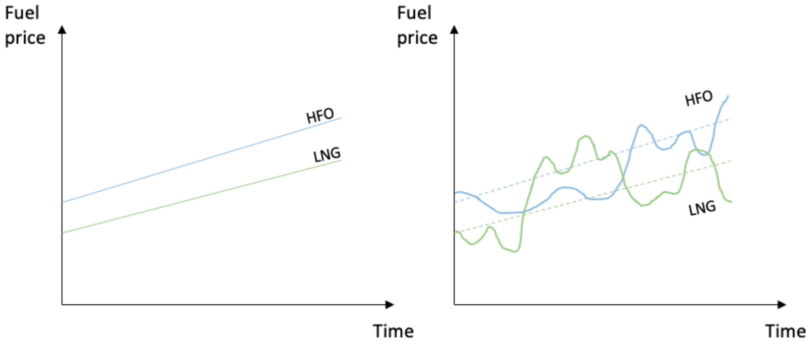


Figure 2.2: Expected fuel price (left), fuel price including variation (right) (inspiration from (Erikstad, 2018)

The takeaway from this is that analysts should be careful of using average forecasts and if possible, consider a wide range of potential future scenarios (de Neufville and Scholtes, 2011).

2.2 Definition of Flexibility

Flexibility is one of the most central terms in this thesis. Thus, to have a proper understanding of its interpretation is important. Flexibility is defined in various ways in the literature, and the one being used in this thesis is the one provided by Ross and Rhodes (2008a):

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

Fricke and Schulz (2005) categorise flexibility under the umbrella term *changeability*, and defines changeability as *"the ability of a system to change easily"*. Furthermore, Fricke and Schulz (2005) decompose changeability into four categories: robustness, agility, adaptability, and flexibility. Figure 2.3 illustrates the four aspects of changeability in more detail. The key take away from this figure is that agility and flexibility include a system external change agent, while adaptability and robustness are not requiring change from an external agent.

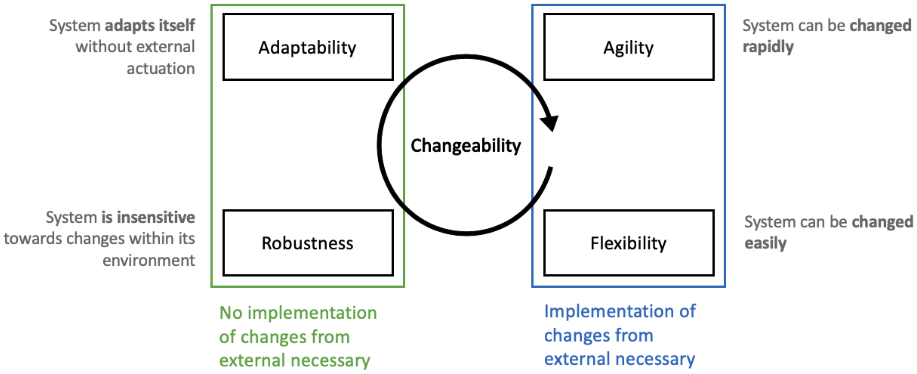


Figure 2.3: The four aspects of changeability (inspired by (Fricke and Schulz, 2005))

2.3 Flexibility in Engineering Design

The future is inherently uncertain, and knowing exactly what the needs of our engineering design will be in the future is impossible. Richard de Neufville and Stefan Scholtes, therefore, propose to include flexibility in engineering designs to reduce the risk associated with uncertainty (de Neufville and Scholtes, 2011). Furthermore, by Lorange (2005) and McManus and Hastings (2005), it is emphasised that not only downside risk comes with uncertainty, also significant upside potential. Thus, having a design which is flexible will in most cases much easier be able to capture this upside potential. Flexibility in design is, therefore, according to de Neufville and Scholtes (2011) routinely improving the performance of the design by 25% or more. In de Neufville and Scholtes (2011), three typical examples of flexible engineering designs are presented, see Table 2.2 below.

Table 2.2: Example of three types of flexible designs (adopted from (de Neufville and Scholtes, 2011; Erikstad and Rehn, 2015))

Flexibility	Example
Change in size	A design might be modular to permit easy addition or contraction of capacity. An example from the maritime industry is length expansion of cruise ships, which is done by adding an extra module in the middle.
Change in function	The system might enable change in function, by permitting users to remove or add function. An example is a container ship that can use both refrigerated containers and conventional containers. Another example is offshore supply vessels with multi-functionality.
Accident protection	Engineering designs typically have systems to protect against accidents. Such systems may, for example, be extra installed power on ships for redundancy purposes.

In engineering design, it was for a long time normal practice to treat systems requirements and constraints relating to the operating context as constant (de Neufville and Scholtes, 2011). This was also the case in early ship design using the well-known design spiral introduced by Evans (1959). However, designing for point forecasts instead of a realistic range of possible future outcomes may quickly create a design without value (de Neufville and Scholtes, 2011). For example, designing a ship today without thinking about future stricter environmental requirements will create a massive risk for this ship of becoming a stranded asset during its lifetime (Hermundsgård, 2020).

Rehn (2018) designate Buxton and Stephenson (2001) of being the first paper to explicitly focusing on aspects of flexibility as a life-cycle property in the ship design literature. In this paper, Buxton and Stephenson (2001) evaluate several levels of upgradeability built into a container ship design, to test if it is economically preferable to have an upgradeability option in the ship design. Flexibility in ship design is also something that has been of increasing interest on military ships during the years, for both reducing initial costs and to more easily modernising ships in service (Schank, 2016).

The term *value-robust* systems is by Ross and Rhodes (2008a) getting great attention. The definition of a value-robust system, is a system that continues delivering stakeholder value in the face of a changing context during its lifetime, either through system change or lack of system change (Ross, 2006). Compared to traditional robustness, is value robustness a wider concept, as it allows the system to be changed in response to uncertainty. Traditional robustness is called passive value robustness, whereas, by including flexibility, an active value robustness approach is obtained (Pettersen, 2015). For example, a *future-proof* design aims to be a *value-robust* design.

Two other ”ilities” often being discussed in the literature related to the changeability and flexibility aspects of engineering designs, and indirectly the value robustness of a design, is versatility and retrofittability. These terms are by Rehn et al. (2018) defined as:

- **Versatility:** the ability of a system to satisfy diverse needs, *without* change of form.
- **Retrofittability:** the ability of a system to satisfy diverse needs, *by* change of form.

From the definitions presented in Figure 2.3, it can be argued that versatility is similar to adaptability and robustness, while retrofittability is more related to flexibility and agility. Rehn et al. (2018) present a case study looking specifically on versatility and retrofittability on a non-transport vessel. By Rehn (2018), it is emphasised that on a general basis, multi-functional ships should be versatile, while single-functional ships should be retrofittable.

A method being used to quantitatively value flexibility in engineering designs under uncertainty is real options analysis (Ross, Rhodes, and Hastings, 2008; Cardin, 2014; Trigeorgis, 1995). The real options analysis and its application for the maritime industry are discussed in the following section.

2.4 Flexibility in Finance and Real Options

Options have its roots in the financial sector, and is by Black and Scholes (1973) defined as *”a security giving the right to buy or sell an asset, subject to certain conditions, within a specified period of time”*. In more simple words, an option represents the *right but not the obligation* to perform some action (Rehn, 2018). Extra emphasis has to be placed on *obligation*, as this is one of the central characteristics for options. This means an option creates flexibility, as an option owner will have the opportunity to postpone decisions. However, note that this flexibility comes for an option premium. Financial options come in a variety of types and classes, where the main categories are described below in Table 2.3 and Table 2.4.

Table 2.3: Define call and put options

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

Table 2.4: Exercise time for options

European	**American**
At maturity	Any time before maturity

In addition to the types of options presented in Table 2.3 and Table 2.4, also several other types of financial options exist: Asian, Bermudan, barrier, forward start, binary, lookback etc. (Wijst, 2013). These are, however, not further described in this thesis.

In 1973, the famous Black and Scholes/Black-Scholes-Merton analytical option-pricing model was published (Black and Scholes, 1973; Merton, 1973), assuming that the stock price moves according to a random walk or Geometrical Brownian Motion (GBM), and only applicable for European options. A method with similarities to the Black and Scholes model is the binomial lattice option-pricing model (Cox et al., 1979). This model can be used for valuing both European and American options.

Real options analysis, first coined by Myers (1977), has its source in the field of financial options. As the name suggests, are real options concerning physical systems, and not financial securities as stocks and bonds, as their underlying value (Wijst, 2013). In Table 2.5, an overview of the main differences between financial and real options is shown.

Table 2.5: Financial options versus real options (Alizadeh and Nomikos, 2009; Rehn, 2015)

Determinant	**Financial option**	**Real option**
General characteristics	Clear	Unclear
Time to maturity	Short	Longer
Underlying values	Smaller	Higher
Tradeable	Yes	No
Influence by management	No effect	High effect

Trigeorgis (1995) presents real options analysis as a methodology for valuing flexibility in engineering design. Real options analysis is also mentioned as a tool for analysing the timing of the effective execution of investment decisions, and to find cost or revenue drivers of projects (Alizadeh and Nomikos, 2009). In Figure 2.6, some common types of real options are presented.

Table 2.6: Some common real options (Wijst, 2013)

Call options	Put options	Compound options
Defer	Default	Phase investments
Expand	Contract	Switch inputs
Extend	Abandon	Switch outputs
Re-open	Shut down	Switch technology

Real Options ”In” and ”On” Projects

Real options can be categorised into being ”in” and ”on” projects (Wang and de Neufville, 2004). Real options ”on” projects treat technology as a ”black box”, meaning that the option is external to the physical system (Wang and de Neufville, 2005). Whereas, real options ”in” projects are options created by changing the design of the physical system, and are due to this internal to the physical system. Thus, as being emphasised in Wang and de Neufville (2005), real options ”in” projects generally require a profound understanding of technology. Table 2.7 presents the main differences between real options ”in” and ”on” projects.

Table 2.7: Characteristics of real options ”in” and ”on” projects (Wang and de Neufville, 2005)

”On” options	”In” options
Value opportunities	Design flexibility
Relatively easy to define	More difficult to define
Valuation is important	Decision is important
Path-dependency less an issue	Path-dependency is an issue

The differentiation between real options ”in” and ”on” projects is important as the methods used for calculating the value of the flexibility associated with each of them differs. For real options ”on” projects, traditional option valuation methods can be applied. However, since real options ”in” projects are more complex than ”on” options, more novel approaches are generally needed for options ”in” projects.

Some types of managerial flexibility are ”always present” for assets in operation, such as the option to abandon, lay-up, delay etc., and are all examples of real options ”on” projects. While, other types of flexibility are not necessarily present for all assets, as for example having the ability to switch between markets or capacity expansion. These kinds of flexibility are related to the design of the asset itself and characterised as real options ”in” projects. Table 2.8 and Table 2.9 provide an introduction to different examples of ”on” and ”in” options in the shipping industry.

Table 2.8: Examples of ”On” options in shipping (inspired by (Alizadeh and Nomikos, 2009))

”On” option	**Description**
Abandon	Option to sell the ship. This option is exercised, for example, if the market is bad.
Lay-up	Option to temporarily stop operating the ship. Typically used when it is unprofitable to run the ship.
Delay	Option to delay a decision or projects. For example, delay an investment in a new ship if the market is unfavourable at a certain point in time.
Expand fleet	Option to expand the fleet. For example, invest in more vessels if the market is good.
Other	Options can be embedded in shipping contracts. Examples are newbuilding options, time-charter extensions etc.

Table 2.9: Examples of ”In” options in shipping (inspired by (Rehn, 2015))

”In” option	**Description**
Switch fuel	Option to switch fuel and engine systems. If new environmental regulations require lower emissions, a ship can switch from one fuel type to another by modifying/rebuilding its energy converters, storage systems etc.
Switch market	Option to switch between different operations or chartering contracts. This can be either due to a versatile ship or by retrofitting the ship.
Expand capacity	Option to expand the capacity of the ship, by a retrofit. For example, by an elongation of a cruise ship or cargo ship through a retrofit.
Capability retrofit	Option to add or modify the capabilities of the ship. For example, by installing a crane that can lift heavier elements on an offshore supply vessel.

Some may argue that ”in” options focus on increasing the upside potential of uncertainty, whereas ”on” options focus on mitigating the downside potential of uncertainty. This thesis concentrates mostly on options ”in” designs, and technology can, therefore, not be treated as a black-box. When that is said, also ”on” options (e.g. the sell option and the lay-up option) are included in the case study later presented in this thesis.

Examples of Real Option Valuation in the Shipping Literature

In this section, a compact literature study of real option valuation examples within the shipping literature is presented.

It took more than 10 years after real options were first coined by Myers (1977) before it was mentioned in the shipping literature (Dixit, 1988; Dixit, 1989), where real options analysis was performed on entry, exit, lay-up and scrapping options. However, during the years, real options analysis in shipping has been increasingly more popular, and several papers have now been published. The most relevant real options studies in shipping for this thesis are summarised in the following.

In Sødal et al. (2008), an analytical real option pricing model is used to value the option to switch between markets using combination carriers. By Knight and Singer (2012), a real options analysis with Monte Carlo Simulation is used to investigate the elongation option on a container ship. Acciaro (2014) investigates the option to defer the investment in an LNG retrofit for environmental compliance. In Pettersen (2015) epoch-era analysis and real options analysis with Monte Carlo simulation are combined to value flexibility in offshore construction vessels. Rehn (2015) evaluates flexibility on a container ship by using real options analysis with Monte Carlo simulations. Ullereng (2016) studies sell, lay-up, scrapping, and retrofit options for platform supply vessels. In Rehn et al. (2018), a combination of epoch-era analysis and real options analysis with Monte Carlo simulation is used to evaluate the relationship between economic performance and flexibility for non-transport vessels.

2.5 Valuing Projects with the Net Present Value (NPV)

Traditionally, projects are being valued by using the Net Present Value (NPV) of a project (Wijst, 2013). The NPV of a project is calculated by discounting the net cash flow of a project using an appropriate discount rate to the present time. The NPV value of the project is then used for decision making, and a project is selected if the NPV is positive, while rejected if the NPV is negative. The NPV formula in its most general form is presented in Equation 2.5.1.

$$NPV = \sum_{t=0}^{N} \frac{R_t - C_t}{(1+r)^t} \tag{2.5.1}$$

Where R_t is the revenue at time t and C_t is the cost at time t, and r is the discount rate over the total number of periods N. Conventional NPV as a methodology for valuing projects has a major disadvantage in the way that it does not include several factors with potentially a significant influence on the success of a project (Alizadeh and Nomikos, 2009; Knight and Singer, 2012). Figure 2.4 depicts the different factors being included in conventional NPV valuation and real option valuation. In conventional NPV valuation, an ”expected” future cash flow and a passive oriented operating strategy where the same strategy is followed independently on how the market conditions develop over time are used. These kinds of assumptions may be adequate for projects with highly predictable cash flows and fixed operational constraints, whereas in other types of projects, these assumptions may underestimate the value of flexibility. The latter scenario will often be the case for projects in shipping (Knight and Singer, 2012). Another reason to be careful by using the conventional (deterministic) NPV approach is the *flaw of averages* (Savage, 2009), discussed in Section 2.1.

The real option valuation overcomes many of the weaknesses of the conventional NPV analysis, and some think that it actually will replace NPV as the central paradigm for investment decisions in the future (Copeland and Anikarov, 2002).

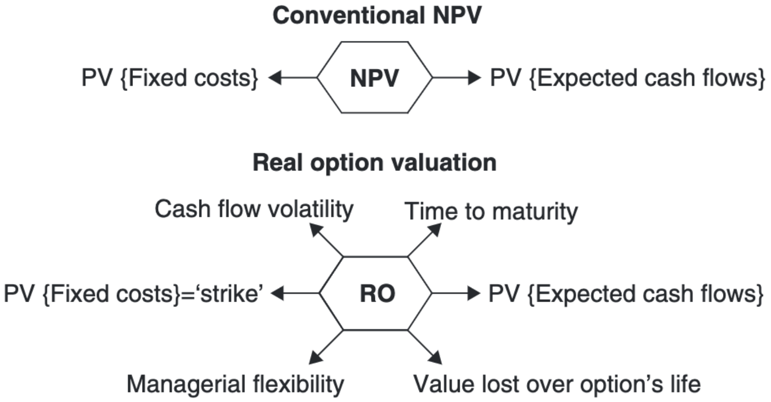


Figure 2.4: Conventional NPV versus real option valuation (adopted from (Cuthbertson and Nitzsche, 2001))

What is essential to be aware of when using NPV as a tool to support decision making is that it does not provide insight into risk. As long as the NPV is positive, the NPV theory states that the investment should provide value to the company. Hence, the investment should be made. However, disruptive events may occur, and having a better understanding of risk would possibly allow us to make better investment decisions. This can be obtained, for example, by combing the NPV method with Monte Carlo simulations, which will be described in more detail in Section 4.3.

In addition, to the NPV method for valuing projects, also other methods exist. Where the most popular methods include: Payback period analysis, Accounting Rate of Return (ARR) and Internal Rate of Return (IRR). Each of these methods has both advantages and drawbacks. However, in this thesis, only the NPV method is described in detail.

2.6 Methods for Identifying Flexibility

A vital fact to remember with real options analysis is that it does not give information about where an option, or flexibility, should be included in the system. Real options analysis only determines which of the options is most preferable to hold (Shah et al., 2009). Hence, having a systematic approach for identifying where flexibility can be introduced in the system is necessary if the real options analysis shall have a value.

It is not a straight forward process to know which flexibilities that will add most value to a system, as it depends on numerous factors. These factors are, according to de Neufville and Scholtes (2011):

- *The nature of the system:* Preferable flexibility for a cargo vessel, will be different compared to the desired flexibility of a copper mine e.g.
- *The kind of uncertainties:* The preferable flexibility will depend on the uncertainties facing the system. Do we want to have the possibility to expand the system easily, or to redeploy capabilities etc.
- *The intensity of uncertainties:* The time aspect of the option to exercise the flexibility is vital with respect to which flexibilities we want to introduce. Are we interested in long-term or short-term flexibility options?
- *The cost of implementing flexibility:* How much effort is needed to obtain the desired flexibility, especially in terms of costs?

There exists an extensive catalogue of different methods that can be applied to identify flexibility in engineering systems, and the preferable method to use will be highly case-specific. Cardin and de Neufville (2008) describes state-of-the-art methodologies for identifying flexibility in complex engineering systems and highlights three methods as particularly important: interview, information-flow and screening. In this thesis, the type of flexibility to introduce into the design is by many means already described by the problem description. Thus, only the most basic ”interview method” is described in more detail in this thesis.

Interview Method

The interview method is the most basic flexibility identification approach and comprises interviews of subject matters experts (Cardin and de Neufville, 2008). Subject matters experts are typically specialist as engineers, managers or operators of the system under consideration or similar system in the case of an innovative system. Shah et al. (2009) point out that interviews with subject matter experts can improve the understanding of the changes that might occur to the system due to changes in exogenous factors. Thus, indicate where flexibility should be implemented. One disadvantage of the interview method that often is mentioned is that the information from the expert may be biased. It is, therefore, important to be aware of this aspect when using the interview method.

Chapter 3

Methods for Modelling the Future

In this chapter methods for modelling the future are presented. First, scenario planning, in general, is discussed. Secondly, a thorough introduction to epoch-era analysis, which is a particularly important method in this thesis, is given. Finally, a brief introduction to the most used stochastic processes for marine applications is provided.

3.1 Scenario Planning

The father of scenario planning is Herman Kahn, who introduced scenario planning through his work for the US military and the RAND Corporation with ”future now thinking” (Kahn, 1967). Scenario planning is the process for exploring possible futures, where two main questions seek to be answered: *”What can conceivably happen?”*, and *”What would happen if...?”* (Lindgren and Bandhold, 2003).

In the process of generating scenarios for the future, it is essential to have a general understanding of the planning horizon of decision makers. The planning horizon of a project is usually decomposed into three categories: strategic, tactical, and operational (Christiansen et al., 2007; de Neufville, 2004). Table 3.1, shows examples from the maritime industry for each of these planning horizons.

Table 3.1: Example of planning horizons in the maritime industry (Christiansen et al., 2007)

Planning horizon	Example from the maritime industry
Strategic (3-10 years/lifecycle)	Ship design, fleet size etc.
Tactical (months to years)	Fleet deployment, routing and scheduling etc.
Operational (days to months)	Ship speed etc.

Design of ships is categorised to be on the strategic level due to the long time horizon (Christiansen et al., 2007). In Alizadeh and Nomikos (2009) and Erikstad and Rehn (2015), it is reported that scenario planning on a strategic level has been used only in a limited degree in the maritime industry, even though it is widely known that the industry is exposed to a great deal of uncertainty. Furthermore, where scenario planning has be used, designing only for the most likely scenario has been general practice (Erikstad and Rehn, 2015).

A variety of approaches for building scenarios exists, including the narrative approach and expert judgement. By Schoemaker (1991), it is emphasised that the narrative approach is the preferable method for cases with a lot of uncertainty and complexity. Furthermore, Rehn (2018) points out that the scenario planning approach is particularly useful in cases where no historical data exists.

Börjeson et al. (2006) highlights that scenarios describing possible futures should be created in a consistent and transparent manner. The epoch-era analysis is a relatively new method aiming to apply a structured scenario planning approach. In this method, eras are used instead of scenarios as a term describing possible future outcomes. The only difference is that eras are path-dependent, and scenarios typically only consider the initial and final contexts (Ross and Donna, 2010).

3.2 Epoch-Era Analysis

The epoch-era analysis was first introduced by Ross and Rhodes (2008b). The epoch-era analysis is a quantitative scenario building technique, where the variables with the highest uncertainty and impact on the system performance over time are described as epoch variables. An epoch represents a possible static system context, in which all epoch variables remain fixed. Figure 3.1 depicts four different epochs, containing a set of n epoch variables.

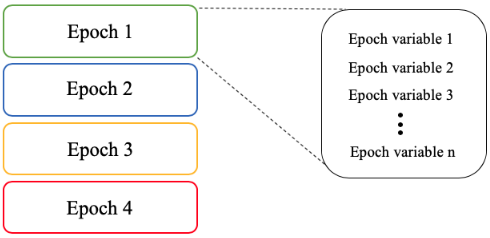


Figure 3.1: Epoch generation

The epoch variables typically originate in domains such as economic and market, technology and infrastructure, policy and regulations, to name some. Several methods can be applied to identify the epoch variables, and may, for example, involve brainstorming and dialogue with subject matter experts (Rehn, 2018). The result is an epoch vector with the epoch variables. Questions that quickly arise is: how many epoch variables should be included? And, how many different values should each epoch variable have? To these questions, there is no single answer, as it is highly case dependent. However, it is important to be aware of these aspects.

An era is constructed by combining epochs along a timeline, usually with a length equal the life cycle of a system or a long-term system context. Eras are, therefore, scenarios describing potential changing contexts over time, and permit different long-term analysis. Figure 3.2, shows an example of an era construction. This figure also illustrates that epoch variables can be given a stochastic development within an epoch in cases where this is considered as important for the analysis and the results.

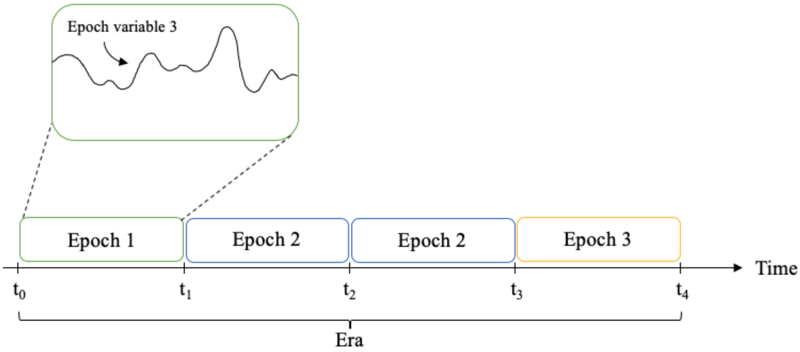


Figure 3.2: Era construction

Eras should be constructed carefully, as they normally have a huge impact on the results in the analysis. By Ross and Donna (2010), the process of constructing eras is described to include four main activities: specify era duration, characterise epoch durations, establish epoch ordering logic, and construct eras. Several methods can be applied to generate eras, including a narrative approach where a story is created (see e.g. (Gaspar et al., 2012)) and simulation models. By using the narrative approach, eras can be constructed based on the analysts and decision makers best assumptions and guesses for the future. In the case of creating eras with simulation, this can be done randomly based on a set of predefined conditions set by the analyst (Rader et al., 2010).

3.3 Stochastic Processes

Stochastic processes are often used for modelling exogenous uncertainty (Erikstad and Rehn, 2015). The stochastic model generates possible time series which can be used as input to simulation models, for example, Monte Carlo simulations. Stochastic processes have a central role in real options analysis, thus having a general understanding of this topic is important. In the following, four common stochastic processes are presented.

3.3.1 Geometric Brownian Motion

A Geometric Brownian Motion (GBM) is a stochastic process in continuous time, where the logarithm of the underlying asset follows a Brownian motion with drift (Erikstad and Rehn, 2015). The well known analytical Black and Scholes formula for valuing European options is an example of an option pricing method using GBM as the stochastic process (Black and Scholes, 1973). A stochastic process is said to follow a GBM if it fulfils the following stochastic differential equation:

$$\frac{dS_t}{S_t} = \kappa dt + \sigma dW_t \tag{3.3.1}$$

Where κ is the drift describing the long term movement, σ is the volatility of S_t, dt is the time increment, and W_t is a Wiener process or Brownian motion. The properties of the GBM is that the current movement is random and independent of the previous states (Erikstad and Rehn, 2015). A disadvantage of the GBM is that it has a tendency to give extreme values, which for many real cases is unfavourable. The GBM is frequently referred to as a ”random walk”, and is in finance often used to model stock behaviour.

3.3.2 Mean Reverting Process

A mean reverting process typically centre on a long-term mean value. One of several methods for modelling mean reversion is the Ornstein-Uhlenbeck (OU), which can be considered as a modification to the GBM model. A stochastic process is characterised to follow an OU process if it fulfils the following stochastic differential equation:

$$dS_t = \mu(\overline{S} - S_t)dt + \sigma dW_t \tag{3.3.2}$$

Where μ is the rate of reversion, the $\overline{S}$ is the mean-reverting value, σ is the volatility of S_t, dt is the time increment, and W_t is a Wiener process or Brownian motion. The higher the μ is, the faster the process will revert back to the mean-reverting value. The mean reverting process has the ability to capturing the logics of supply and demand, which is an important principle in economics. Where a rise in price may cause more supply, which later cause a falling price. Thus, the mean reverting process is path-dependent, as the movement of the price depends on its previous state. An example where a mean reverting process is being used is in Sødal et al. (2008), where an analytical real option pricing model is used to valuing the option to switch between markets.

3.3.3 Autoregressive Motion

The Autoregressive (AR) motion, first introduced by Yule and Walker in the 1930s, is a random process that uses observations from the previous time step as input to a regression equation for predicting its value in the next step. Note that the AR is a special case of the Autoregressive-Moving-Average (ARMA) model of time series. The AR model is defined as:

$$X_t = c + \sum_{i=1}^{p} \varphi_i X_{t-i} + \epsilon_t \tag{3.3.3}$$

Where X_t is the variable modelled, c is a constant, φ_i ... φ_p are the parameters of the model, and ϵ_t is random noise. The AR model can be used to model market momentum and market cycles, due to its dependency on the prior state. Making the AR a suitable method for shipping, as market cycles are frequently seen in this industry (Stopford, 2009).

3.3.4 Jump-Diffusion Process

The jump-diffusion process, first introduced by Merton (1976), is a stochastic process that includes both jumps and diffusion. A stochastic process follows a jumping-diffusion process if it can be represented in the following form:

$$\frac{dS_t}{S_t} = \kappa dt + \sigma dW_t + (J-1)dN(t) \tag{3.3.4}$$

Where κ is the drift describing the long term movement, dt is the time increment, σ is the volatility of S_t and W_t is a Wiener process or Brownian motion. The last term in Equation 3.3.4 represents the jumps, where J is the jump size, and $N(t)$ is the number of jumps that occurred up to time t. The jump size can follow any distribution but is often given by a lognormal distribution. The Jump-diffusion process is frequently used in financial modelling. For design problems, the jumps modelled in the jump-diffusion process can be sudden changes in technology, regulations, oil price etc.

3.4 Stochastic Processes in Marine Systems Design

The stochastic process used in the calculations normally has a large influence on the results. Thus, the analyst should, therefore, act thoroughly when selecting stochastic processes. Furthermore, one should strive to use as simple stochastic processes as possible. As a simple or less complex stochastic processes is both easier to implement into the model and for a non-technical decision maker to understand and accept. Table 3.2 shows some examples of marine applications for the stochastic processes.

Table 3.2: Examples of stochastic processes in marine systems design (Erikstad and Rehn, 2015)

Stochastic process	**Example of marine application**
Geometric Brownian Motion	Modelling oil and asset prices on relatively short term.
Mean-Reversion process	Modelling differences between fuel prices for ships using dual fuel engines.
Autoregressive Motion	Modelling cyclical shipping markets in the long term.
Jump-diffusion process	Modelling sudden change in e.g. technology, regulations, oil price.

Chapter 4

Valuing Flexibility by Real Options Analysis

This chapter presents real options analysis as a tool for quantifying the value of flexibility in engineering design. Real options analysis is used as an umbrella term for the methodologies used for valuing real options, and the methods that are included in this section is: Black and Scholes option pricing formula, binomial option pricing and Monte Carlo simulation. Which by Wang and de Neufville (2005) is highlighted as the three most important valuation techniques for real options.

4.1 Analytical Solutions

Erikstad and Rehn (2015) define analytical solutions for valuing options as: *"Analytical solutions are exact solutions to differential equations that express the change in option value relative to all the key variables that affect its value"*. Key advantages with analytical solution methods are that they usually are both easier and quicker than the other solution methods. However, for non-conventional options, the analytical solution approach may be unsuitable.

4.1.1 Black and Scholes Option Pricing

The most famous analytical solution approach for valuing options is the Black and Scholes option pricing formula for valuing European call and put options (Black and Scholes, 1973; Merton, 1973). Thus, as a result of its significance in the option pricing theory, a short and overall introduction to its methodology is given in this thesis.

By solving a partial differential equation describing the value of the option over time, the Black and Scholes formula for valuing European call options (see Equation 4.1.1) and European put options (see Equation 4.1.2) can be derived.

$$BS_{Call} = S_0 N(d_1) - Xe^{-rT} N(d_2) \tag{4.1.1}$$

$$BS_{Put} = Xe^{-rT} N(-d_2) - S_0 N(-d_1) \tag{4.1.2}$$

Where S_0 is the price of the underlying asset following a stochastic process (usually the geometrical Brownian motion), σ is the volatility of returns of the underlying asset, X is the exercise price at maturity, T is the time to maturity, r is the risk-free interest rate, and $N(d)$ represents the cumulative normal distribution function. Where d_1 and d_2 are defined by the following equations.

$$d_1 = \frac{ln(\frac{S_0}{X}) + (r + \frac{1}{2}\sigma^2)T}{\sigma\sqrt{T}} \tag{4.1.3}$$

$$d_2 = d_1 - \sigma\sqrt{T} \tag{4.1.4}$$

The Black and Scholes option pricing formula relies on several critical assumptions, where the arbitrage-enforced pricing assumption is the most prominent. Furthermore, the arbitrage-enforced pricing only works if a replicating portfolio can be created, and when the option and the replicating portfolio can be traded. By Wang and de Neufville (2005), it is precised that, *"If arbitrage-enforced pricing does not work for a real options project, there is no sense to talk about Black-Scholes formula or risk-neutral valuation"*. Replicating portfolios are almost impossible to define for "in" options. In Wang and de Neufville (2005), the problem of creating replicating portfolios is further emphasised, and asks the following question, *"how might one replicate the real options of strengthened footing and columns for a parking garage?"*. The Black and Scholes option pricing approach is, therefore, in most cases, unsuitable for valuing more complex real options "in" engineering design.

4.2 Tree Building Methodologies

Tree building methodologies establish scenarios in discrete time steps into branches, hence creating a structure with similarities to a tree. Moreover, each scenario in the tree is given a probability. By Erikstad and Rehn (2015) it is described that trees come in a variety of forms, as: binomial or multinomial, recombining or non-recombining and use multiplicative or additive terms.

Trees that recombine results in a lattice structure, which gives a lower computational time compared to a non-recombining tree. The reason for this, is that for non-recombining trees the number of states increases exponentially, instead of linearly as for the lattice structure. A shortcoming of the lattice structure is that the option value has to be path independent since there are several paths with equal probability to a given state. This assumption is often adequate for financial options, however, not necessarily for real options (Wang and de Neufville, 2004). Thus, to solve real options, it can be argued that non-recombining trees should be used. However, for complex problems, these trees may quickly become extremely large.

4.2.1 Binomial Option Pricing

The binomial option pricing model was first introduced by Cox et al. (1979), and has during the years become a common option pricing approach in finance and for real options ”on” projects. As in the Black and Scholes model, the binomial option pricing method is based on creating a risk-neutral portfolio, consisting of an option and the underlying asset, which for the binomial option pricing method is assumed to follow a binomial process (Erikstad and Rehn, 2015).

In Figure 4.1, a two-period recombining binomial lattice, where it is assumed that the value of the underlying asset S follows discrete time steps Δt shown. The asset value S_0 can increase by a multiple of *u* or decrease by a multiple of *d* at each time step Δt, and the probability of upward movement is *p*, and downward movement is (1 - *p*).

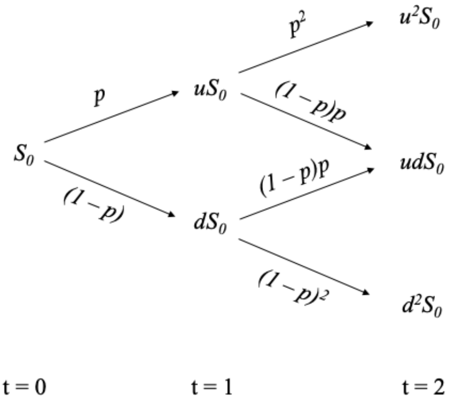


Figure 4.1: Two-period recombining binomial lattice (inspired by (Cox et al., 1979))

For a standard binomial lattice model, the upward multiplier *u*, downward multiplier *d* and the risk-neutral probability p can be found by using the asset’s volatility σ and the risk-free rate *r*. By making the assumption that *u* = 1/*d*, we can find *u*, *d* and *p* by using the following equations:

$$u = e^{\sigma\sqrt{\Delta t}} \tag{4.2.1}$$

$$d = e^{-\sigma\sqrt{\Delta t}} \tag{4.2.2}$$

$$p = \frac{e^{-r\Delta t} - d}{u - d} \tag{4.2.3}$$

Below, the binomial option-pricing formula is presented.

$$O = \frac{pO_u + (1-p)O_d}{1+r} \tag{4.2.4}$$

By using the binomial option pricing formula, together with strategic exercise actions made in each node depending on the type of option under evaluation, the future value of an option can be found. Thus, by discounting the future value, the present value of the option can be obtained.

The lattice presented in Figure 4.1 is an example of a path-independent tree, as one can take several paths, and still end up in the same state. This makes the computational process easier and less time-consuming. However, for some real options, this approach may be to over-simplified (Wang and de Neufville, 2004).

The binomial lattice model may work very well for financial options and real options ”on” projects. However, for real options ”in” projects, this approach quickly becomes unsuitable, especially due to:

- Real options ”in” projects are usually path-dependent. Thus, the binomial lattice model cannot be used (Wang and de Neufville, 2005). Cardin, de Neufville, and Geltner (2015) describes this by an example, *”an up-down movement in demand or price may lead to a different sequence of engineering decisions (e.g. build, or not build), than a down-up movement over two periods.”*
- The binomial lattice model is unable to capture binary events. Hence, unable to model technology and regulations, which usually is in this format (Pettersen, 2015).

A method which is able to overcome many of the shortcomings of the Black and Scholes method and the binomial option pricing method is simulation. Which for path-dependent real options ”in” projects will be both better and easier to use for valuing the real options.

4.3 Simulations - Monte Carlo Simulation

Simulation is a tool that can be used to a wide variety of application areas, and have shown great relevance for valuing flexibility in engineering design. The two types of methods presented above for valuing real options clearly suffer from shortcomings, especially for real options ”in” projects, which is the main topic in this thesis. However, fortunately, Monte Carlo simulation has shown great applicability to solve more complex path-dependent problems, such as real options ”in” projects (Pettersen and Erikstad, 2017; Rehn et al., 2018).

Monte Carlo simulation was introduced by Metropolis and Ulam (1949) as a method to utilise computer simulation to examine probabilistic outcomes in uncertain environments. Since that time, the method has become one of the most used methods to approximate numerical solutions for problems that are hard to solve analytically. In more simple words, an Monte Carlo simulation tries to seek an answer to the question: *”what is the expected outcome distribution given known systematic uncertainties?”* (Rader et al., 2010).

In Figure 4.2 below, the general Monte Carlo simulation process is described.

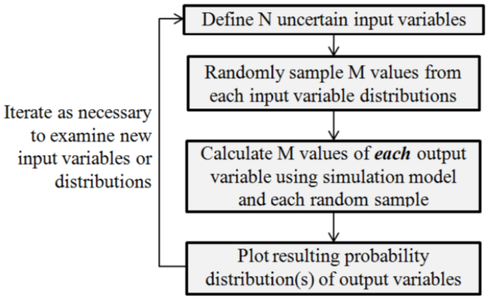


Figure 4.2: The Monte Carlo simulation process (Rader et al., 2010)

By following the process described in Figure 4.2, the Monte Carlo simulation method transforms distributions of uncertain input variables into a performance distribution for a system or a design. The performance of a design in the context of real option valuation is usually monetary. Hence, a typical measure used is the NPV.

Monte Carlo simulation provides a flexible method for valuing complex real options for which analytical methods are either difficult or impossible to use. According to de Neufville and Scholtes (2011) is Monte Carlo simulation the preferable real options analysis methodology for valuing flexibility in engineering design.

4.3.1 Target Curves

As mentioned above, Monte Carlo simulation transforms distributions of uncertain inputs into a performance distribution of a system or a design. Thus, a typical way of representing the performance distribution is through target curves or the cumulative probability distribution (in finance, this curve is often known as the *Value-at-Risk* curve) as illustrated in Figure 4.3.

In target curves, it is common practice to indicate the average value or expected value of the distribution as a vertical line on the graph, which for an NPV valuation refers to the Expected Net Present Value (ENPV) (de Neufville and Scholtes, 2011). Which is simply the average of the NPV's from all simulation rounds, and represents the average value of the project.

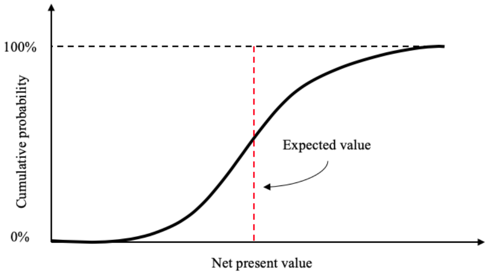


Figure 4.3: Target curve or cumulative distribution curve

If the target curve presents both negative and positive NPV values, then the target curve shows both the upsides and the downsides of the investment. Thus, give the decision maker better insight into the risk associated with the investment. For example, if project A has both a higher ENPV and a target curve that are crossing the vertical zero NPV line below the target line for project B. Then, it can be argued that project A, generally, is a more safe and most likely a more preferable investment decision than project B (de Neufville and Scholtes, 2011). The example is illustrated in Figure 4.4 below.

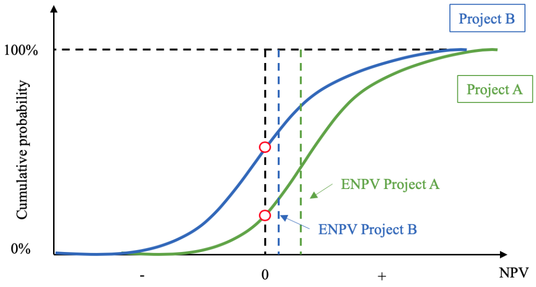


Figure 4.4: Example of how target curves illustrates risk

4.3.2 Valuing Flexibility

To value flexibility in design, the expected value of the flexible design can be subtracted with the expected value of the inflexible design, as presented in Equation 4.3.1 below (Hassan et al., 2005).

$$\text{Value of flexibility} = E(NPV)_{flexible} - E(NPV)_{inflexible} \tag{4.3.1}$$

Additionally, the value of flexibility can be presented by including the cumulative NPV plot for both the inflexible design and the flexible design in the same target curve plot, similar to what is shown in Figure 4.4 above.

4.3.3 Decision Rules

Monte Carlo simulation, as a methodology, permits easy implementation of decision rules (or triggering rules) for the exercise of options. By using, ”IF”, ”ELSE” and ”THEN” programming statements, the simulation model can act as the management team would have done in a real-world scenario. For example, ”IF”: Zero-emission zones are introduced in the area where the ship operates, ”THEN”: Exercise the retrofit-option to fulfil this regulation, ”ELSE”: sell the ship. The decision of selecting the retrofit or the sell option is then based on a decision rule decided by the management of the ship. For example, the decision rule could have been to exercise the option that maximises the future NPV value for the rest of the operating life of the ship.

Monte Carlo simulation as a method makes the implementation of decision rules much more simple and straightforward, compared to analytical solutions and the binomial option pricing method (Knight and Singer, 2012). Besides, various decision rules can be tested in the Monte Carlo simulation, which makes it possible to test different management strategies.

4.4 Other Aspects to Consider When Valuing Flexibility

4.4.1 Discount Rate

In an NPV valuation of a project, a discount rate is needed to discount the cash flow from future value to the present value. The question is then, what should this discount rate be? The discount rate is highly company-specific (Rehn et al., 2018), and can, for example, be based on the return that the investor expects on his/her investment or the cost of borrowing the money. For example, if shareholders expect a 10% return, then that rate can be used as the discount rate for calculating the NPV. On the other side, if the firm pays 4% interest on its debt, this may be the discount rate used to calculate the NPV of the project.

For a project with a lot of risk, a higher discount rate will be used, as more payback are required for riskier investments. In the case of higher discount rates, the value of flexibility is lower, as the future profits will have a smaller contribution to the overall cash flow for the project through its lifetime. Generally, high discount rates make short-term cash flows more valuable, and long-term cash flows less valuable. Thus, projects with high discount rates will prefer to have lower initial costs. Discount rates are often a typical parameter being tested in a sensitivity analysis.

4.4.2 Sensitivity Analysis

A sensitivity analysis is a test of the robustness of the results, and how much the results depend on the assumptions made in the modelling. By de Neufville and Scholtes (2011) the importance of sensitivity analysis is specified, however, they also point out that: *Assessment of uncertainty is also uncertain*. Performing a sensitivity analysis is a part of good practice, and all analyses should incorporate this.

A critical question for a designer to ask is: Would reasonable changes in our assumptions lead us to change our preferred design? If a specific design A is less sensitive to the assumptions made, compared to design B, then the designer can be more confident that design A is the best design to select. However, in the opposite case, where both designs depend greatly on the assumptions made, then the designer will have to be more careful in his/her design conclusions.

Chapter 5

Framework for Valuing Flexibility

This chapter presents a generic framework building on epoch-era analysis and real options analysis with Monte Carlo simulation for valuing flexibility in ship design. The framework uses a step-wise approach, and the methods used within step 2-6 have been outlined in more detail in previous chapters. Numerous papers have been used as inspiration to build this framework, where Rehn et al. (2018) and Pettersen and Erikstad (2017) are the most important ones. The framework strives to be as generic as possible, and it intends to assist decision makers for all types of ships. Figure 5.1 illustrates the step-wise framework.

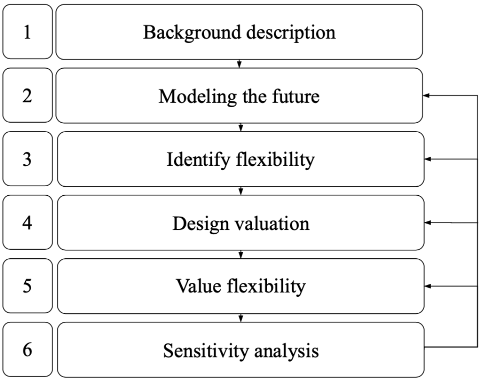


Figure 5.1: The flexibility valuation framework

In the following, each step in the framework is described in more detail.

Step 1: Background description

The first step in the process for valuing flexibility in ship design is to understand the problem and to set the boundaries. Central questions often asked at this step are: What kind of ship(s) and shipping segment are analysed? What kind of needs and requirements does this ship have (e.g. power generation, space, etc.)? Does the decision maker have any specific preferences? etc. This step is all about creating communication between the decision maker and the analyst, and for the analyst to better understand the situation.

Step 2: Modelling the future

The method used for modelling the future in this framework is epoch-era analysis. This method is more thoroughly elaborated in Chapter 3.2 and involves selecting epoch variables and building eras. Several methods exist for identifying epoch variables, and for building eras (or future scenarios). To identify epoch variables, both brainstorming and dialogue with subject matter experts are feasible options. Eras are built based on the epochs and can be generated either through a narrative approach, or randomly through a simulation model by following a set of conditions set by the analyst.

Step 3: Identify flexibility

To have a systematic approach for identifying where flexibility can be introduced in the system is important. Some of the methods that can be used for identifying flexibility in engineering systems are mentioned in Section 2.6. Furthermore, which of the methods that will be the most favourable will be highly case-specific.

Step 4: Design valuation

In this step, each ship design is valued in each era. Different methods can be used for valuing projects, as described in Section 2.5. The one selected to be investigated in more detail in this thesis is the NPV method. However, also, other methods could have been used. Thus, which of the valuation methods the decision maker want to use in the flexibility analysis could be a typical question to ask in *Step 1: Background description*.

The next step for valuing the designs are then to develop a simulation model within an appropriate software tool, which is used to generate cash flows for each ship design in each era (assuming that the NPV method is used). The simulation model is built based on the preferences of the decision maker. An example of a preference that is important for the analyst developing the simulation model to be aware of, is the *decision rule(s)*, which has been described in Section 4.3. It is in this step also important to select where the stochastic element(s) (or random element) should be introduced in the simulation model.

Step 5: Value flexibility

This step has a strong connection to the previous step, as the values generated from *Step 4: Design valuation* are used to estimate the values of flexibility in this step.

This flexibility valuation framework uses Monte Carlo simulations for valuing flexibility. Hence, the value of flexibility can be presented in various ways, e.g. through target curves or by the ENPV, as described in Section 4.3. The key is that the value (or performance) of the baseline ship (inflexible ship) has to be used as a baseline in order to obtain a value of the flexibility introduced in the flexible ship design(s).

Step 6: Sensitivity analysis

The final step of the flexibility valuation framework is a sensitivity analysis. This sensitivity analysis aims to see how the performance of the flexible and the inflexible ship designs varies by varying the input to the calculation. Furthermore, to test the value robustness of the flexible designs. Parameters with high uncertainty, are usually tested in a sensitivity analysis.

Chapter 6

Environmental Regulations in Shipping

In 2015, 195 of the world's nations signed the Paris Agreement, and by that committed to implement actions for preventing the global temperature from exceeding 2°C compared to pre-industrial levels, and to pursue efforts to limit the temperature even further to 1.5°C (UN, 2015). International shipping was not included in the Paris Agreement, but the International Maritime Organisation (IMO), as the regulatory body for the industry, is committed to implement actions for reducing greenhouse gas emissions from international shipping (IMO, 2020).

International shipping currently accounts for about 2-3% of global greenhouse gas emissions. It also contributes significantly to emissions of nitrogen oxides (NO_x), sulphur oxides (SO_x) and particulate matter (PM) close to shore or to coastal communities, impacting on the environment and human health (e.g. Endresen et al., 2003; Corbett et al., 2007; OECD, 2011; Winebrake et al., 2009; Sofiev et al., 2018).

In this chapter, a general introduction to environmental regulations in shipping is provided.

6.1 Environmental Regulations

By nature, the maritime industry is international, regulations and standards should, therefore, be agreed, adopted and implemented on an international basis. The IMO is the forum, on behalf of the United Nations (UN), taking care of this process (IMO, 2019).

The process of introducing new regulations in the IMO is relatively slow and involves normally the following steps: Identification of an area of concern, development of rules, adoption of rules, ratification of rules and entry into force (Svensen, 2019). As a result of the slowness in the IMO and an increasing focus on emissions from the world's nations, environmental regulations are also being introduced on regional (EU etc.) and local levels (national level, ports etc.). In Figure 6.1, a bottom-up presentation of actors influencing the environmental regulatory framework in shipping is illustrated.

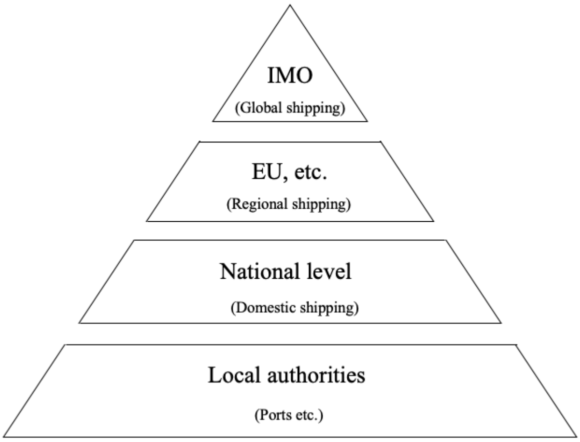


Figure 6.1: Levels of environmental regulations

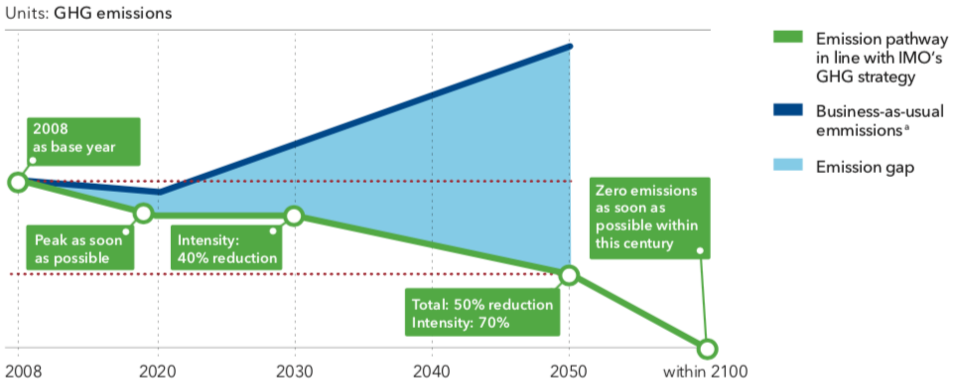
The fact that environmental requirements can be introduced on many different levels, as presented in Figure 6.1, causes much uncertainty for shipowners. In the following subsections, the main types of emissions from shipping, and their corresponding regulatory framework are presented in more detail.

6.1.1 Greenhouse Gas (GHG) Emissions

In April 2018, the IMO adopted an initial strategy for reducing GHG emissions from shipping (IMO, 2018), and is the first time in history that the world's nations have agreed on dramatically to reduce GHG emissions from ships. The GHG strategy from the IMO does more specifically aim to:

- Reduce the GHG emissions from shipping by at least 50% by 2050 compared with the levels in 2008, regardless of maritime trade growth.
- Reduce the average carbon intensity (CO_2 per tonne-mile) by at least 40% by 2030 and 70% in 2050. Meaning that ships need to operate more energy efficient.

Lastly, the ultimate vision of the IMO is to phase out GHG emissions as quickly as possible within this century, meaning going into ”zero-emission” or ”carbon-neutral” concepts. Figure 6.2 illustrates the IMO GHG strategy.



Total: Refers to the absolute amount of GHG emissions from international shipping.
Intensity: Carbon dioxide (CO_2) emitted per tonne-mile.

Figure 6.2: The IMO GHG emission strategy (adopted from (DNV GL, 2018))

GHG emissions are a global problem and expected to be the main challenge for the maritime industry in the next decades to come. Currently, the IMO is discussing which specific measures to introduce to follow up the initial GHG strategy (DNV GL, 2019c). However, at this point, what these measures will include more specifically is still highly uncertain.

The measures can be separated into two horizons, short/mid-term and long-term. In the short/mid-term horizon to 2030, improvements of the already mandatory Energy Efficiency Design Index (EEDI) and Ship Energy Efficiency Management Plan (SEEMP) is expected as potential measures (DNV GL, 2019c). It is also reported that *market-based measures*, as carbon pricing (carbon tax) is being considered. In the long-term perspective to 2050, more radical options are investigated, as requiring carbon-neutral fuels.

The initial GHG strategy adopted in 2018 is going to be revised and updated in 2023 based on information gathered from its *Data Collection System*[1] and from the fourth IMO GHG study (DNV GL, 2018). The fourth IMO GHG study is currently under development and planned to be submitted to the MEPC 76 during autumn 2020.[2]

In general, as pointed out above, the introduction of new regulations by the IMO usually take some time, and it is according to DNV GL (2019c) unlikely that any new regulations related to GHG emissions will be in place before 2023-2025. In the following, the potential short- and mid-term measures from the IMO are described in more detail.

Short/mid-term - Energy-Efficiency Requirements

The energy-efficiency requirements were adopted as amendments to MARPOL Annex VI in 2011 and entered into force 1st of January 2013. Making the Energy Efficiency Design

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[1] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Data-Collection-System.aspx

[2] http://www.imo.org/en/MediaCentre/PressBriefings/Pages/11-MEPC-74-GHG.aspx

Index (EEDI) mandatory for all new ships, and the Ship Energy Efficiency Management Plan (SEEMP) mandatory for all ships (both new and existing).[3]

The EEDI aims to stimulate more efficient ships in general and to establish a minimum efficiency level of new ships depending on ship type and size more specifically. Furthermore, the EEDI levels are to be tightened incrementally every five years. The SEEMP is on the management level of the ship, and includes, for example, improved voyage planning, more frequent cleaning of the hull and the propeller etc.

Another technical measure being considered by the IMO is the Energy Efficiency Existing Ship Index (EEXI)[4], which could require ships in operation to meet a set of energy efficiency requirements. However, at this point in time, the EEXI is still uncertain.

Market-Based Measure - Carbon Price

Carbon pricing is mentioned as a market-based measure that the IMO potentially will introduce for reducing GHG emissions. However, whether carbon pricing is going to be introduced or not, and the size of the carbon pricing if it is introduced, is still uncertain.

Currently, the EU is also considering carbon pricing as a measure for reducing GHG emissions from ships. The European Commission unveiled the new *Green Deal*[5] the 11^{th} of December 2019 describing a roadmap for making the European Union (EU) the first climate-neutral continent. One of the points in this roadmap was a formal intention to re-include shipping into the EU's Emission Trading System (ETS).[6] A system it was removed from in 2017. If this is going to happen or not is still being discussed. However, if it happens, the EU could potentially be the first place in the world where carbon pricing is introduced on ships.

6.1.2 Emission Control Areas (ECAs)

In 2005, the first Emission Control Area (ECA) was introduced by the IMO in the Baltic Sea. Followed by, the North Sea ECA in 2006, the North American ECA in 2012 and the US Caribbean ECA in 2014. ECAs aims to cut emission from ships close to shore in the hope of enhancing human health, by mitigating SO_x emissions, and/or PM and NO_x emissions. In Figure 6.3, a map illustrating the four ECAs is presented. The map also depicts the domestic ECAs in China and the sulphur regulation in EU ports from 2010.

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[3] http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Technical-and-Operational-Measures.aspx

[4] http://www.imo.org/en/MediaCentre/PressBriefings/Pages/26-ISWG-GHG.aspx

[5] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal

[6] https://www.hellenicshippingnews.com/european-commission-green-deal-includes-maritime-in-emissions-trading-system/

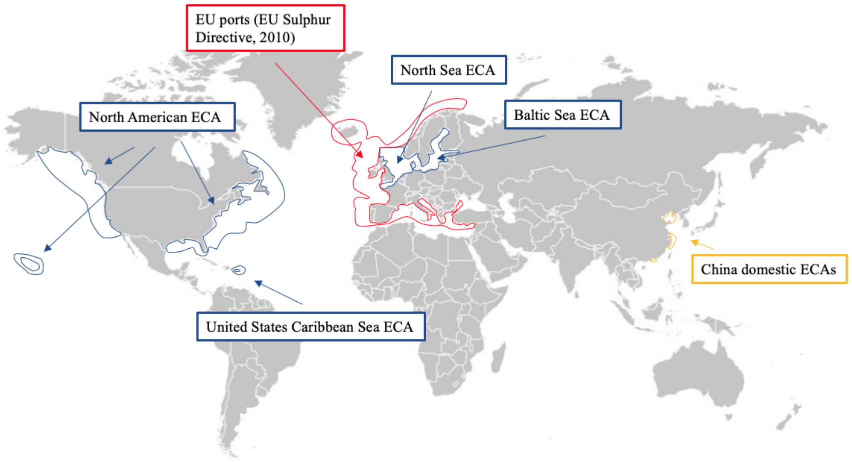

Figure 6.3: Map showing the four ECAs (introduced through IMO), the EU port sulphur regulation and the domestic ECAs in China (not introduced through IMO)

Through the years, the emission limits within the ECAs have gradually become stricter, and it has also been discussed whether more ECAs should be established. In the following, the emission limits for NO_x, SO_x and PM both globally and in the ECAs are described in more detail.

6.1.3 SO_x Emissions

Sulphur oxide (SO_x) emissions from shipping are regulated both regionally and globally. In Table 6.1, the current SO_x emission limits for ships are presented.

Table 6.1: SO_x emission requirements on global and local levels (DNV GL, 2018; DieselNet, 2019)

Area	Sulphur limit [m/m]	Scrubber allowed?
Globally	0.5%	Yes
ECA	0.1%	Open-loop restrictions in certain areas
EU ports	0.1% in selected areas	Open-loop restrictions in certain areas
ECAs in China[a]	0.5% (0.1% in inland waterways)	Only closed-loop
California	0.1% within 24 nm	No, only through research exemption

[a] In 2022, parts of the ECA will go down to a 0.1% sulphur limit.

As Figure 6.1 shows, restricts certain ports and areas the use of open-loop scrubbers.

6.1.4 NO_x Emissions

Nitrogen oxide (NO_x) emissions are regulated both on a global and a regional level. In Table 6.2, the different NO_x IMO Tier phases are shown. Note that the IMO NO_x regulations apply to ships based on their construction date, and the rated speed of the engine decides the emission limit inside each tier.

Table 6.2: Description of the requirements set out in the MARPOL Annex VI regulation 13 describing allowable NO_x emissions in g/kWh in the different IMO NO_x tier phases (MEPC, 2008)

Tier	**Ship construction date on or after**	**Total weight cycle emissions limit (g/kWh)** n = engine's rated speed (rpm)		
		$n < 130$	n = 130 - 1999	$n \geq 2000$
I	1 January 2000	17.0	$45 \times n^{-0.2}$ e.g. 720 rpm - 12.1	9.8
II	1 January 2011	14.4	$44 \times n^{-0.23}$ e.g. 720 rpm - 9.7	7.7
III[a]	1 January 2016/2021	3.4	$9 \times n^{-0.2}$ e.g. 720 rpm - 2.4	2.0

[a] Only applied to ships operating in ECA zones.

The Tier III regulation only applies to vessels operating in the ECAs:

- The North-American ECA for ships constructed after 1st of January 2016.
- The United States Caribbean Sea ECA for ships constructed after 1st of January 2016.
- The Baltic Sea ECA for ships constructed after 1st of January 2021.
- The North Sea ECA for ships constructed after 1st of January 2021.

6.2 Port Incentives - Environmental Port Index (EPI)

Port-based incentives are an example of market-based measures to promote more environmentally friendly ships, by differentiating port fees based on vessels' environmental performance. Today, several such schemes are in use, where the Environmental Shipping Index (ESI) is the dominating method (Bragadin and Pititto, 2017) (see Appendix A for a map showing port-based incentives in EU ports).

A more novel method for measuring ships environmental performance in port, compared to the ESI, is the Environmental Port Index (EPI).[7] The EPI uses actual fuel consumption

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[7] https://www.dnvgl.com/maritime/green-shipping-programme/GSPPilotProject.html

for each port calls, thus different from the other port fee systems. The EPI has since 2017 been developed in Norwegian cruise ports together with DNV GL and aims to support sustainable and eco-friendly cruise ships. The EPI is initially targeted to the cruise industry, but will later also include other classes of ships.

Based on the environmental performance of the cruise ship during its time in port an EPI score is calculated, ranging from 0 (lowest) to 100 (highest). This score is then used to calculate the fee the cruise ship has to pay for its visit in the port. If the EPI score is high, the cruise ship will get a discharge on its port fee, whereas if the EPI score is low, the port fee is increased. A cruise ship can, therefore, based on the EPI score, either be penalised or rewarded.

6.3 Environmental Regulations Towards 2030

The future is inherently uncertain, and it is difficult to predict new regulations for the years to come. Questions like: What will the IMO implement as measures to mitigate GHG emissions from ships after 2023? What will the EEXI include? Will market-based measures like carbon pricing be introduced on a global basis? Will shipping in the EU be included in the ETS, making carbon pricing initially a local phenomenon? Furthermore, how many ports will include intensives as the EPI to support eco-friendly ships? There is currently a lot of unanswered questions. However, what we can be sure about is that new environmental regulations will come. In Figure 6.4, an overview of potential environmental regulations towards 2030 is presented.

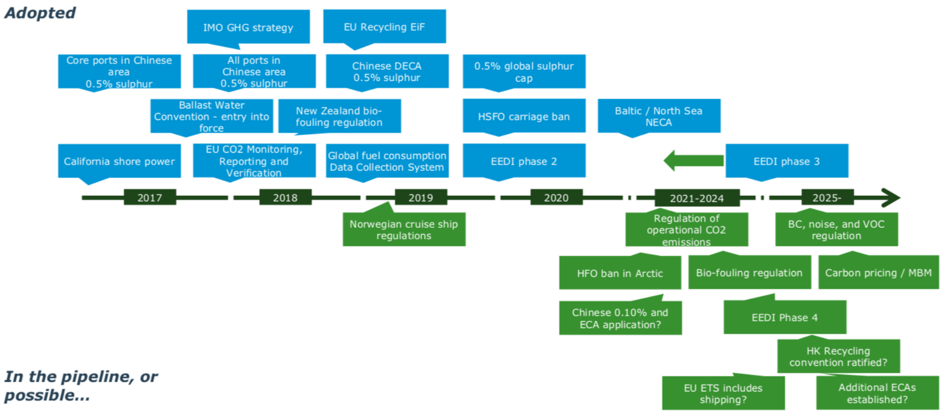

Figure 6.4: Possible future environmental regulations in shipping. Forecast by Eirik Nyhus - Director, Environment in DNV GL (DNV GL, 2019b)

There are potentially a lot that may occur in the environmental regulatory framework for ships in the coming years, as presented in Figure 6.4. Thus, investing in a ship that is prepared for stricter environmental regulations will potentially have a high value.

To comply with future GHG regulations, new technology and other types of fuels will be required. The next chapter, therefore, aims to provide an introduction to energy converters and alternative fuels with the potential of delivering low- and zero-emission solutions for deep-sea shipping.

Chapter 7

Technology for Ships - Energy Converters and Fuels

Over the last decades, Heavy Fuel Oil (HFO) has been the favourable fuel to select when designing a new ship, due to several reasons as its low cost, high energy density and global availability. However, HFO has on main disadvantage, as it creates high global and local emissions. The pressure on shipping to operate more environmentally friendly has never been higher, and the IMO is now preparing specific measures for reducing GHG emissions, as described in Chapter 6. Thus, to comply with future environmental regulations, both innovative energy converters and new types of fuels will be required on ships (Lloyd's Register and UMAS, 2020).

In this chapter, an overview of flexible maritime energy converters and alternative fuels with the potential of being low- and zero-emission solutions for deep-sea shipping is presented.

7.1 Maritime Energy Converters

Energy converters for shipping include internal combustion engines, gas turbines, maritime fuel cells, electric motors and nuclear reactors. In this thesis, it was determined to focus on internal combustion engines and maritime fuel cells, as these have the potential of reducing emissions and to provide flexibility for deep-sea operating ships in general, and cruise ships more specifically.

7.1.1 Internal Combustion Engines

The Internal Combustion Engine (ICE) is a well-known technology for converting chemical energy in the fuel into mechanical power and is today by far the most used energy convert for ships. Marine ICEs are typically grouped into three categories, based on their number of strokes to complete one power cycle and the speed of the crankshaft (DNV GL, 2019a):

- **Slow-speed engines (80-140 RPM):** 2-stroke engines used for propulsion in large vessels.
- **Medium-speed engines (300-900 RPM):** Normally four-stroke engines applicable to be used both for propulsion and auxiliary. Can be used to a wide range of ship types.
- **High-speed engines (>900 RPM):** Four-stroke engines used for propulsion on smaller vessels and high-speed vessels. Additionally, used for auxiliary power purposes.

Two types of mechanisms exist for creating combustion in the cylinder chamber: spark-ignition (SI) (otto-cycle) and compression-ignition (CI) (diesel-cycle). Further on, which of the mechanisms that are used is determined by the properties of the fuels.

One ICE system that has experienced increasing popularity during recent years is the dual fuel engine. The dual fuel engine provides flexibility, and described in more detail in the following.

Maritime Dual Fuel Engines

A dual fuel engine is a diesel engine that can run on both gaseous and liquid fuels (Escudier and Atkins, 2019). The gaseous fuel is usually LNG, while the liquid fuels are typically HFO, Marine Diesel Oil (MDO) or liquid biofuels (e.g. Hydrogenated Vegetable Oil (HVO)). The main advantage of the dual fuel engine is that it enables ships to comply with requirements in ECA zones by running in gas mode on LNG, while for the rest of the time to select fuels based on availability and price. Wärtsilä reports that the switching between fuels are made seamlessly in dual fuel engines, and without loss in power or speed (Wartsila, 2020). Thus, a dual fuel engine both facilitate flexibility and enhance environmental performance.

Selecting an LNG dual fuel engine for the design will also create flexibility for the future, as the ship potentially can run on zero-carbon or carbon-neutral fuels as electrofuels (e.g. e-diesel and e-methane), Liquefied Biogas (LBG), hydrogen and ammonia when these are available. The electrofuels and LBG can be used as drop-in fuels in the engine system. Hydrogen and ammonia, on the other side, will most likely require more modifications/rebuilding of the engine, fuel supply system and storage tanks (DNV GL, 2019c). Designing ships with LNG dual fuel engine systems will, therefore, enable shipowners to prepare for the future, and to create a more future-proof ship design (DNV GL, 2018; DNV GL, 2019c).

7.1.2 Maritime Fuel Cells

Fuel cells are considered to be one of the most promising future technologies for power generation on ships (van Biert et al., 2016). A fuel cell converts the chemical energy of the fuel into electrical energy through electrochemical reactions. Different types of fuel cells are available, and their name is reflected by the materials used in the electrolyte membrane (DNV GL, 2019a). The two fuel cells types that have been identified as most promising for maritime application are the Proton Exchange Membrane Fuel Cells (PEMFC) and the Solid Oxide Fuel Cells (SOFC) (DNV GL, 2017; Battelle Memorial Institute, 2016; E4tech, 2019; de Vries, 2019). These are, therefore, the fuel cell types that are further described in this thesis.

Proton Exchange Membrane Fuel Cell (PEMFC)

The Proton Exchange Membrane Fuel Cell (PEMFC) is today the most commercialised fuel cell type, and multiple fuel cell driven ships have already taken this technology into use (Kim et al., 2020). PEMFCs can only use high purity hydrogen (MariGreen, 2018). Hence, if ammonia shall be applied in a PEMFC, cracking and purification are required (de Vries, 2019). The electrical efficiency of the PEMFC system is reported to be in the range of 50-60%, and the excess heat is to low for making heat recovery feasible. Hydrogen used in a PEMFC provide zero-emission power generation.

The PEMFC system is also produced as a high-temperature alternative and is called High-Temperature PEMFC (HT-PEMFC). This system is less sensitive to poisoning by carbon monoxide and sulphur compared to the conventional PEMFC system and operates at temperatures up to 200°C (DNV GL, 2019c). The material requirements are therefore higher for the HT-PEMFC, compared to the PEMFC as it operates at higher temperatures. The electrical efficiency of the HT-PEMFC is usually slightly higher or equal to the PEMFC, and the overall system efficiency of the HT-PEMFC can be increased by using heat recovery. However, the technological maturity of the HT-PEMFC is still significantly lower than for the PEMFC.

Solid Oxide Fuel Cell (SOFC)

The Solid Oxide Fuel Cell (SOFC) technology has less experience of being used on ships compared to the PEMFC technology. However, even though SOFC has fewer applications in the maritime industry, the SOFC technology can be characterised as mature (Baldi et al., 2019). SOFCs have a higher efficiency than PEMFCs, and able to achieve electrical efficiencies beyond 60%. Another key advantage of the SOFC compared to the PEMFC is that ammonia can be used directly without the need for cracking and purification (de Vries, 2019). The SOFC technology is more flexible when it comes to fuels, compared to the PEMFC technology, and able to run on H_2, LNG, MGO, methanol, and biofuels (biodiesel and biogas) (DNV GL, 2019c).

The SOFC technology does, however, also have some shortcomings. Both cost and the system volume for the SOFC technology is significantly higher compared to PEMFC. Furthermore, SOFCs struggles to handle load variation during transient operations, as peak loads due to heavy weather e.g. Thus, to overcome the shortcomings of the SOFC technology, several papers have investigated the option of combining SOFCs with PEMFCs and batteries to both lowering the investment cost and to better handle load fluctuations (e.g. Baldi et al., 2019; Kim et al., 2020). An EU sponsored test project is currently under development for testing SOFCs and ammonia on the supply vessel ”Viking Energy”.[1]

In Table 7.1, the expected lifetime and cost estimates for the PEMFC (low-temperature) and SOFC technology are presented.

Table 7.1: Lifetime and cost estimates for fuel cell technology (Kim et al., 2020; IRENA, 2019)

Technology	Equipment cost	Expected life	Life increase[a]	Cost decrease[b]
PEMFC	1000-1500 $/kW	6 years	25%	42%
SOFC	5500 $/kW	5 years	25%	42%

[a] Increased rate after each replacement.
[b] Decreased rate after each replacement.

As can be seen in Table 7.1, the cells in the fuel cell system will have to be replaced after a given set of operating cycles (typically 5-6 years). The cost of this operation is by E4tech (2014), and Brynolf et al. (2018) estimated to be in the range of 50-60% of the initial fuel cell investment cost. This is a significant cost, and it is crucial to be aware of this extra cost when evaluating fuel cells in ship designs. However, Table 7.1, also shows that the fuel cell cost is expected to decrease during the years, resulting most likely in lower cost for cell replacements in the future.

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[1] https://eidesvik.no/news-archive/-article391-330.html

7.2 Alternative Fuels for Ships

In this section, the most promising alternative fuels providing low- and zero-emission solutions for deep-sea shipping are described. For a fuel to be a viable option for deep-sea shipping, it must satisfy a set of requirements, as sufficient: production capacity, bunkering infrastructure, competitive fuel price, environmental performance, energy density, safety etc.

Describing one of the alternative fuels and its performance in each of the requirements specified above could by itself have been a master thesis. It has, therefore, to be emphasised that this section aims to give an *overview* of the most promising alternative fuels for shipping. However, where it is considered important to go in more detail, this has been done.

The alternative fuels considered in this thesis are:

- Liquefied Natural Gas (LNG)
- Liquefied Petroleum Gas (LPG)
- Biofuels (Hydrogenated Vegetable Oil (HVO), Liquefied Biogas (LBG))
- Methanol
- Ammonia
- Hydrogen
- Electrofuels (E-diesel, E-methane)

When evaluating potential fuels for ships, a large number of different parameters needs to be taken into consideration. Therefore, to give a proper overview and systematic representation of the results from this comprehensive study, Table 7.2 is established. In this table, the most critical parameters (or Key Performance Indicators (KPIs)) for each fuel type and its energy converter are given a colour based on its performance in comparison to an ICE running on HFO. In total, five different colours are used, where dark green is very good, and red is very bad.

To establish the qualitative results presented in Table 7.2, recently published studies investigating alternative fuel for ships (e.g. DNV GL, 2019c; DNV GL, 2018; DNV GL, 2019a; DNV GL, 2017; Lloyd's Register and UMAS, 2020; Lloyd's Register, 2017) and expert advice from specialists within low- and zero-emission fuels for ships was used.

Note that the fuels have been categorised within three main *families* of energy sources: fossil-based, bio-based and electro-based.

It has to be emphasised that also other types of alternative fuels and production pathways could have been included in Table 7.2. However, the ones included in the table is considered as the most promising ones for shipping at this point in time (Lloyd's Register and UMAS, 2020). Nuclear-powered ships, for example, are a relevant zero-carbon pathway. However, it is scoped out of this thesis as it still faces significant barriers, especially related to the safety aspect.

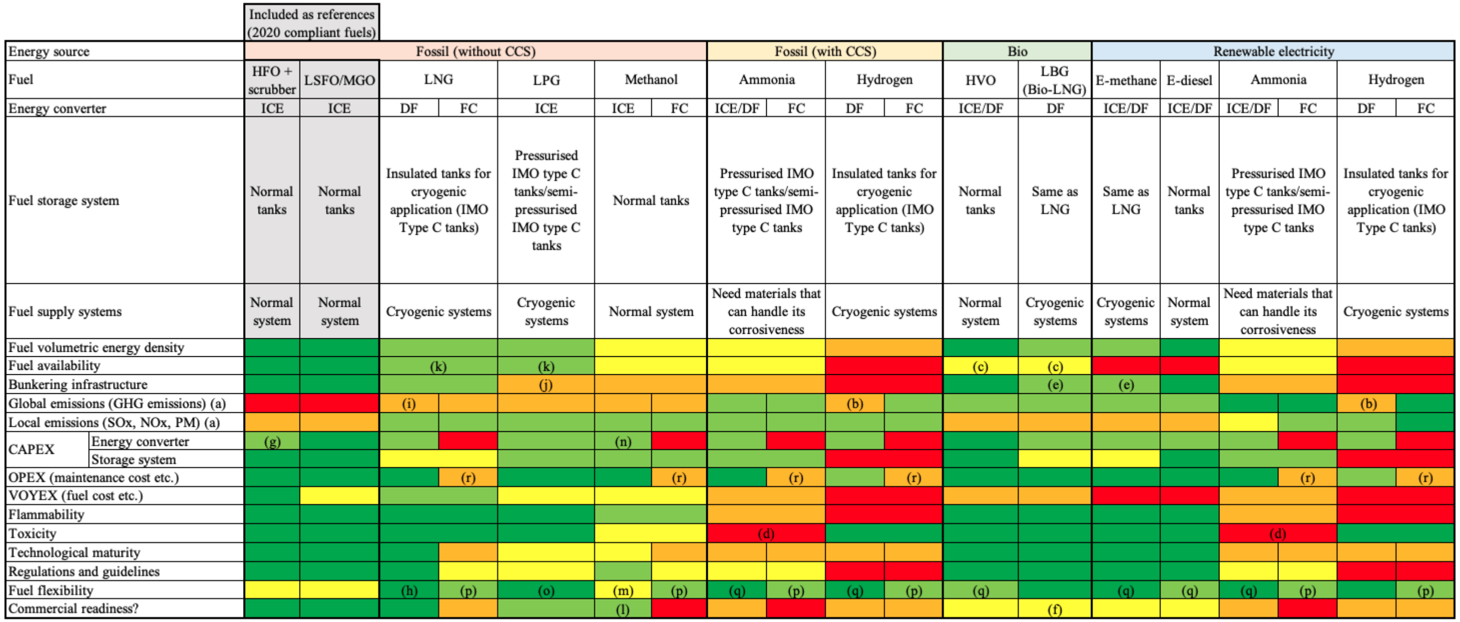

Table 7.2: Alternative fuel comparison table (CCS = Carbon capturing and storage, FC = Fuel cell, ICE = Internal combustion engine, DF = Dual fuel engine) (DNV GL, 2019c; DNV GL, 2018; DNV GL, 2019a; DNV GL, 2017; Lloyd's Register and UMAS, 2020; Lloyd's Register, 2017)

		Included as references (2020 compliant fuels)																		
Energy source		Fossil (without CCS)							Fossil (with CCS)				Bio		Renewable electricity					
Fuel		HFO + scrubber	LSFO/MGO	LNG		LPG	Methanol		Ammonia		Hydrogen		HVO	LBG (Bio-LNG)	E-methane	E-diesel	Ammonia		Hydrogen	
Energy converter		ICE	ICE	DF	FC	ICE	ICE	FC	ICE/DF	FC	DF	FC	ICE/DF	DF	ICE/DF	ICE/DF	ICE/DF	FC	DF	FC
Fuel storage system		Normal tanks	Normal tanks	Insulated tanks for cryogenic application (IMO Type C tanks)		Pressurised IMO type C tanks/semi-pressurised IMO type C tanks	Normal tanks		Pressurised IMO type C tanks/semi-pressurised IMO type C tanks		Insulated tanks for cryogenic application (IMO Type C tanks)		Normal tanks	Same as LNG	Same as LNG	Normal tanks	Pressurised IMO type C tanks/semi-pressurised IMO type C tanks		Insulated tanks for cryogenic application (IMO Type C tanks)	
Fuel supply systems		Normal system	Normal system	Cryogenic systems		Cryogenic systems	Normal system		Need materials that can handle its corrosiveness		Cryogenic systems		Normal system	Cryogenic systems	Cryogenic systems	Normal system	Need materials that can handle its corrosiveness		Cryogenic systems	
Fuel volumetric energy density		🟩	🟩	🟢		🟢	🟨		🟨		🟧		🟩	🟢	🟢	🟩	🟨		🟧	
Fuel availability		🟩	🟩	🟢 (k)		🟢 (k)	🟨		🟨		🟥		🟨 (c)	🟨 (c)	🟥	🟥	🟨		🟥	
Bunkering infrastructure		🟩	🟩	🟢		🟧 (j)	🟧		🟧		🟥		🟩	🟢 (e)	🟢 (e)	🟩	🟧		🟥	
Global emissions (GHG emissions) (a)		🟥	🟥	🟧 (i)	🟧	🟧	🟧	🟧	🟢	🟢	🟧 (b)	🟢	🟢	🟢	🟢	🟢	🟩	🟩	🟧 (b)	🟩
Local emissions (SOx, NOx, PM) (a)		🟧	🟧	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟧	🟧	🟧	🟧	🟨	🟢	🟢	🟩
CAPEX	Energy converter	🟢 (g)	🟩	🟢	🟥	🟢	🟢 (n)	🟥	🟢	🟥	🟢	🟥	🟩	🟢	🟢	🟢	🟢	🟥	🟢	🟥
	Storage system	🟩	🟩	🟨		🟢	🟢	🟢	🟢		🟥		🟩	🟨	🟨	🟩	🟢		🟥	
OPEX (maintenance cost etc.)		🟩	🟩	🟩	🟧 (r)	🟩	🟩	🟧 (r)	🟩	🟧 (r)	🟢	🟧 (r)	🟩	🟩	🟩	🟩	🟩	🟧 (r)	🟢	🟧 (r)
VOYEX (fuel cost etc.)		🟩	🟨	🟢		🟨	🟨		🟧		🟥		🟧	🟧	🟥	🟥	🟧		🟥	
Flammability		🟩	🟩	🟩		🟩	🟢		🟧		🟥		🟩	🟩	🟩	🟩	🟧		🟥	
Toxicity		🟩	🟩	🟩		🟩	🟨		🟥 (d)		🟩		🟩	🟩	🟩	🟩	🟥 (d)		🟩	
Technological maturity		🟩	🟩	🟩	🟧	🟨	🟨	🟧	🟧	🟧	🟧	🟧	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧
Regulations and guidelines		🟩	🟩	🟩	🟨	🟨	🟢	🟨	🟨	🟨	🟥	🟥	🟩	🟩	🟩	🟩	🟨	🟨	🟥	🟥
Fuel flexibility		🟨	🟨	🟩 (h)	🟢 (p)	🟩 (o)	🟨 (m)	🟢 (p)	🟩 (q)	🟢 (p)	🟩 (q)	🟢 (p)	🟢 (q)	🟩	🟩 (q)	🟢 (q)	🟩 (q)	🟢 (p)	🟩	🟢 (p)
Commercial readiness?		🟩	🟩	🟩	🟧	🟢	🟢 (l)	🟥	🟧	🟥	🟧	🟧	🟨	🟨 (f)	🟨	🟨	🟧	🟥	🟧	🟧

(a) Life cycle perspective (well-to-wake). (b) Will be blended with other conventional fuels. (c) Currently produced in limited amounts. (d) Ammonia is toxic, creating safety concerns with the fuel. (e) Can use the same bunkering infrastructure as LNG. (f) "Hurtigruten" was the first company to sign a long-term contract (2019) for large volume of LBG supply to their cruise vessels (Kystruten Bergen - Kirkenes) (g) Because of the scrubber. (h) Provide fuel flexibility both to liquid fuels and gas fuels (Can potentially use both hydrogen or ammonia, however, retrofit will be needed). (i) Reported to reduce CO2 emission with around 20% compared to HFO. (j) The bunkering infrastructure is still a barrier for LPG as a marine fuel. (k) The fuel production is large enough to cover shipping. (l) Methanol as an alternative fuel have recently been forecasted a limited uptake as an alternative fuel for shipping (DNV GL, 2019a). (m) Methanol in an ICE provide limited fuel flexibility. (n) Mainly two-stroke engines in operation. (o) Can be a bridging technology to ammonia, as LPG and ammonia requires much of the same systems (storage etc.) (p) Will provide flexibility especially if the SOFC technology is used. (q) If dual fuel engines are used (this will also be dependent on the fuel storage system and the fuel supply system installed on board the ship). (r) The cells need to be replaced approximately every 5-6 years, creating high costs.

In the following, some of the elements in Table 7.2 are described in more detail.

Energy Source

Many of the alternative fuels can be produced through several different sources. Ammonia and hydrogen, for example, can either be produced sustainable through an electrolysis process with renewable electricity or from natural gas (with Carbon Capturing and Storage (CCS)). Today, the latter option without CCS is the main production path for ammonia and hydrogen, as this is a cheaper production method and natural gas is generally readily available. Note that CCS will not ensure that 100% of the CO_2 emissions are captured (Lloyd's Register and UMAS, 2020). Hence, only the renewable electricity pathway will make ammonia and hydrogen 100% zero-carbon fuels in an LCA point of view.

Hydrogen has generally an important role for alternative fuels, as it can form the basis for various electrofuels. Electrofuels is an umbrella term for synthetic fuels such as diesel, methane and methanol when they are produced from H_2 and CO_2 (carbon-based fuels), or ammonia produced from H_2 and nitrogen (nitrogen-based fuels), using renewable electricity for the production. Electrofuels have a high potential of reducing GHG emissions but suffers currently from high costs and extensive energy requirements.

Fuel Availability

A shipowner will only invest in technology and fuels that are available at the time the ship is delivered. Consequently, for a fuel to be a viable option, it has to be produced in sufficient amounts, and the required infrastructure for the fuel must exist where the ship operates (DNV GL, 2019c). Today, LNG and LPG are the only alternative fuels that are produced in sufficient amounts to cover the accumulated energy requirement for the entire shipping industry (DNV GL, 2019a). Furthermore, for all of the alternative fuels mentioned in this thesis, the production capacity and/or the bunkering infrastructure for ships is still a barrier (DNV GL, 2019a).

For example, e-diesel and e-methane, are currently only produced in minimal amounts and mostly on a pilot-scale (Heyne et al., 2019). However, the infrastructure is not considered as a boundary for e-diesel and e-methane, as it is assumed that they can be used in existing diesel and LNG infrastructure (DNV GL, 2019a). Other fuels with the potential of being used in existing infrastructure are HVO and LBG.

Global/Local Emissions

In the coming years, it is expected that the IMO will have an increased focus on upstream emissions from fuels, and not only emissions from a tank-to-wake point of view. Hence, providing Life Cycle Assessments (LCA) when evaluating fuels is likely to be more important in the years to come. An LCA, well-to-wake, approach was because of this applied in Table 7.2.

For biofuels does the life cycle emissions greatly depends on the feedstock used to produce the fuel, there is, for example, a massive difference in emissions between palm oil and forest materials. Few studies have so far been conducted on assessing the environmental impacts of electrofuels (Brynolf et al., 2018). However, what is clear is that for carbon-based electrofuels to have a climate benefit, the CO_2 must come from CCS (Brynolf et al., 2018). For ammonia and hydrogen to have a climate benefit, they should be produced from natural gas with CCS, or but even more preferably through an electrolysis process using renewable electricity.

As precised in Chapter 6, the IMO aims to go into zero-emission or carbon-neutral solutions as quickly as possible. The question is then, which of the solutions presented in Table 7.2 are able to comply with either one or both of these requirements? The answer is presented in Table 7.3, where 1 is used for 100% zero-emission compliance, and 2 is used for either zero-carbon or carbon-neutral compliance. Note that the emissions are in a tank-to-wake point of view.

Table 7.3: Overview of zero-emission and carbon-neutral or zero-carbon solutions of the options presented in Table 7.2 (inspired by (DNV GL, 2020)))

Fuel type	Energy converter	Category	Comment
Hydrogen	Fuel cell	1,2	100% zero-emission operation.
Hydrogen	Combustion engine	2	Emission of NO_x, PM and smoke.[a]
Ammonia	Fuel cell	1,2	100% zero-emission operation.
Ammonia	Combustion engine	2	Emission of NO_x, PM and smoke.[a]
HVO	Combustion engine	2	Emission of NO_x, PM and smoke.
LBG	Combustion engine	2	Emission of NO_x, PM and smoke.
E-methane	Combustion engine	2	Emission of NO_x, PM and smoke.
E-diesel	Combustion engine	2	Emission of NO_x, PM and smoke.

[a] The emissions of PM and visual smoke will be low.

Fuel Storage System

Most of the alternative fuels considered in this thesis have different characteristics, hence creating different requirements to the engine system, fuel storage system and fuel supply system. Ammonia as an example is corrosive to copper, copper alloys, nickel and plastics, these materials should because of this be avoided in an ammonia system (DNV GL, 2019a). LNG as another example requires insulated tanks for cryogenic application as it needs to be stored at a temperature lower than -162°C, whereas liquefied hydrogen has to be stored at a temperature of -253°C. Both LBG and e-methane are expected to have more or less the same characteristics as LNG, thus will require an LNG storage system. In Table 7.4 below, an overview of the characteristics of the different fuels is presented.

Table 7.4: Overview of characteristics for the different fuels (DNV GL, 2019a; Kim et al., 2020)

	HFO	LNG	Methanol	LPG	LBG (a)	HVO	E-diesel (b)	E-methane	Liquid Ammonia	Liquid hydrogen
Volumetric energy density [MJ/l]	36	22	14	24	22	32	34	22	12	10
Gravimetric energy density [MJ/kg]	42	49	20	47	49	37	43	55	18	120
Boiling point [°C]	700	-162	64.7	-42	-162	313	700	-162	-33	-253
Flash point [°C]	60	-188	11-12	-104	-188	>61	60	-188	132	Not defined
Autoignition temperature [°C]	250	537	47	410-580	537	204	250	537	650-657	500-577
Flammability limits (volume % in air)	6.3-12.3	4-15	6.7-36	1.8-10.1	4-15	0.6-7.5	6.3-12.3	4-15	15-28	4-74.2

(a) LBG and E-methane is assumed to have the same caracteristics as LNG.
(b) E-diesel is assumed to have much of the same characteristics as HFO.

Fuel Flexibility

At this moment in time, no-one can with certainty say which of the alternative fuels that will become the most preferable option for shipping (DNV GL, 2019c). Investing in a ship design that provides fuel flexibility can due to this be of high value and reduce risk. This could include investing in dual fuel solutions and/or fuel ”ready” solutions which prepares the ship for a future retrofit, by laying the groundwork when the ship is initially designed and constructed.

The main obstacle for a system to use different fuels are often related to the storage system and not the engine system (DNV GL, 2019c). The reason for this is that it usually is much easier to rebuild an engine on board a ship, compared to installing heavier and larger storage tanks. An LNG fuelled ship using dual fuel engines will because of this have a huge potential for fuel flexibility as it can handle both cryogenic fuels and non-cryogenic fuels. The LNG fuelled ship can then potentially use LBG, HVO, e-methane, e-diesel, ammonia or hydrogen in the future when these fuels are available for ships. Some of these fuels will be used as drop-in fuels, whereas ammonia and hydrogen, will require more modifications to the system. Another system that potentially may create flexibility is LPG systems, as LPG is similar to Ammonia (de Vries, 2019).

Today, MAN Diesel & Turbo and Wärtsilä, two of the leading marine engine manufacturers aim to deliver systems that provide as much flexibility as possible.[2] Especially ammonia as a potential zero-carbon fuel in internal combustion engines is of high interest these days and expected to be tested on board ships soon (less than 2-3 years).[3,4]

7.2.1 Fuel Price

Predicting future fuel prices is difficult, even in the short term (DNV GL, 2019c). Many of the fuels presented above have no or little background of being used on ships, due to lack in technology, bunkering infrastructure for ships and/or production capacity, making the

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[2] https://marine.mandieselturbo.com/docs/librariesprovider6/technical-papers/the-man-b-amp-w-duel-fuel-engines-starting-a-new-era-in-shipping

[3] https://www.wartsila.com/media/news/25-03-2020-wartsila-advances-future-fuel-capabilities-with-first-ammonia-tests-2669590

[4] https://www.tu.no/artikler/motorprodusentene-tester-ammoniakk-kan-gi-nullutslippsskip-for-2030/488522

fuel price prediction even harder as we have minimal experience with them. The mechanisms driving the fuel price are many and complex and include, among others, market developments (supply/demand), production costs, distribution costs etc.

In the following, the main drivers for the production costs of the alternative fuels are presented (note that the retail price is included where possible). The main aim of this is to highlight the uncertainties associated with the production costs, and how the fuel price may change in the future. As several of the fuels can be produced from various sources, the fuels are categorised into three subgroups based on their main source: fossil-based, electro-based and bio-based.

Fossil-Based Fuels

The fossil-based fuels under consideration are HFO, LNG, Methanol, LPG, hydrogen from natural gas with CCS (*blue* hydrogen) and ammonia from natural gas with CCS (*blue* ammonia). Today, HFO and LNG are widely used for ships, and their retail price is found to vary between around 200-700 USD/tonne during the years.[5] For fossil methanol, the fuel price is shown to be in the range of 200-400 USD/tonne, and LPG is shown to be in the range of 300-600 USD/tonne during the last five years.[5]

The production cost of *blue* hydrogen and ammonia is mainly influenced by the natural gas price. Today, the production cost of liquefied *blue* hydrogen is estimated to be in the range of 3000-5300 USD/tonne, and for *blue* ammonia in the range of 400-800 USD/tonne (Lloyd's Register and UMAS, 2020). In IRENA (2019) the cost of producing hydrogen from natural gas with CCS is thoroughly investigated and gives a good picture of how the production prices vary based on the natural gas price (see Appendix B).

Electro-Based Fuels

Another production pathway for hydrogen and ammonia is through renewable electricity, in an electrolysis process. When renewable electricity is used for producing hydrogen and ammonia, the fuels are defined as *green*. Hydrogen is as described earlier a basis for different electrofuels, such as e-methane and e-diesel.

The production of carbon-based electrofuels can be divided into individual steps, as: electricity production, electrolysis to produce hydrogen, capturing of CO_2, and fuel synthesis. Brynolf et al. (2018) provide a thorough study of the production cost for electrofuels and is used as the primary source for this section. Based on a literature study, Brynolf et al. (2018) highlight that the most important factors affecting the production cost for all electrofuels are the capital cost of the electrolyser and the electricity price. The production costs for electrofuels are found to vary significantly in the literature. For e-methane, for instance, one study estimates the cost at 150-1500 USD/tonne (Giglio et al., 2015), while another report, a cost of 5200-9800 USD/tonne (De Saint Jean et al., 2015). Brynolf et al. (2018) also provide their own study, trying to estimate the production cost for electrofuels by using a scenario-based approach. In their base case scenario, the production price of e-methane and e-diesel is estimated to be in the range of 2400-2800 USD/tonne in 2015

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[5] https://afi.dnvgl.com/Statistics?repId=4

and 1900-2500 USD/tonne in 2030. Note that distribution costs are not being included in these estimates (Brynolf et al., 2018). In Lloyd's Register and UMAS (2020), the storage and distribution costs are included together with the production cost and estimate that the price of e-diesel will be in the range of 5600-9000 USD/tonne, and for e-methane in the range of 3800-6200 USD/tonne depending on the electricity price. This shows that the production cost of electrofuels is very uncertain.

The factors with the greatest influence on the production cost of *green* hydrogen and ammonia are the electricity cost and the cost of the electrolysers (IRENA, 2019). Today, *blue* hydrogen and ammonia are cheaper than *green* hydrogen and ammonia. However, as electrolysis becomes cheaper and more renewable electricity becomes available, this may potentially change in the future.

In IRENA (2019), the cost of producing hydrogen from renewable electricity is shown to be approximately 2600-6900 USD/tonne (see Appendix B). By also including liquefaction and storage at the port, the price for *green* hydrogen is estimated to lay in the range of 6200-11000 USD/tonne today, depending on the electricity price (Lloyd's Register and UMAS, 2020).

For *Green* ammonia, the production cost is expected to range between 1000-1700 USD/tonne, depending on the electricity price (Lloyd's Register and UMAS, 2020).

Bio-Based Fuels

Price projections for marine biofuels are uncertain, and current literature is poor. To use the approach of estimating the production cost of the biofuels today, and in the future, and use this price as a fuel price estimate is not appropriate as this not accounts for the supply constraints (Lloyd's Register and UMAS, 2020). The availability of sustainable feedstock for biofuels is expected to be limited. Hence, if the production capacity is pushed to the maximum, this could cause a significant increase in the fuel price.

The two bio-based fuels under consideration are the advanced biofuels HVO and LBG. By Brown et al. (2020) it is emphasised that advanced biofuels are more expensive than conventional fossil fuels. The production cost of HVO is reported to be in the range of 600-1000 USD/tonne, and LBG in the range of 400-1300 USD/tonne (Maniatis et al., 2017; Brown et al., 2020). The factors contributing to the production price is capital, operating and feedstock costs. For HVO, for instance, the production costs are dominated by the feedstock costs, which is reported to make up to 65-80% of the production costs. In total, the production costs are reported to potentially be reduced by between 5-27% compared to the current cost estimates (Brown et al., 2020). However, even though the production cost may decrease, Lloyd's Register and UMAS (2020) could not find evidence that the biofuel price was going to decrease in the future, as a result of limited availability. Furthermore, large local differences in production costs are expected.

In Appendix D, a summary table presenting the current estimates of production cost for the different alternative fuels is presented.

Estimating the Future Fuel Price

Based on the production costs of the fuels presented above, and a recently published study by Lloyd's Register and UMAS (2020), the retail fuel price is estimated for the different alternative fuels between 2020 and 2050. The price estimates are shown in Table 7.5 below.

Table 7.5: Summary table presenting estimates of fuel price range between 2020-2050 (DNV GL, 2019a; DNV GL, 2019c; Brynolf et al., 2018; Brown et al., 2020; IRENA, 2019; Lloyd's Register and UMAS, 2020; NCE Maritime CleanTech, 2019)

Energy source	**Fuel types**	**Min-Max**
Fossil	HFO	200 - 700 USD/tonne
	LNG	200 - 700 USD/tonne
	LPG	300 - 600 USD/tonne
	Methanol	200 - 400 USD/tonne
Fossil (CCS)	*Blue* hydrogen	2200 - 5300 USD/tonne
	Blue ammonia	400 - 800 USD/tonne
Bio	HVO	800 - 4000 USD/tonne
	LBG	1100 - 4800 USD/tonne
Renewable electricity	E-methane	2300 - 6000 USD/tonne
	E-diesel	3500 - 9000 USD/tonne
	Green hydrogen	3400 - 11000 USD/tonne
	Green ammonia	500 - 1700 USD/tonne

Table 7.5 shows that the fuel price for each of the fuels is highly uncertain. Thus, having the flexibility to switch between fuels will potentially have a high value for a ship. Furthermore, it has to be emphasised that local variations in the fuel price will be experienced. However, these are not further evaluated in this thesis.

Chapter 8

Case Study - Flexibility in Cruise Ship Design

In this chapter, the flexibility valuation framework presented in Chapter 5 is applied in a realistic case study for investigating the value of flexibility in cruise ship design. Before starting on the case study, a short introduction to the cruise industry and critical environmental requirements for cruise ships are presented. After that, two different cruise ship designs with flexibility are proposed and analysed in the flexibility valuation framework.

8.1 The Cruise Industry

Exploring the world by cruise ships has been popular for decades, and in recent years, the cruise ship industry has been reported as one of the fastest-growing segments in the tourism sector (Sanches et al., 2020). Data from *The Cruise Market Watch* shows a steep increase in the number of passengers travelling with cruise ships, from 3.7 million passengers in 1990 to around 26.9 million in 2019 (Cruise Market Watch, 2020). By Erixon (2018), it is pointed out that there are several possible reasons for this development, where a more globalised economy and the ease of obtaining information from the internet since the 1990s are some of them. In Appendix C, the development of the cruise industry from 1990-2019 is illustrated in a figure.

In the Third IMO GHG Study from 2014, it was reported that 520 cruise ships operated on a global basis, making the cruise industry to account for only 0.6% of all ships in the world shipping fleet (IMO, 2014). Figure 8.1 illustrates the distribution of the number of ships within each ship category in 2014 on a global basis.

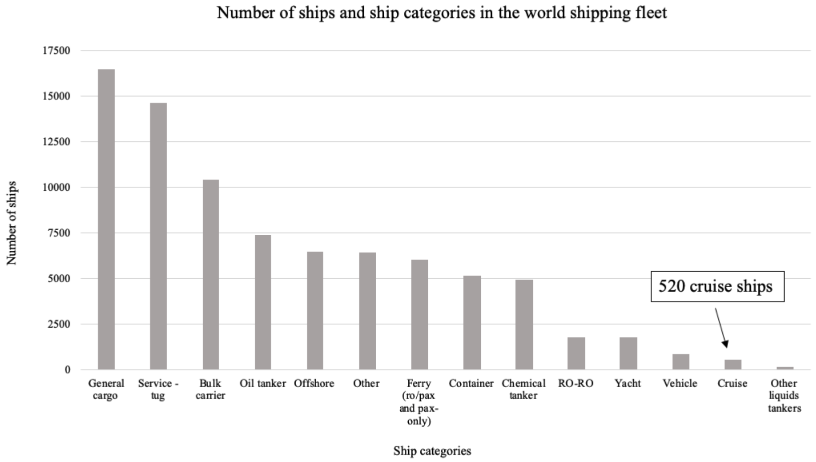

Figure 8.1: Number of cruise ships in the world shipping fleet from the Third IMO GHG Study 2014 (IMO, 2014)

Cruise ships are usually large and require a lot of energy both for propulsion and to run its hotel. Today, most of the cruise ships are running on conventional fossil fuels, causing large global and local emissions. Furthermore, in the Third IMO GHG Study, it was estimated that the world's cruise ship fleet contributed with around 35 million tonne CO_2 on an annual basis, as presented in Figure 8.2. The world's cruise ship fleet contributes, therefore, significantly to global emissions, even though the number of cruise ships on a global basis is fairly low compared to other shipping segments.

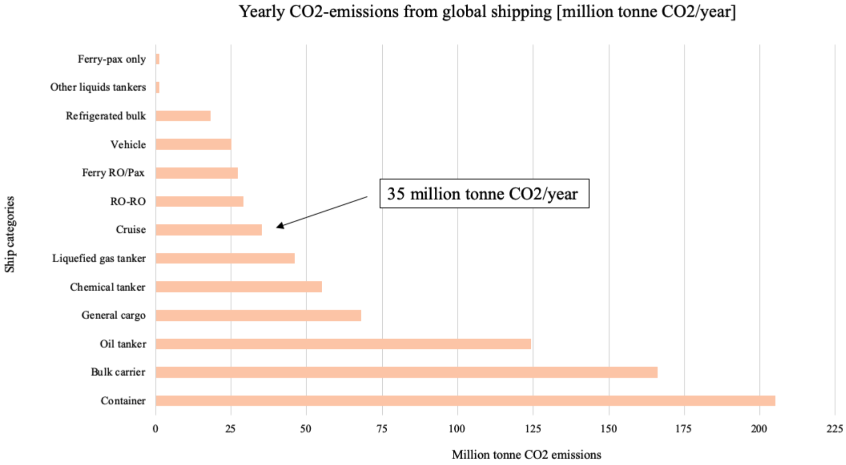

Figure 8.2: Estimate of CO_2-emissions from cruise ships from the Third IMO GHG Study 2014 (IMO, 2014)

Furthermore, as cruise ships operate a lot of its time close to shore and coastal communities, local emissions as NO_x, SO_x and PM are of high concern, as these impacts both the environment and the human health (Mjelde et al., 2019). With the increasing focus on the climate in general and more awareness about cruise ships emissions, the industry is now more than any other shipping segment being pushed to become ”greener” and to pollute less to the air. In the following, based on the topics presented in Chapter 6, the environmental regulations facing the cruise industry more specifically are presented.

Global Regulations - GHG Emissions

Currently, the IMO is discussing specific measure to introduce to follow up the initial GHG strategy, and a Fourth IMO GHG Study is under development for assisting the decisions. However, what these specific measures will include is still highly uncertain. By now, only measures for the short-/mid-term have been mentioned, for example, the EEXI and carbon pricing. However, what the EEXI include, and the actual carbon price is still uncertain. Furthermore, whether the carbon pricing is going to be introduced on a global basis, or locally in, e.g. the EU, is also uncertain.

The IMO's main goal is to phase out fossil fuels as quickly as possible. Thus, a restriction saying that cruise ships only can run on zero-emission or carbon-neutral fuels at a certain point is not unthinkable. Furthermore, what can be a possible scenario, is that cruise ships will be more heavily restricted regarding emissions than what other shipping sectors are, as cruise ships are used for tourism and *travelling for pleasure*.

Local Regulations - NO_x, SO_x and PM Emissions

Cruise ships operate significant portions of its time close to shore and in ports, hence local emissions as NO_x, SO_x and PM are of great concern from cruise ships, and much more than for any of the other shipping segments.

Moreover, cruise ships operate parts of its time within ECAs, which restricts emissions of NO_x, SO_x and PM, and EU ports which restricts SO_x emissions in port. It is also possible, as proposed in Figure 6.4, that more ECAs are being introduced in the coming years, for example, in the Mediterranean.[1]

Local Zero-Emission Areas - The Norwegian World Heritage Fjords

In 2005, the two fjord areas, the Geirangerfjord area and the Nærøyfjord area were inscribed on the UNESCO world heritage list. These fjord areas are popular cruise destinations, and the small village Geiranger is one of the most visited ports in Norway, with over 200 port calls in 2019.[2] As a result of this, the emission levels within the fjord areas have during the cruise season been reported to be too high (Rambøl, 2017), and new local environmental regulations entered into force 1^{st} of March 2019. Moreover, during the years, these regulations are announced to become stricter (Norwegian Maritime Au-

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[1] https://www.argusmedia.com/en/news/1908464-mediterranean-eca-may-be-proposed-next-year-imo

[2] https://www.stranda-hamnevesen.no/cruise-calls

thority, 2019). The environmental regulations for the Norwegian world heritage fjords are specified in Table 8.1 below.

Table 8.1: Environmental regulations in the Norwegian world heritage fjords (Norwegian Maritime Authority, 2019)

Emission type	
SO_x	0.1% (Only closed-loop scrubber/hybrid scrubber in closed mode)
NO_x[a]	Tier I by 1^{st} of January 2020
	Tier II by 1^{st} of January 2022
	Tier III by 1^{st} of January 2025

[a] The ship has to comply independent of its construction date.

Furthermore, from 2026 the Norwegian Parliament have decreed that only zero-emission ships will be allowed entrance into the fjords, making this the first zero-emission zone in the world. Whether the regulation is going to be a 95% zero-emission regulation or 100% zero-emission regulations is still unclear (Roald, 2020; DNV GL, 2020). However, what can be said about this regulation is that it is rigorous and that a radical shift is required for cruise ships to be able to comply with this.

Cruise Ports Pushing for Greener Cruise Ships

Today, around 25% of the large ports around the globe are using port-based environmental incentives to differentiate port fees (Mjelde et al., 2019). Moreover, during the years, this number is expected to increase. In this thesis, the Environmental Port Index (EPI) is in focus, which is a novel port fee differentiating scheme. Cruise ships have many port calls during a year of operation, and the cost from each port call is during the year added up to become a significant portion. Hence, having a cruise ship with low environmental impacts gives a higher EPI score, and consequently a lower port fee.

Other types of port incentives are also considered for driving investment in green technology on cruise ships. These might be local initiatives, as giving booking priority and assigning more attractive docking areas for greener ships (Mjelde et al., 2019). However, these initiatives are not further investigated in this thesis.

Cruise Tourists Pushing for Greener Cruise Ships

Another aspect that also needs to be considered is the increasing emission awareness and climate focus from the cruise tourists. In a telephone correspondence with a cruise expert in DNV GL, it was emphasised that the climate focus from the cruise tourists potentially causes a higher risk for cruise ships to become ”stranded assets”, than environmental regulations introduced by either the IMO or local authorities (Hermundsgård, 2020). It was also highlighted that only reducing the speed (possible measure in the EEXI) would potentially not be enough to comply with the expectations from the cruise tourists. Thus, he emphasised that it is not unlikely that cruise tourists will require zero-emission or zero-carbon operations for cruise ships in the coming years.

8.2 Flexibility Valuation Analysis

The flexibility valuation framework presented in Chapter 5 is now used to investigate the value of designing cruise ships with flexibility to comply with future environmental requirements.

8.2.1 Step 1: Background Description

A decision maker who want to receive an analysis of the value of designing cruise ships with flexibility to comply with future environmental requirements, has the following set of thoughts and preferences:

- Want to design a cruise ship similar to the Celebrity Edge cruise ship delivered in 2018, and owned by The Royal Caribbean Cruise Line.
- Want to operate the cruise ship in at least 30 years, and in the same route as Celebrity Edge (with some extensions). See the map presented in Figure 8.3.
- The decision maker has seen the increasing trend of travelling with cruise ships during the years, and do not think the cruise ship market will be a barrier for the success of the cruise ship designs. Hence, in the analysis, he wants the market to remain good and robust for the next 30 years.
- The decision maker think that cruise ships will be one of the first segments in the shipping industry that will have to comply with zero-emission requirements.
- The decision maker wants to use the NPV method in the flexibility analysis.
- The newbuild cost of the cruise ships should be as low as possible.

The Cruise Ship Route

The Celebrity Edge has since its maiden voyage in December 2018 operated weekly Eastern and Western Caribbean sailings during the winter season, and in the Mediterranean during the summer season.[3] In Figure 8.3, the sailing route for the Celebrity Edge during the 2019 cruise season is illustrated based on AIS data. Note that the ”green” line along the Norwegian coastline is an extension to the initial route sailed by the Celebrity Edge. Hence, the cruise ship route used in this case study includes both the green and the blue line shown in Figure 8.3.

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[3] https://maritimt.com/nb/batomtaler/celebrity-edge-022019

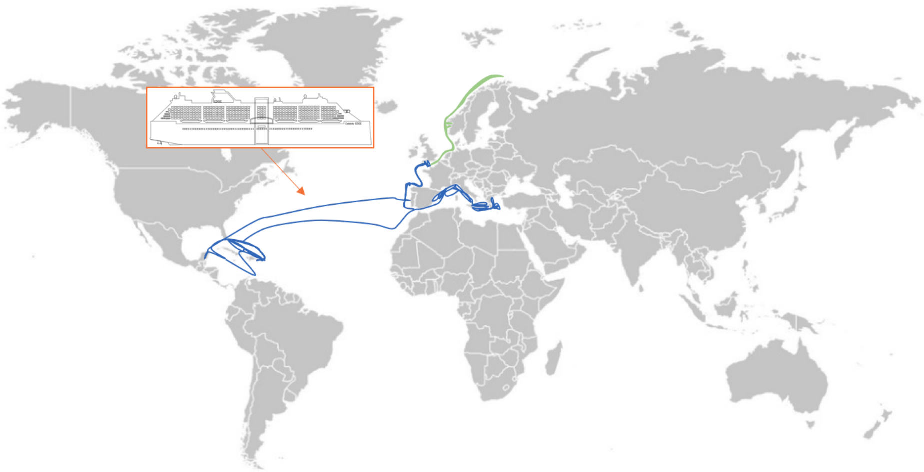

Figure 8.3: Celebrity Edge's sailing route for the 2019 cruise season (Blue: The actual 2019 route from AIS data, Green: ”case study extension”) (Mjelde, 2020)

Baseline ship - Celebrity Edge

To find a *value of flexibility*, a baseline ship has been used for comparison reasons. The cruise ship selected as the baseline ship in this thesis is the two-year-old Celebrity Edge. More information about this ship is given in Appendix E.1 and E.2. In this case study, it is assumed that the cruise ship is installed with both scrubbers and Selective Catalytic Reduction (SCR) technology, as we want the ship to comply with NO_x IMO Tier III and SO_x IMO 0.1% regulations. The newbuild cost of the baseline ship is reported to be around 1,000 mUSD. In Figure 8.4, a simplified illustration of the baseline cruise ship is presented.

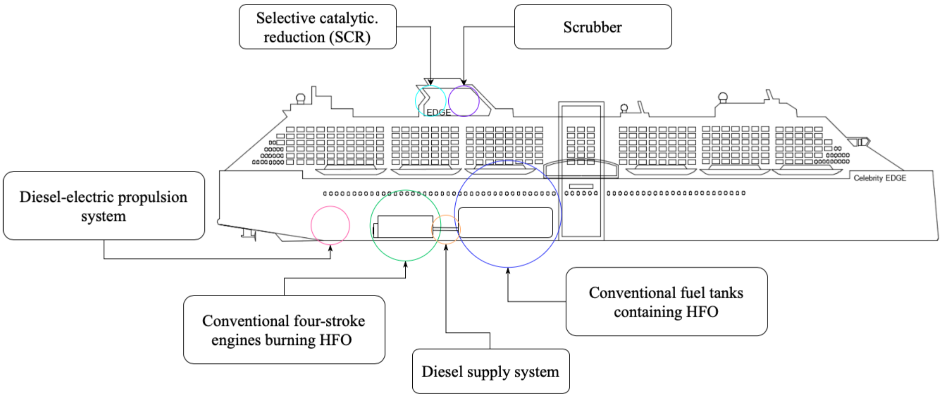

Figure 8.4: Simplified illustration of the baseline cruise ship, Celebrity Edge

8.2.2 Step 2: Modelling the Future

Identifying Epoch Variables

The epoch variables included in the analysis should be the variables with both the highest uncertainty and impact on the performance of the cruise ship design. Epoch variables can be found by various methods. In this case study, an interview approach is used. Furthermore, after being in dialogue both with experts in the cruise industry and maritime environmental regulations, 19 different epoch variables were selected. In Appendix E.4, the epoch variables and their values are presented in more detail. All of the epoch variables are exogenous, meaning that they are outside the control of the stakeholder investing in a new cruise ship. Note also, that the epoch variables remains constant within each epoch. The length of each epoch is set to be five years.

Era Generation

The eras are constructed according to the narrative storytelling approach. The reason for using this approach is that it captures the expectations of both the shipowner and the maritime experts. Hence, making it possible for a stakeholder to create different future scenarios (eras) which captures believable causal relationships between epochs in the future. It is important to precise that if a technology first is mature, or if a stricter environmental regulations first have been introduced, it will not disappear in the following epochs. Furthermore, it is assumed that each era has the same probability of occurring.

Using the same methodology when establishing the eras is vital for consistency. The same ”mindset” is, therefore, applied when creating the story behind each of the eras. Each era is followed by an illustrative figure, to illustrate how technology, alternative fuels and regulations move against each other in the next 30 years. In Appendix E.5, the quantitative versions of the eras used in the analysis are presented.

After investigating the map of where the cruise ship is planned to sail during the next 30 years, it came visible that local regulations being introduced in the EU and Norway would have great impacts on the success of the cruise design. Hence, political action plans both from the Norwegian Government (Government of Norway, 2019) and the EU Commission[4] were investigated and form the basis for the local regulations described in the eras. For global regulations, the IMO’s GHG strategy from 2018, and its planned revision in 2023 are central. Furthermore, to create eras that are as realistic as possible, were experts in the Norwegian Maritime Authority and DNV GL contacted. Note also that the expected increasing pressure from cruise passengers for greener ships are included when evaluating environmental regulations in the eras.

In era 1 to era 3 a lower bound in the HFO and LNG fuel price is maintained. The electricity price is assumed to be 0.05 USD/kWh in 2023 and to linearly decrease to 2050 down to 0.02 USD/kWh. Furthermore, the natural gas price is assumed to be constantly equal to 300 USD/tonne.

In era 4, which is equal to era 3 except for the fuel price, the upper bound of the fuel prices

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[4] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal

is tested. Here, an electricity price of 0.1 USD/kWh in 2023, which is assumed to linearly decrease down to 0.05 USD/kWh in 2050 is used. In era 4 the natural gas price is assumed to be constantly equal to 600 USD/tonne.

Note also that the following definition of zero-emission is used in this case study:

- 95% reduction in GHG.
- 0.1% SO_x.
- NO_x Tier III.

In the following, the story behind each of the four eras used in this case study is presented.

- **Era 1 - ”Baseline scenario”**

  The main characteristics of this era are that both new environmental regulations, technology, and alternative fuels are being introduced against 2050. Both SO_x and NO_x emissions are already heavily regulated, and the focus is expected to be on measures for reducing GHG emissions. The IMO GHG strategy is going to be revised in 2023, however, as new regulations usually take some time in the IMO, no new regulations are expected before 2025 at its earliest, and most likely closer to 2030. The specific GHG reducing measures that are going to be implemented by the IMO on ships in operation are still very uncertain. In this era, it is assumed that only complying with a potential EEXI regulation will be inadequate to be competitive against other cruise companies. Today, and in the coming years, the cruise passengers are expected to be increasingly more focused on the environmental footprint from the cruise ships. Hence, introducing new fuels providing zero-emission operation is assumed to be required in this era. In this era, a global zero-emission requirement on cruise ships is expected by the beginning of epoch 4 (2038-), either from the IMO or indirectly by the cruise passengers. Market-based measures, as carbon pricing is being considered by the IMO, and will presumably be introduced from the beginning of epoch 2 (2028-) on a global scale and with a low price in the beginning. Norway is assumed to continue as a pioneer in the green shipping development, and a zero-emission regulation in the Norwegian world heritage fjords is expected to be introduced in epoch 2 (2028-). Port authorities are expected to contribute to make the cruise industry ”greener”, and the Environmental Port Index (EPI) is assumed to increase its popularity during the years. In 2030, the number of cruise ports using EPI is assumed to be 50%, while increasing to 75% in 2050.

  Development in technology for low- and zero-emission shipping, and an increase in alternative fuel production and infrastructure is expected in this era. Ammonia to be used in an internal combustion engine is likely to be commercially available for cruise ships at the beginning of epoch 2 (2028-), after being thoroughly tested by engine manufacturers.

  Investments in renewable energy, primarily wind and solar, is expected to make electrofuels (E-diesel and E-methane) more relevant, but not available before epoch 4

(2038-). Biofuels can use the same bunkering infrastructure as LNG, however, biofuels are most likely produced in a very low amount, and assumed to be unavailable until epoch 3 (2038-). Ammonia will gradually receive a more important role in the fuel mix for cruise ships and expected to be available from epoch 2 (2028-). Ammonia is assumed to continue to be produced from natural gas until 2030-2040, but slowly being produced more and more from renewable electricity. HFO is assumed to be available during the entire era.

LNG is assumed to be cheaper than HFO in this era. All fuels are expected to decrease in price during the years, except for the biofuels which are assumed to increase in price.

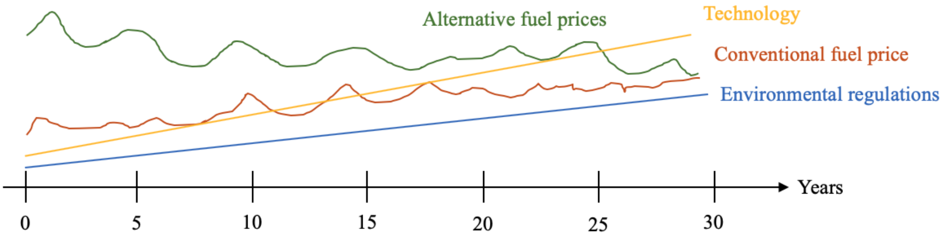

Figure 8.5: Illustration of the development within era 1 (only for illustrative purposes)

- **Era 2 - ”Conservative Scenario”**

  The main characteristics of this era are that new environmental regulations, technology, and alternative fuels are being introduced against 2050, but with a significantly lower pace than in Era 1. Both SO_x and NO_x emissions are already heavily regulated, and the focus is expected to be on measures for reducing GHG emissions. The IMO GHG strategy is planned to be revised in 2023, and which measures that are going to affect the cruise ship industry is still uncertain. In this conservative era, it is assumed that the IMO is unable to decide which measures to make for reducing GHG emissions. This results in that no environmental regulations from the IMO is assumed to be introduced before 2030. Local regulations in the Norwegian world heritage fjords are assumed to be introduced not before epoch 3 (2033-). It is assumed that it takes a long time before global zero-emission requirements are introduced for cruise ships, and the pressure from the cruise passengers is assumed to remain moderate during the lifetime of the cruise ship. A global zero-emission requirement is, therefore, assumed being introduced not before the beginning of epoch 6 (2048-). A global carbon tax is assumed to be introduced at the beginning of epoch 4 (2038-), but on a lower price level than in Era 1. The port authorities are expected to push for greener cruise ships in a limited degree, and only 25% of the cruise ports are using the EPI in 2050.

  The development in new technology and infrastructure for alternative fuels is assumed to, generally, go slowly in this era. The testing of ammonia is assumed to encounter problems, making ammonia in combustion engines not commercially available for cruise ships before epoch 3 (2033-).

Investments in renewable energy production, primarily wind and solar, are assumed to be delayed. Hence, electrofuels (E-diesel and E-methane) are most likely not available before epoch 5 (2043-). Biofuels (HVO and LBG) are assumed to be available from epoch 4 (2038-). HFO is assumed to be available during the entire era.

LNG is assumed to be cheaper than HFO in this era, and all fuels are expected to decrease in price during the years, except for the biofuels which are assumed to increase in price.

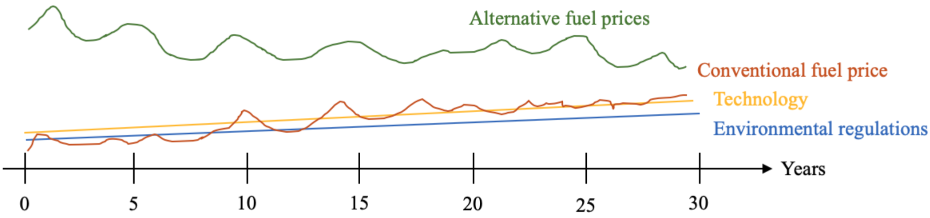

Figure 8.6: Illustration of the development within era 2 (only for illustrative purposes)

- **Era 3 - ”Green-ambition Scenario (Low fuel price)”**

The main characteristics of this era are that new environmental regulations, technology and alternative fuels are introduced against 2050, and with a higher pace than in Era 1. Both SO_x and NO_x emissions are already heavily regulated, and the focus is expected to be on measures for reducing GHG emissions. The IMO GHG strategy is planned to be revised in 2023. Since it usually takes some time in the IMO to introduce a new regulation, it is likely that no regulations most likely will come before epoch 2 (2028-). The EU is expected to be impatient in this era, and a local carbon tax in EU waters is introduced, as shipping has been incorporated into the ETS on the recommendation by the new ”Green deal” from the EU Commission. All ships sailing in EU waters is as a result of this required to pay a carbon tax in epoch 1 (2023-2027). In epoch 2 (2028-), it is assumed that the IMO is introducing a global carbon tax. The carbon tax is initially low but expected to increase during the years. Norway introduces the world’s first zero-emission zone in epoch 2 (2028-) (a bit later than initially planned). A global regulation requiring zero-emission operations for cruise ships is in this era assumed to be introduced in epoch 4 (2038-), mainly due to a high pressure from the cruise passengers. The EPI is expected to be introduced in many cruise ports in this era, and in 2050 over 75% of all large cruise ports are using this scheme.

Development within low- and zero-emission technologies for ships are expected in this era. Ammonia in a combustion engine is thoroughly tested around 2025, and commercially available for cruise ships from epoch 2 (2028-).

Investment within renewable energy is assumed, primarily within solar and wind, making electrofuels (E-diesel and E-methane) available from epoch 3 (2033-). Biofuels are expected to be available for cruise ships in epoch 2 (2028-), as the production is assumed to increase. Ammonia is assumed to be available from epoch 2 (2028-), and HFO is assumed to be unavailable in epoch 6 (2048-).

LNG is assumed to be cheaper than HFO in this era. All fuels are expected to decrease in price during the years, except for the biofuels which are assumed to increase in price.

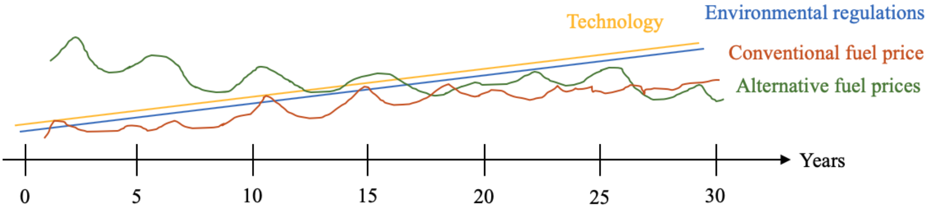

Figure 8.7: Illustration of the development within era 3 (only for illustrative purposes)

- **Era 4 - "Green-ambition Scenario (High fuel price)"**

  This era is a high fuel price version of era 3. Thus, everything is equal between era 3 and 4 except for the fuel prices.

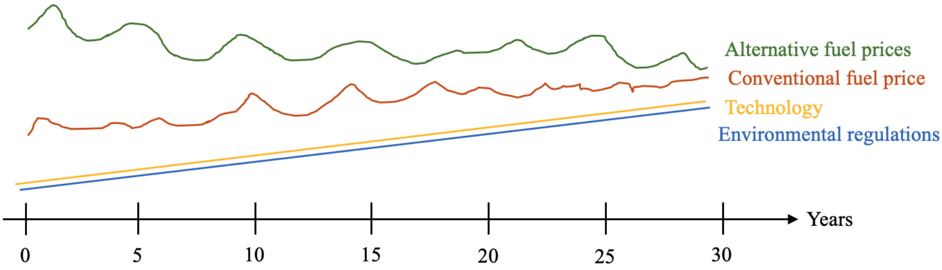

Figure 8.8: Illustration of the development within era 4 (only for illustrative purposes)

8.2.3 Step 3: Identify Flexible Design Alternatives

The focus in this case study is to test how flexibility in cruise ship design can be used to better handle; uncertain future environmental regulations; greener expectations from the cruise passengers; and future alternative fuels and technologies. Thus, the type of flexibility designed for in the cruise ship should relate to these aspects.

Based on the maritime environmental regulatory framework for shipping in Chapter 6, the different alternative fuels and energy converter technologies in Chapter 7, and recommendations from experts within the maritime industry, the following two designs were highlighted as attractive candidates to be analysed in the flexibility valuation model.

1. **Versatile design:** LNG dual fuel cruise ship design.
2. **Retrofittable design:** Ammonia ready cruise ship design.

It can be argued that the LNG dual fuel cruise ship design should be defined as an "adaptable" design, instead of a "flexible", as we assume that no modifications to the system are needed to run on different alternative fuels (see definition of flexibility in Section 2.2). Thus, some may say that it would be better to use "changeable" cruise ship designs instead of "flexible" as a collective term of the cruise ship designs. However, as flexibility as a term is generally better known by non-technical decision makers than changeability, it was decided to stick to the flexibility term in this thesis.

There are many reasons why these designs are interesting to investigate, where the main one is that they provide solutions that comply with future environmental regulations such as a zero-emission regulation (95% zero-emission regulation, NO_x IMO Tier III and IMO 0.1% SO_x), see Table 7.3.

In the following, each design is described in more detail. Note that the Celebrity Edge is used as the baseline cruise ship design and that the flexible designs only modifies the inner part of the Celebrity Edge. Note also that a small comment on the safety aspect for each of the flexible designs are provided, as this is a particularly important aspect for cruise ships.

LNG Dual Fuel Cruise Ship Design

In this flexible design, LNG systems are installed on board Celebrity Edge. LNG fuelled cruise ships have become a popular option in recent years, and today around 35 LNG power cruise ships are in operation and on order.[5]

An LNG fuelled ship will require a set of other systems compared to a conventional diesel-fuelled ship. In Figure 8.9, a simplified illustration of the systems installed on board the LNG dual fuel cruise ship is presented.

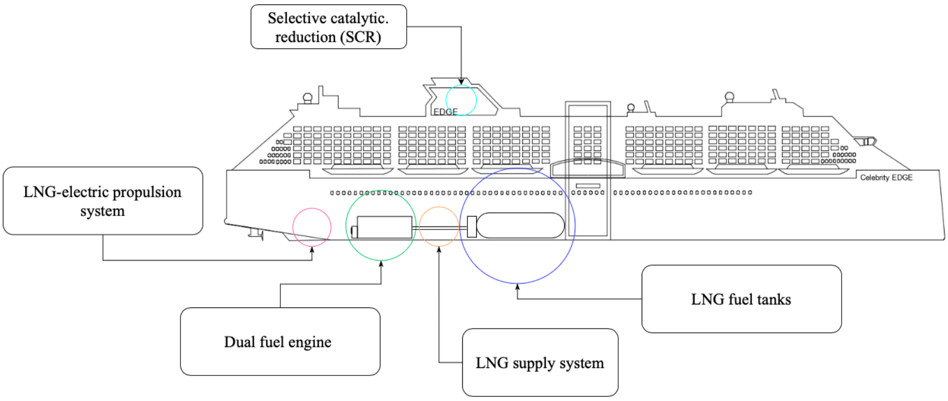

Figure 8.9: A simplified illustration of the LNG dual fuel cruise ship design

LNG Dual Fuel Engine

LNG dual fuel four-stroke engines are installed on board the cruise, making it able to run on both gas and liquid fuels. LNG in a dual fuel engine eliminates SO_x emissions, and also the IMO NO_x Tier III requirement can be fulfilled if the right engine or abatement technology is used.

In this case study, SCR technology is installed to make the cruise ship compliant with NO_x regulations in the ECAs. The cost for this system is already included in the baseline design, and not further considered for this design. Note that the LNG dual fuel design does not require a scrubber to comply with SO_x regulations.

LNG Storage

The boiling point of LNG is approximately -163°C at 1 bar absolute pressure. As a result of this, LNG needs to be stored in insulated tanks for cryogenic application to reduce the amount of boil-off to the atmosphere. Several different tank types for LNG exists, and for this case study, insulated IMO type C tanks are used. The insulation needed in the LNG tanks, makes them larger in volume, heavier and more costly compared to conventional storage tanks. Furthermore, as LNG have a lower volumetric energy density compared

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[5] https://afi.dnvgl.com/KnowledgeHub

to HFO, larger tank volumes are required for the LNG cruise ship design (see Appendix E.3).

Safety

The primary safety concerns with LNG is its cryogenic temperature (can cause freeze burns and eye damage), the flammability and vapour dispersion characteristics. Note that LNG in liquid state will not burn nor explode. LNG is a non-toxic substance, and long term environmental impacts from a potential release are negligible. The international regulation for LNG on ships is defined by IMO in, The International Code of Safety for Ships using Gases or other Low-Flash Fuels (IGF Code), which came into force in 2017. All ships using LNG have to comply with the requirements set out in the IGF Code, and LNG as a fuel for cruise ships is considered as a safe option as long it is properly handled.

Additional Capital Cost

An LNG fuelled ship have higher requirements for storage tanks and the fuel supply system compared to conventional alternatives. Additionally, investing in dual fuel engines is more expensive than conventional diesel engines (Wartsila, 2020).

The additional cost for installing LNG systems on a large cruise ship is in a recent study by DNV GL estimated to be in the range of 10-14 million USD (Mjelde et al., 2019). In this cost estimate it is assumed that the following is included:

- Engine upgrades
- Fuel supply system
- Fuel storage
- Engineering and installations costs

Generally, it is difficult to find good cost estimates, and the estimate provided by Mjelde et al. (2019) is considered as the most reliable of the ones that were assessed. In the case study, the additional cost for the LNG systems was assumed to be 12 mUSD.

Ammonia Ready Cruise Ship Design

In this flexible design, ammonia tanks and ammonia fuel supply systems are installed into the initial design. This is done to make a potential retrofit to ammonia at a later point in time both feasible and less expensive. Ammonia is intended to be used within the already installed ICE's on board the cruise ship, by rebuilding them. This will save space and most likely reduce the retrofit cost. The ”ammonia ready design option” evaluated in this case study follows much of the same mindset as the already well known ”LNG ready design option” which have been applied to a large number of ships (around 143 ships globally[6]).

In Figure 8.10, a simplified illustration of the ammonia ready cruise ship design is shown.

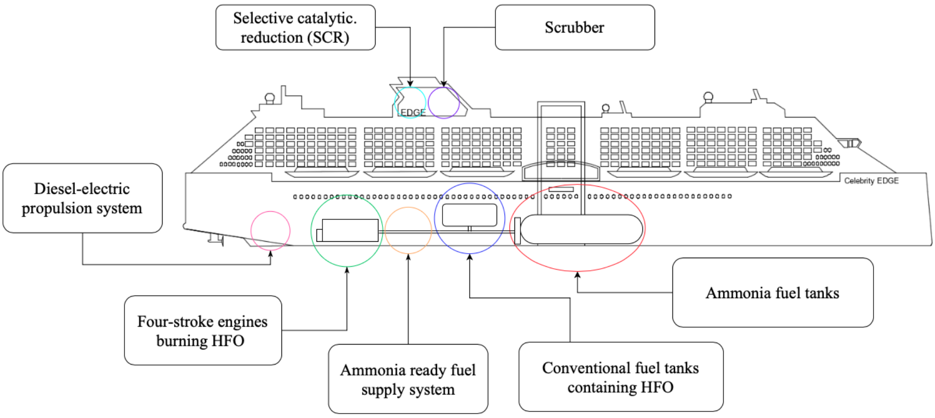

Figure 8.10: A simplified illustration of the ammonia ready cruise ship design

Note that both SCR technology and scrubbers are installed to make the cruise ship compliant with SO_x and NO_x regulations in ECAs when HFO is used in the system. These costs are already included in the baseline design, hence not considered in more detail here.

Burning ammonia will lead to NO_x emissions, hence having SCR technology already installed in the initial design will potentially be of value after the ammonia option has been exercised.

Ammonia Engine

Today, as mentioned before in the thesis, several research projects testing ammonia in ICE's are initiated.[7,8] Ammonia has a high auto-ignition temperature and narrow flammability limits (15-28% by volume in air) as shown in Table 7.4. Resulting in unstable

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[6] https://afi.dnvgl.com/Statistics

[7] https://www.wartsila.com/media/news/25-03-2020-wartsila-advances-future-fuel-capabilities-with-first-ammonia-tests-2669590

[8] https://www.tu.no/artikler/motorprodusentene-tester-ammoniakk-kan-gi-nullutslippsskip-for-2030/488522

combustion conditions at very low and very high engine speeds (Ash and Scarbrough, 2019). To better control the combustion, hydrogen has in several studies been applied as a promoter in ammonia engines. Hydrogen holds the lowest ignition energy, highest combustion velocity and widest flammability range. Therefore, only a small amount of hydrogen added to the air-ammonia mixture is effective to speed up the combustion (Pozzana et al., 2012). Carbon-fuels could also have been used as promoters. However, the best and carbon-free promoter is considered to be hydrogen (Kim et al., 2020).

Ammonia-hydrogen mixtures can be used both in ICEs using Compression Ignition (CI) or Spark Ignition (SI). However, de Vries (2019) states that using SI instead of CI most likely will reduce the amount of harmful emissions the most. As a result of this, at the point when the cruise owner wants to exercise the option of using ammonia as a fuel, the engines are assumed to be rebuilt to SI engines and using a mixture ratio between NH_3 and H_2 as precised in Table 8.2.

Table 8.2: Assumed NH_3-H_2 mixture for SI engine

Fuel	Weight Ratio
NH_3	95%
H_2	5%

Cracking

The dissociation process of ammonia into nitrogen and hydrogen gas is called *cracking*, and the chemical reaction is (Ogden, 2002):

$$2NH_3 \longrightarrow N_2 + 3H_2 \tag{8.2.1}$$

It is assumed that a separate fuel tank for hydrogen not is necessary as an onboard reformer can be used to crack ammonia into hydrogen and nitrogen simultaneously as the fuel is burnt (Kim et al., 2020).

Ammonia Storage

Ammonia can be stored in a liquid state either in a pressurised tank at 20°C and 10 bar, or refrigerated at -34°C and 1 bar (de Vries, 2019). The storage system normally used for ammonia, and also used for this cruise design, is pressurised IMO type C tanks (DNV GL, 2019a). The cost of these tanks will be higher than conventional tanks, but, lower than for LNG tanks as less insulation is required to prevent boil-off.

Safety

The principal concern of ammonia as a fuel for ships is safety (ICS, 2018), especially due to its toxicity. Exposure to ammonia can potentially cause caustic burns, lung damages and death. Measures to prevent hazardous concentrations of ammonia in enclosed spaces is due to this important, such as proper ventilation and leakage detectors. In case of a condition causing rising pressure inside the ammonia tanks, ammonia can be released by utilising vent masts. However, this option may lead to unacceptable ammonia concentrations in the public areas on board the cruise ship, and methods to solve this has to be further investigated (de Vries, 2019).

Furthermore, ammonia is corrosive to copper, copper alloys, nickel and plastic. These materials should, therefore, be avoided in an ammonia power system (DNV GL, 2019a).

Additional Capital Cost

There is little experience of ammonia as a fuel for ships in general, and none for cruise ships. To obtain robust capital investment costs for ammonia systems on cruise ships is due to this challenging. However, from maritime experts within environmental technology in DNV GL, it was emphasised that the cost for installing LPG systems could be used as a fair assumption. Brinks and Chryssakis (2017) study LPG as a fuel for ships and estimates that the extra cost for installing LPG compared to LNG is approximately 50% less. In the cost, it is assumed that the following is included:

- Engine upgrades
- Fuel supply system
- Fuel storage
- Engineering and installations costs

Based on the cost estimates for the LNG dual fuel cruise ship, the additional capital cost for the ammonia ready ship compared to the baseline design is assumed to be in the range of 5-7 mUSD. Moreover, as engine upgrades will be provided at a later point in time, it is expected that the initial capital cost will be in the lower range of this estimate. In this case study, the additional cost for preparing the cruise ship for ammonia was assumed to be 6 mUSD, and the retrofit cost was assumed to be 2 mUSD.

8.2.4 Step 4: Design Valuation

In this step, each cruise ship design is valued by using the eras created in *Step 2* and the NPV method in a Monte Carlo simulation model. The simulation model is generated in MATLAB[9], and in the following, the setup and the elements included in this simulation model is described. Note that the term ”valuation model” is used as a synonym to the MATLAB model.

Real Options for a Cruise Owner

Step 1: Problem description describes the main concerns of the decision maker, pointing at stricter environmental regulations and increasing pressure from the cruise tourists for greener cruise ships. Hence, having an insight into what kind of options or responses a cruise ship owner has when facing new environmental regulations and greener expectations is vital.

Figure 8.11 presents the most typical options (or responses) for a cruise ship owner when new environmental regulations are introduced. In real option terminology, response 1 is an in-option, while response 2 and response 3 are on-options.

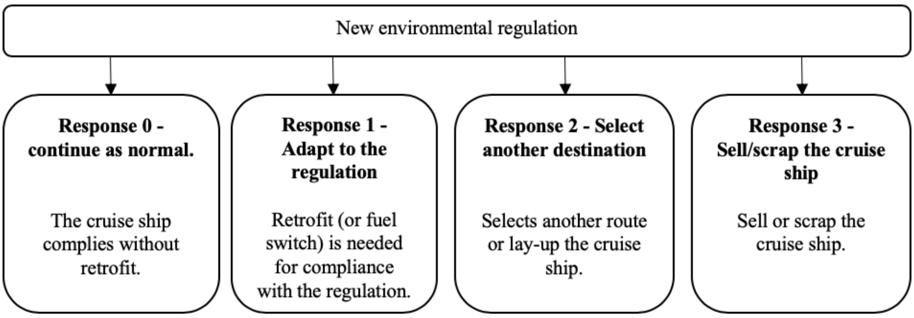

Figure 8.11: Potential responses by a cruise ship owner on new environmental regulations (inspired by (Menon Economics, 2018))

In- and On-options in the Valuation Model

The on-options and in-options included in the valuation model for each cruise ship design are presented in Table 8.3 below. From this table, it can be seen that all of the options mentioned in Figure 8.11 are included in the valuation model. Note also that the on-options are equal for all of the cruise ships, while the in-options varies for each design.

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[9] The MATLAB code has been attached in its own file to this document.

Table 8.3: Options included in the valuation model for each cruise ship design, if a local or global zero-emission regulation is introduced

Cruise design	Option type	Maturity[a]	Description
Baseline	In-option	5 years	Switch to HVO or E-diesel.
	On-option	5 years	Avoid to sail that route.
	On-option	5 years	Sell/scarp the cruise ship.
LNG dual fuel	In-option	7 days [b]	Switch to the cheapest fuel of HVO, LBG, e-methane or e-diesel.
	On-option	5 years	Avoid to sail that route.
	On-option	5 years	Sell/scrap the cruise ship.
Ammonia ready	In-option	5 years	Retrofit to ammonia as a fuel.
	On-option	5 years	Avoid to sail that route.
	On-option	5 years	Sell/scrap the cruise ship.

[a] The interval between each time this option is given to the design.
[b] Each cruise trip is assumed to be over 7 days.

A critical assumption made in the valuation model is that until the time a local or global zero-emission regulation has been introduced, the cruise ships are assumed to operate as they were initially designed. Which means that as long no local or global zero-emissions regulation is introduced, the cruise ships are not given the options presented in Table 8.3. Hence, the baseline design will operate with HFO in its diesel engines, the LNG dual fuel design will select the cheapest available fuel of LNG, HVO, LBG, e-diesel and e-methane, and the ammonia ready design will operate with HFO in its diesel engines.

It can be argued that the LNG dual fuel design is an exception from the ”no environmental regulation entails no action” rule, as this design is allowed to switch between fuels. The reasoning behind this is that the fuel-switching option is an inherent feature of this design and should because of this be given to the design from day one.

Within each epoch, the epoch variables remain constant (see quantitative era representation in Appendix E.5). This is the reason why the cruise owner only are given the option to retrofit, avoid to sail that route, or scrap or sell the cruise ship at the beginning of each epoch and with five years intervals as presented in Table 8.3.

The two epoch variables ”Local zero-emission regulation” and ”Global zero-emission regulation” control in many ways the valuation model, as no action will be made to the design before any of these two occurs. Figure 8.12 presents the paths a cruise owner can choose between if a global or local zero-emission regulation is introduced between epoch 1 and epoch 2. Note also that the cruise ship will ”operate as normal” if no zero-emission regulations are introduced.

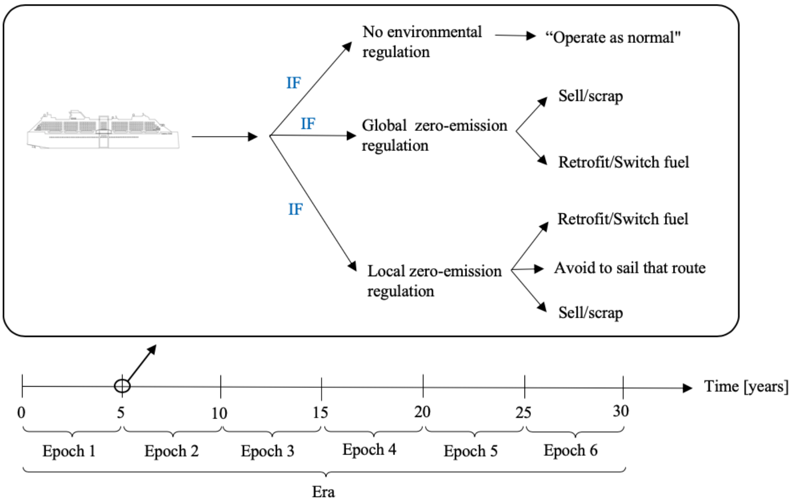


Figure 8.12: Options given to the cruise ship in the valuation model (after 5 years of cruise ship operations)

- **IF - "No environmental regulation"**

If no local or global zero-emission regulation has been introduced between epoch 1 and epoch 2 in Figure 8.12, the cruise ship will "operate as normal", and the same set of questions will be asked between epoch 2 and epoch 3, as shown in Figure 8.13 below. This process will continue until a global or local zero-emission regulation occurs.

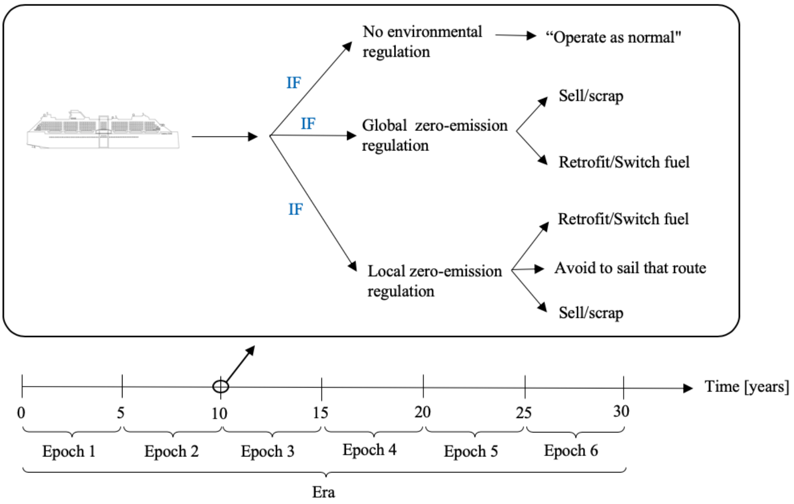


Figure 8.13: Options given to the cruise ship in the valuation model (after 10 years of cruise ship operations)

- **IF - ”Global zero-emission regulation”**

If a global zero-emission regulation occurs between epoch 1 and epoch 2 in Figure 8.12, the shipowner has only two options, either sell/scrap or retrofit/switch fuel. There are no environmental regulations in the valuation model which is stricter than the global zero-emission regulation. Hence, if a cruise ship first comply with this, it is assumed to comply with all types of environmental regulations until 2050 and onward.

- **IF - ”Local zero-emission regulation”**

If a local zero-emission regulation is introduced between epoch 1 and epoch 2 in Figure 8.12, the cruise ship owner has three options, sell/scrap, avoid to sail that route or retrofit/switch fuel. If the cruise owner selects to ”Avoid to sail that route” the valuation model is set to reduce the revenue with the same amount as the cruise ship would have gained if it chose to retrofit and sail the ”local” route. ”Avoid to sail that route” is, therefore, the same as to temporarily *lay-up* the cruise ship.

If the option of ”Avoid to sail that route” is chosen, the valuation model has to check if a global zero-emission regulation occurs in the next epoch, see Figure 8.14 below. Note that the valuation model assumes that if a local zero-emission regulation first has occurred, then it cannot occur new local zero-emission regulations in the following epochs.

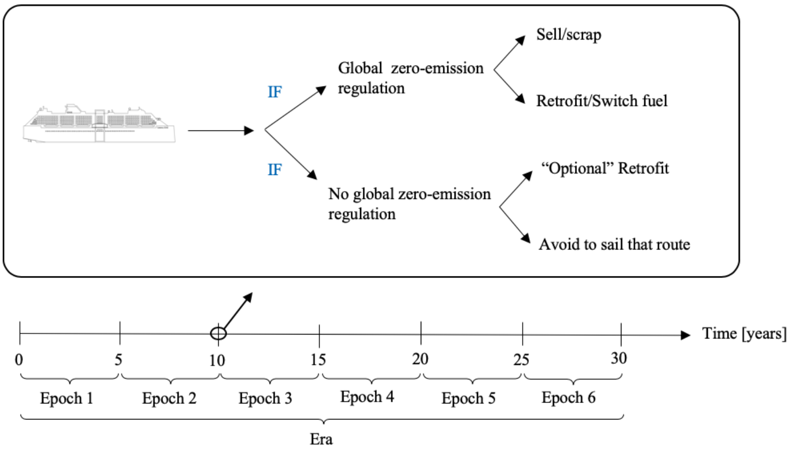


Figure 8.14: Options given to the cruise ship in the valuation model if ”Avoid to sail that route” are chosen in the epoch before

As shown in Figure 8.14, if a global zero-emission regulation is not introduced between epoch 2 and epoch 3, the shipowner that selected to ”Avoid to sail that route” between epoch 1 and epoch 2, have again two options. Either to do an ”optional retrofit” for complying with the local zero-emission regulation or again ”Avoid to sail that route”. If the option of ”Avoid to sail that route” is used one more time, then the same questions as shown in Figure 8.14 are again asked between epoch 3 and epoch 4. Meaning that as long

”Avoid to sail that route” is selected, this process will continue until a global zero-emission regulation occurs.

An important assumption to be aware of in the valuation model is that if the baseline design, the LNG dual fuel design or the ammonia ready design choose to retrofit (or ”switch fuel”) due to a local zero-emission regulation. Then they will also be able to fulfil a global zero-emission regulation at a later point in time.

The next question is then: *if a local or global zero-emission regulation is introduced, which path should the shipowner select?* Should he/she sell/scrap, retrofit/switch fuel or avoid to sail that route. This question is answered by the decision rule described in the following.

Decision Rules

A real option should only be exercised if it adds value to the project. In the valuation model, the NPV is used as the valuation parameter, and the decision rule applied in this case study is, therefore, to choose the real option that maximises the NPV for the rest of the lifetime of the cruise ship.

Moreover, by using the epoch-era analysis together with real options analysis, we will at every point in time know what will occur in the future, as the eras are already defined. Therefore, for example, if a local zero-emission regulation occurs, the valuation model will be able to check the NPV result for all of the three options (retrofit, avoid to sail that route, sell/scrap), and select the one that gives the highest NPV.

We have also one more decision rule in this case study, and that is for the LNG dual fuel design to always select the cheapest available fuel. In Table 8.4, the decision rules used in this case study are described with more simple words.

Table 8.4: Decision rules in the valuation model

Zero-emission regulations	Choose the option that maximises the NPV for the residual lifetime of the cruise ship.
Fuel selection (LNG dual fuel design)	Choose the cheapest available fuel.

Cash Flow Generation

The performance of the different cruise ship designs is measured with the NPV method. The NPV formula used in the valuation model is presented in Equation 8.2.2 below.

$$NPV = \sum_{t=0}^{N} \frac{R_t - C_t + FV_N}{(1+r)^t} \tag{8.2.2}$$

Where R_t is the revenue in year t, C_t is the costs in year t, FV_N is the value of the cruise ship at the end of its lifetime (in this case after 30 years of operation), r is the discount rate, and N is the total number of years discounted over.

To calculate the NPV of the designs, we need to generate the annual cash flow over 30 years of operations. This is the core of what the valuation model described above does. The different elements included in the cash flow are presented in Equation 8.2.4 below.

$$\begin{aligned}\text{Cash flow} &= R_t - C_t \qquad (8.2.3)\\ &= \text{Revenue} - \text{CAPEX} - \text{OPEX} - \text{VOYEX} \qquad (8.2.4)\end{aligned}$$

Where:

- **Revenue:** The income the ship creates from providing its service.
- **CAPEX (Capital Expenditure):** The total price of the new-build, as well as loans, interests and other financial costs related to the construction of the vessel.
- **OPEX (Operational Expenditure):** Day-to-day costs, mainly consisting of fees, repairs and maintenance and crewing.
- **VOYEX (Voyage Expenditures):** Expenditures unique to the voyage, as fuel cost, port and transit fees and pilot fee.

A thorough introduction to how the revenue, CAPEX, OPEX and VOYEX have been included in the valuation model is given in Appendix E.7. Note that the elements included in the revenue, CAPEX, OPEX and VOYEX are only the elements that will be different for the cruise ship designs. This means that the overall cash flow generated by the valuation model most likely will be higher than it actually would have been for a real cruise ship. As different cost elements, e.g. the crew cost has not been included in the cash flow calculation. This will result in very high NPV results and is something to be aware of when evaluating, e.g. the ENPV results from the analysis.

Stochastic Fuel Prices

The fuel price is difficult to predict and associated with much uncertainty, as described in Section 7.2.1. Furthermore, in order to value the switching option for the LNG dual fuel design properly, the fuel price should vary within the epochs. As a result of this, the fuel prices are modelled stochastic and assumed to follow a Geometrical Brownian Motion (or random walk) within each epoch. See Appendix E.7.4 for more information about how the stochastic fuel price is included in the valuation model.

Moreover, as we want to create a performance distribution with a Monte Carlo simulation, stochastic behaviour (or some randomness) is a requirement. Note that fuel price is the only element in the valuation model with stochastic development within the epochs.

Parameters in the Valuation Model

In Table 8.5, a set of input parameters used in the valuation model is presented.

Table 8.5: Parameters in the valuation model

Parameter	Value
Operational time	30 years
Construction time	2 years
Total modelling time	32 years
Interest rate on loan	3.225%
Loan ratio[a]	80%
Discount rate[b]	5%
Port calls (average)	290 /year
Revenue per passenger	250 USD/passenger/day
Length of a cruise trip	7 days
Annual number of days on cruise[c]	365 Days/year
Scrap price[b]	250 USD/Lightship weight

[a] Percentage of the newbuild cost.
[b] After advice from cruise expert in DNV GL.
[c] This number is adjusted for drydock or shipyard in the valuation model.

In Table 8.6, the assumed time in local CO_2 and local zero-emission zones is shown.

Table 8.6: Assumed time in ”local zones”

Time in local CO_2 tax zone[a]	50% of the year
Time in local regulation zone[a]	20% of the year

[a] Only relevant if they have been introduced by the eras.

8.2.5 Step 5: Value Flexibility

To obtain a *value of flexibility*, the NPV results for the flexible cruise ship designs are compared against the performance of the baseline cruise ship design (inflexible design). Flexibility can be valued in different ways, as pointed out in Chapter 5. In this case study, target curves and the ENPV are used.

8.2.6 Step 6: Sensitivity Analysis

As a final step in the flexibility valuation framework, a sensitivity analysis is undertaken. This is done in order to assess the robustness of the results from the analysis and to better understand the impacts of the parameters and the variables on the results.

The model relay on certain parameters that are particularly difficult to estimate, and therefore prone to large uncertainty. In the list below, the parameters that are investigated in the sensitivity analysis are presented:

- Discount rate.
- Newbuild cost of the flexible designs.
- Retrofit cost for the ammonia ready design.
- Number of cabins lost due to larger fuel storage tanks for the ammonia ready design.
- Retrofit time for the ammonia ready design.

8.3 Modelling Assumptions

The most central assumptions made for the flexibility valuation are summarised in the list below.

1. **Cruise ship market:** The cruise ship market is assumed to continue its growth also in the coming years. The cruise ship market is because of this not perceived as a barrier for the cruise ship designs to be successful.
2. **Shipyard:** In the valuation model, it is assumed that there is free capacity in yards to do the retrofit and that the equipment to be installed on board the cruise ship is available.
3. **Newbuild cost:** The first half of the newbuild cost is assumed to be paid in the first construction year, and the other half when the ship is delivered (year two).
4. **Dry dock:** The cruise ship is assumed to use a standard five years dry dock interval.
    (a) A normal dry docking is set to 14 days.
    (b) The ammonia retrofit is assumed to take 14 days.
5. **Loan:** The loan is an annuity loan with a balloon, re-paid over 30 years, which starts when the cruise ship is delivered.
6. **Retrofit cost:** The retrofit cost is assumed to be paid by money the cruise ship owner has in his/her own pocket, meaning that no loan is required.
7. **Port costs:** The Environmental Port Index (EPI) is used in the model to reduce and increase port fees.
8. **Storage capacity:** The fuel storage tanks on board the cruise ships are assumed to have a capacity of 10 days.

9. **Loss in revenue:** If one cabin is lost, the passenger capacity of the cruise ship is decreased with two passengers.
10. **Lightship weight:** The lightship weight is assumed equal for all cruise ship designs.
11. **Slow steaming:** Speed reduction as a measure implemented in the EEXI to reduce emissions is not being considered in this thesis.
12. **Sell option:**
    (a) The value of the cruise ship during its lifetime is assumed to be represented by its book value.
    (b) The loan is assumed to be paid down if the ship is sold or scrapped.
13. **Regulation:** The regulations needed for ammonia is assumed to be in place at the point when the ammonia retrofit option is exercised.
14. **Costs:** The cost of emission abatement technology is assumed to be already included in the new build price.
15. **Engine efficiency:** Assuming the same engine efficiency (40%) for all of the fuels used in an ICE system.
16. **Era:** Each era is assumed to have the same probability of occurring.
17. **Local zero-emission regulation:** If a local zero-emission regulation first has occurred, then it cannot occur new local zero-emission regulations in the following epochs.

Chapter 9

Results

In this chapter, the results from the case study are presented. Before presenting the results, the objective of this thesis is repeated.

The objective of this thesis is to investigate the value of designing cruise ships with flexibility to comply with future environmental requirements, by preparing for technological innovations and alternative fuels.

To better understand how each flexible design performs, the results are presented in two different ways:

1. Each flexible design is compared to the baseline design in each era.
2. Each flexible design is compared to the baseline design over all eras by selecting eras arbitrarily in each simulation round.

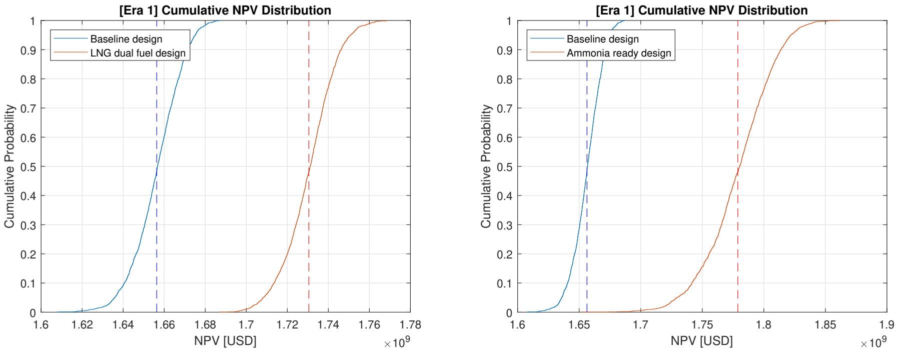
Finally, the results from the sensitivity analysis are shown. The number of simulations is set to 2000 for all of the results presented in this chapter.

9.1 Flexible Designs Versus Baseline Design in Each Era

In this section, the performance of each cruise ship design in each era is presented.

Era 1 - ”Baseline Scenario”

The NPV performance in era 1 for the flexible cruise ship designs in comparison to the baseline design is presented in Figure 9.1. In Era 1, it is assumed that both environmental requirements, technology and alternative fuels develop during the lifetime of the cruise ships. Hence, it is to assume that the flexible cruise ship designs will provide value in this era. Figure 9.1 confirms this assumption, as it shows that both the LNG dual fuel design and the ammonia ready design performs better than the baseline design in this era.



(a) Baseline design versus LNG dual fuel design **(b)** Baseline design versus ammonia ready design

Figure 9.1: Target curves for the baseline design, the LNG dual fuel design and the ammonia ready design in era 1 (2000 simulations)

The ammonia ready ship performs particularly well in era 1, as Table 9.1 shows. The main reason for this is that the technology for ammonia, and ammonia as a fuel is available already in epoch 2. Which makes the ammonia ready design able to comply with the local 95% zero-emission regulation introduced in epoch 2.

The baseline design and the LNG dual fuel design are unable to comply with the local 95% zero-emission regulation introduced in epoch 2, as the 95% zero-emission compliant fuels are unavailable. This results in a significant loss of income for these two ship designs (20% decrease in the annual income over five years), and gives the ammonia ready design an advantage in this era.

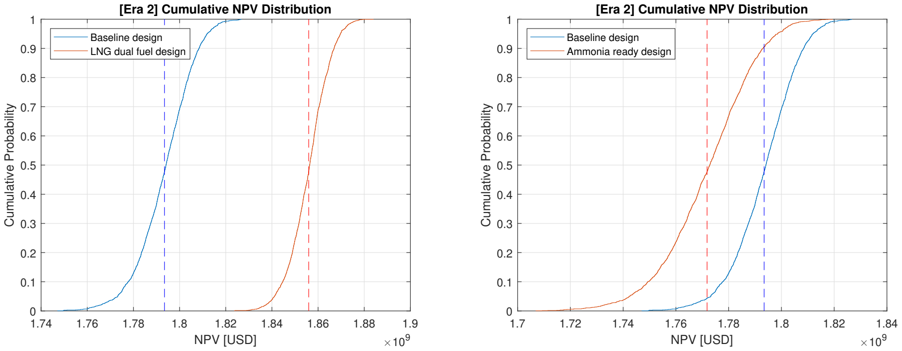
Nevertheless, as Table 9.1 shows, the value of flexibility for the LNG dual fuel design is high in era 1. The reason for this is that the LNG dual fuel design is able to comply with the local 95% zero-emission regulation in epoch 3, as HVO and LBG then are available. Furthermore, as the LNG dual fuel design can switch between fuels easily, the VOYEX cost can be significantly reduced by switching to LNG when sailing outside of the local 95% zero-emission zone. Hence, the fuel switching option for the LNG dual fuel design shows to have a high value.

Table 9.1: Estimating the value of flexibility in era 1 (numbers in millions)

Ship design	ENPV [mUSD]	Value of flexibility [mUSD]
Baseline	1,657	-
LNG dual fuel	1,731	74
Ammonia ready	1,779	122

Era 2 - ”Conservative Scenario”

The NPV performance in era 2 for each of the flexible designs compared to the baseline design is presented in Figure 9.2. Era 2 represents a conservative scenario, where little development within environmental requirements, technology and alternative fuels are assumed. It is, therefore, to expect that especially the flexibility introduced by the ammonia ready ship will have little value in this era.



(a) Baseline design versus LNG dual fuel design

(b) Baseline design versus ammonia ready design

Figure 9.2: Target curves for the baseline design, the LNG dual fuel design and the ammonia ready design in era 2 (2000 simulations)

As we expected, the ammonia ready design performs poorly compared to the baseline design in era 2, and the value of flexibility is negative. There are several reasons for this, e.g. that global zero-emission regulations are introduced late in era 2, the number of ports using EPI is low throughout the era, and the carbon tax is introduced late and at a low level. Furthermore, the ammonia ready design is unable to use its embedded flexibility in epoch 3 for complying with the local 95% zero-emission regulation, as ammonia is assumed to be unavailable. Lastly, the ammonia ready design has not the flexibility to switch between fuels when the option of switching to ammonia have been exercised. This results in a higher annual VOYEX cost than for the baseline design and the LNG dual fuel design when only a local 95% zero-emission regulation has been introduced.

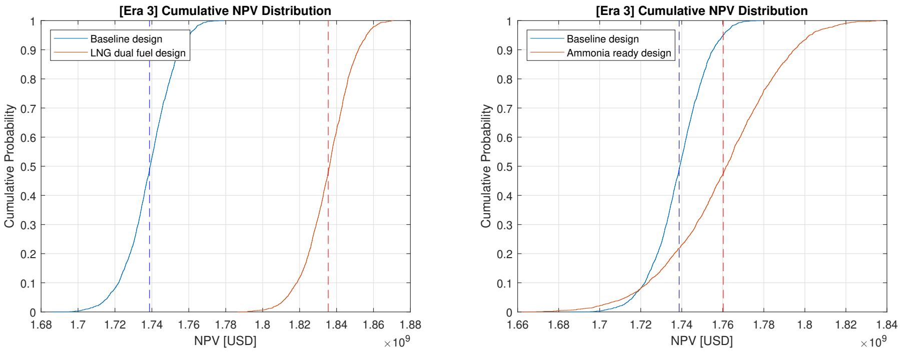
The LNG dual fuel design performs well in era 2, and its value of flexibility is high, as shown in Table 9.2. The reason for this is that it can run on LNG for a long time without introducing 95% zero-emission fuels, which creates lower VOYEX costs than for the baseline design. Furthermore, after HVO and LBG are introduced in epoch 4, the LNG dual fuel design can comply with the local 95% zero-emission zone. The ship can then run on 95% zero-emission compliant fuels for 20% of the time, while selecting the cheapest available fuel of LNG, HVO, LBG, e-methane and e-diesel for the rest of the year. Hence, as also seen in era 1, the fuel switching flexibility for the LNG dual fuel design shows to have a high value.

Table 9.2: Estimating the value of flexibility in era 2 (numbers in millions)

Ship design	ENPV [mUSD]	Value of flexibility [mUSD]
Baseline	1,793	-
LNG dual fuel	1,856	63
Ammonia ready	1,772	-21

Era 3 - "Green-Ambition Scenario (Low Fuel Price)"

The NPV performance in era 3 for each of the flexible cruise ship designs compared against the NPV performance of the baseline cruise ship design is presented in Figure 9.3. Era 3 is called a "green-ambition scenario", and both new environmental requirements, technologies and alternative fuels are expected in this era. The development of the fuel price in era 3 is assumed to be equal to the fuel price development in era 1 and era 2.



(a) Baseline design versus LNG dual fuel design **(b)** Baseline design versus ammonia ready design

Figure 9.3: Target curves for the baseline design, the LNG dual fuel design and the ammonia ready design in era 3 (2000 simulations)

In Figure 9.3, it can be seen that the flexible designs perform better than the baseline design. Hence, flexibility has a value in era 3. The LNG dual fuel design performs particularly well in era 3, and its flexibility has a high value, as shown in Table 9.3. The reason for this is that HVO and LBG are available already in epoch 2, making the LNG dual fuel design able to comply with the local 95% zero-emission regulation. Furthermore, VOYEX costs can be reduced by running on LNG for the time outside of the local 95% zero-emission zone, giving the LNG dual fuel design an advantage over the baseline design, as LNG is assumed to have a lower price than HFO.

The ammonia ready design performs well in this era, and its flexibility has a positive value. However, the VOYEX costs are much higher for the ammonia ready ship compared to the LNG dual fuel ship as it is not allowed to switch between fuels after its engines are rebuilt to run on ammonia. This is the main reason why the value of flexibility for the ammonia ready design is significantly lower than for the LNG dual fuel design in era 3.

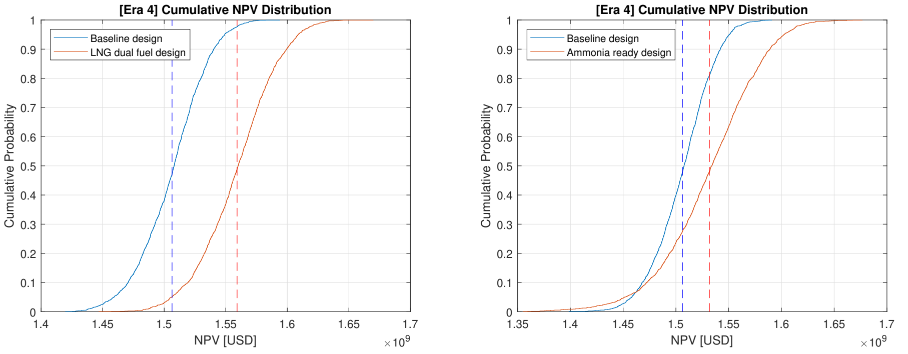
If we look at the ENPV results, it can be seen that the baseline design performs better in era 3 than in era 1. The reason for this is that HVO and e-diesel are introduced at an earlier point in time in era 3. Thus, making the baseline ship able to comply with the local 95% zero-emission requirement and avoids loosing revenue.

Table 9.3: Estimating the value of flexibility in era 3 (numbers in millions)

Ship design	ENPV [mUSD]	Value of flexibility [mUSD]
Baseline	1,735	-
LNG dual fuel	1,836	101
Ammonia ready	1,761	26

Era 4 - "Green-Ambition Scenario (High Fuel Price)"

The NPV performance in era 4 for each of the flexible cruise ship designs compared against the NPV performance of the baseline cruise ship design is presented in Figure 9.4. Era 4 is equal to era 3, except for the fuel price development, which is in the higher range in era 4.



(a) Baseline design versus LNG dual fuel design

(b) Baseline design versus ammonia ready design

Figure 9.4: Target curves for the baseline design, the LNG dual fuel design and the ammonia ready design in era 4 (2000 simulations)

Figure 9.4 and Table 9.4 shows that the flexible designs perform better than the baseline design, also when the fuel prices are in the higher range. Thus, the value of flexibility is positive for both of the flexible designs.

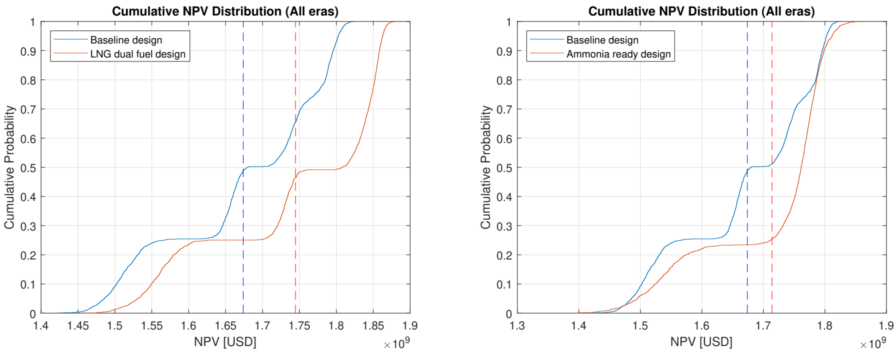
When comparing the results from era 3 and era 4, it is seen that the fuel price has a high influence on the ENPV performance of the cruise ship designs. The results show that the value of flexibility in the LNG dual fuel design decreases significantly when the fuel price increases. Whereas, the value of flexibility for the ammonia design increases a small part. The main reason for the significant decrease in flexibility value for the LNG dual fuel design, is that the price increase ratio for all of the fuels is not equal, thus some increases more than others. However, the results from era 4 show that the fuel price has a high impact on the economy of the cruise ships.

Table 9.4: Estimating the value of flexibility in era 4 (numbers in millions)

Ship design	ENPV [mUSD]	Value of flexibility [mUSD]
Baseline	1,504	-
LNG dual fuel	1,557	53
Ammonia ready	1,534	30

9.2 Flexible Designs versus Baseline Design in All Eras

In this section, the NPV performance of the flexible designs compared to the baseline design are evaluated when eras are selected arbitrarily in each simulation round. In order to make the simulation arbitrarily, pseudo-random numbers between 0 and 1 are picked from a uniform probability distribution. The probability for selecting each era is set to be equal. The results of this analysis are shown in Figure 9.5 below.



(a) Baseline design versus LNG dual fuel design

(b) Baseline design versus ammonia ready design

Figure 9.5: Target curves for the baseline design, the LNG dual fuel design and the ammonia ready design for all eras (2000 simulations)

Figure 9.5 shows that both of the flexible cruise ship designs perform better than the baseline design over all eras. Furthermore, Table 9.5 shows that the value of flexibility for the LNG dual fuel design is almost twice as high as the value of flexibility for the ammonia ready design. The results then show that the LNG dual fuel design performs best of the two flexible cruise ship design when evaluating over all of the four eras included in this case study. However, the results in Table 9.5 also shows that the flexibility introduced by the ammonia ready design has a significant value when evaluating over all eras.

Table 9.5: Estimating the value of flexibility (numbers in millions)

Ship design	ENPV [mUSD]	Value of flexibility [mUSD]
Baseline	1,670	-
LNG dual fuel	1,746	76
Ammonia ready	1,710	40

9.3 Sensitivity Analysis

The parameters under investigation in this sensitivity analysis are:

1. Discount rate.
2. Newbuild cost.
3. Retrofit time for the ammonia ready design.
4. Retrofit cost for the ammonia ready design.
5. The Number of cabins lost due to larger tanks in the ammonia ready design.

In the sensitivity analysis, the flexible designs are evaluated over all eras, as done in Section 9.2 above, and the number of simulations is set to 2000.

Discount Rate

Four different discount rates were tested in the valuation model to investigating the impact of the discount rate. The results of this analysis are shown in Table 9.6.

Table 9.6: Sensitivity analysis of the discount rate

Discount rate	ENPV [mUSD]			Value of flexibility [mUSD]	
	Baseline	LNG DF	Ammonia	LNG DF	Ammonia
2.5%	2,749	2,853	2,827	104	78
5%	1,670	1,746	1,710	76	40
7.5%	1,017	1,068	1,038	51	21
10%	0,602	0,640	0,607	38	5

[a] Baseline = Baseline design, LNG DF = LNG dual fuel design, Ammonia = Ammonia ready design.

The results are as we assumed them to be. With lower discount rates, the value of flexibility increases. In the opposite case, when the discount rate increases the value of flexibility decreases, as future cash flows become less valuable. In the case study, 5% was used as the discount rate.

Newbuild Cost

Five different newbuild costs for both of the flexible cruise ship designs were tested to investigate the impact of the newbuild cost on the value of flexibility. The results of the analysis are presented in Table 9.7 and Table 9.8.

Table 9.7 shows the results for the LNG dual fuel design. Here, it can be seen that the value of flexibility increases when the newbuild cost decreases, while decrease when the newbuild cost increases. Thus, having a low initial investment cost is preferable. The newbuild cost used for the LNG dual fuel design in the case study was 1,012 mUSD.

Table 9.7: Sensitivity analysis of the newbuild cost of the LNG dual fuel cruise ship (numbers in millions)

Newbuild cost [mUSD]	**ENPV [mUSD]**		**Value of flexibility [mUSD]**
	Baseline	**LNG DF**	**LNG DF**
1,005	1,670	1,751	81
1,010	1,670	1,748	78
1,012	1,670	1,746	76
1,015	1,670	1,740	70
1,020	1,670	1,738	68

[a] Baseline = Baseline design, LNG DF = LNG dual fuel design.

In Table 9.8, the results for the ammonia ready design are shown, and the results are the same as for the LNG dual fuel design. With lower initial investment, the value of flexibility increases, while it decreases when the newbuild cost increases. The newbuild cost used in the case study for the ammonia ready design was 1,006 mUSD.

Table 9.8: Sensitivity analysis of the newbuild cost of the ammonia ready cruise ship (numbers in millions)

Newbuild cost [mUSD]	ENPV [mUSD]		Value of flexibility [mUSD]
	Baseline	Ammonia	Ammonia
1,003	1,670	1,718	48
1,006	1,670	1,710	40
1,009	1,670	1,708	38
1,012	1,670	1,703	33
1,015	1,670	1,695	25

[a] Baseline = Baseline design, Ammonia = Ammonia ready design.

Retrofit Time for the Ammonia Ready Design

The time needed for rebuilding the ammonia ready design to be a cruise ship using ammonia will create a loss in revenue. In Table 9.9, the results from the sensitivity analysis are shown, and it can be seen that the number of days needed for the retrofit has a significant impact on the value of flexibility for the ammonia ready design. In the case study, it was assumed that 14 days were required for the ammonia retrofit.

Table 9.9: Sensitivity analysis of the retrofit time for the ammonia ready design

Days	ENPV [mUSD]		Value of flexibility [mUSD]
	Baseline	Ammonia	Ammonia
0	1,670	1,725	55
5	1,670	1,719	49
10	1,670	1,715	45
14	1,670	1,710	40
20	1,670	1,704	34
25	1,670	1,698	28
30	1,670	1,694	24
35	1,670	1,687	17

[a] Baseline = Baseline design, Ammonia = Ammonia ready design.

Retrofit Cost for the Ammonia Ready Design

Six different retrofit costs were tested to investigate the impact of the retrofit cost on the value of flexibility for the ammonia ready design. The results are presented in Table 9.10

and show that the retrofit cost has a minor effect on the value of flexibility for the ammonia ready design. In the case study, the retrofit cost for the ammonia ready design was assumed to be 2 mUSD.

Table 9.10: Sensitivity analysis of the retrofit cost for the ammonia ready design (numbers in millions)

Retrofit cost [mUSD]	ENPV [mUSD]		Value of flexibility [mUSD]
	Baseline	Ammonia	Ammonia
0	1,670	1,716	46
2	1,670	1,710	40
4	1,670	1,709	39
6	1,670	1,707	37
8	1,670	1,706	36
10	1,670	1,704	34

[a] Baseline = Baseline design, Ammonia = Ammonia ready design.

The Number of Cabins Lost due to Larger Tanks in the Ammonia Ready Design

In Table 9.11, the impact of cabins lost due to larger tanks on the value of flexibility for the ammonia ready design is presented. The results are as we expected, and shows that losing cabins will affect the value of flexibility heavily for the ammonia ready design. Furthermore, in Table 9.11, it can be seen that if the number of cabins lost becomes very large, the value of the flexibility introduced by the ammonia ready design becomes negative. In the case study, it was assumed that no cabins were lost due to larger tanks.

Table 9.11: Sensitivity analysis of the number of cabins lost due to larger tanks on board the ammonia ready cruise ship

Cabins lost	ENPV [mUSD]		Value of flexibility [mUSD]
	Baseline	Ammonia	Ammonia
0	1,670	1,710	40
20	1,670	1,703	33
40	1,670	1,692	22
60	1,670	1,680	10
80	1,670	1,672	2
100	1,670	1,666	-4

[a] Baseline = Baseline design, Ammonia = Ammonia ready design.

Chapter 10

Discussion

In this chapter, the results from the case study are discussed. The chapter is divided into four parts: a general discussion of the results, investigating the robustness of the results, discussion on how we model the future, and a general discussion of other aspects and assumptions made in the case study.

10.1 General Discussion of the Results

The results presented in Section 9.1 show that the flexible designs perform better than the baseline design (inflexible design) in all eras, except for one. The exception is in era 2, where the baseline design performs better than the ammonia ready design. Thus, with the assumptions made in the case study, the results show that there is no value of investing in the ammonia ready design if era 2 occur.

In Section 9.2, we investigated the performance of each flexible design compared to the baseline design over all eras. The results from this analysis show that both of the flexible designs perform better than the baseline design when we evaluate the performance over all eras. Hence, with the assumptions made in the case study, the results show that investing in one of the flexible cruise ship designs is a better decision than investing in the baseline design on a general basis.

The flexible cruise ship design that shows best overall performance is the LNG dual fuel design, with an almost twice as high value of flexibility compared to the ammonia ready design when evaluating over all eras (see Table 9.5). It can be argued that this is a logical result, as the LNG dual fuel cruise ship is a more versatile design compared to the ammonia ready design. On the other hand, the results show that the ammonia ready design is the one with the highest maximum value of flexibility when investigating each era separately. This is also a result that can be argued to be as expected, as the ammonia ready design is a more specialised design than the LNG dual fuel design, and should, therefore, perform very good for certain future scenarios. Furthermore, the ammonia ready design has its maximum value of flexibility in era 1, and it can be argued that we expect this era to occur more than the others as it is a baseline era. Thus, saying that the LNG dual fuel design is the most preferable design to choose of the two flexible design only as it performs best on an averages basis is possibly inadequate.

The ENPV performance for the cruise ship designs varies greatly for the different eras, which indicates that the results are highly sensitive to the development of environmental requirements, technology, and alternative fuels in the future. Furthermore, after investigating the results in even more detail, it is seen that the ”fuel price” and the ”revenue” have a particularly high impact on the ENPV performance of the cruise ships.

One of the reasons why the LNG dual fuel cruise ship performs better than the baseline cruise ship is that it is able to reduce VOYEX cost by always choosing the cheapest fuel, and to maintain a high revenue by complying with 95% zero-emission regulations when that is required (if 95% zero-emission compliant fuels are available). The ammonia ready design has a clear disadvantage compared to the LNG dual fuel design in the way that it cannot switch between fuels when it first has been rebuilt to run on ammonia. The ammonia ready design does, therefore, have to run on a more expensive fuel also outside of the local 95% zero-emission zone, creating higher VOYEX costs than for the LNG dual fuel design.

Which design to choose of the LNG dual fuel design and the ammonia ready design is not a straight forward decision to make. The ammonia ready design has a very high performance in the ”baseline era”, which could be argued to be the era that we expect the most to occur. The LNG dual fuel design, on the other hand, has a better performance over all eras and is more versatile. Thus, to conclude that one of the cruise ship designs is a better decision than the other is difficult as it is highly dependent on how the future develops. However, the analysis shows that future-proofing cruise ships with flexibility generally has a high value. Furthermore, it can be argued that selecting the LNG dual fuel design is based on the results from the case study a safer design choice than the ammonia ready design.

Unfortunately, the flexibility analysis is unable to properly capture the risk picture of the investments in the cruise ship designs, as only positive NPV values are obtained from the analysis. There are several reasons for that only positive NPV values are generated in the analysis. One of them is that the revenue per passenger is kept constant equal to 250 USD/passenger/day during the 30 years of operation, and the cruise ships are assumed always to be fully booked. Another reason is that only the costs that will be different between the cruise ship designs have been included in the analysis, meaning that, e.g. crew costs are not included in the calculations. The ENPV results from the analysis are, therefore, most likely too high. Introducing more cost elements into the flexibility analysis is therefore proposed in further work. Additionally, if we had evaluated more eras, we would have obtained a higher spread in the NPV results, which most likely would create target curves going from negative to positive NPV values.

10.2 Robustness of the Results

A sensitivity analysis was performed to check the robustness of the results. The sensitivity analysis tested five different parameters with high uncertainty, and the results are shown in Section 9.3. The results from this sensitivity analysis support aspects already discussed at the beginning of this chapter. Especially the fact that revenue has a high impact on the performance of the cruise ships. For example, losing cabins due to larger tanks in the ammonia ready design shows to have a high impact on the performance of the ammonia ready design, as losing cabins will indicate a loss in revenue (see Table 9.11).

That revenue is important to the performance of the cruise designs is also shown in the sensitivity analysis of the ”retrofit time for the ammonia ready design”. Where a long time needed for the retrofit indicates high revenue losses and affects the performance of the ammonia ready design greatly. This brings us into the ”agility” aspect of changeability (see Section 2.2, Figure 2.3), which is related to the time aspect of changing a system. The results from the sensitivity analysis then show that it is preferable to have a design that is as agile as possible, meaning that the retrofit can be made rapidly.

Another parameter with high impact on the value of flexibility is the discount rate. The results from the discount rate analysis are shown in Table 9.6 and they show that if we reduce the discount rate, the value of flexibility increases for the flexible designs. While, by increasing the discount rate, the value of flexibility decreases. This is what we expected, as with high discount rates, future cash flows become less valuable, and being flexible is given a lower value. Being aware of the impact of the discount rate when using the NPV method for valuing flexibility is therefore vital.

If we look at the impact of the newbuild cost in Table 9.7 and Table 9.8, it can be seen that the effect of the newbuild cost is less than for the discount rate, loss of cabins and time for retrofit. However, the newbuild cost has an impact, and we should strive to make this cost as low as possible in order to maximise the value of flexibility. Again, if the initial cost for the flexibility becomes too large, the value of flexibility will be reduced significantly and in the worst-case disappear.

The ammonia ready design has to be retrofitted for running on ammonia, which will cause an additional cost for the shipowner. The impact of this retrofit cost on the value of flexibility for the ammonia ready design was tested in the sensitivity analysis. The results from this analysis are presented in Table 9.10 and shows that the retrofit cost has a minor impact on the value of flexibility for the ammonia ready design. The main reason for this is that this cost becomes small compared to, for example, losing revenue as a result of not being able to comply with the environmental regulations. However, when that is said, it can be seen that the retrofit cost has an impact, and we should aim to keep this as low as possible for maximising the value of flexibility.

What can be seen from the results obtained in the sensitivity analysis is that flexibility comes with a cost, and if this cost becomes too high, the value of having flexibility in the design will either be very low or totally disappear. This is, for example, greatly shown in the sensitivity analysis of the impact of losing cabins, which shows that if to many cabins are lost due to larger tanks the value of flexibility may quickly become very small.

In the case study, it was assumed that the cruise ships were sailing with a full utilisation rate at every point in time, which means that the cruise ships were always fully booked. As a result of this, the number of cabins lost due to larger tanks will for the ammonia ready design have a very high impact on the ENPV performance of this cruise ship. The utilisation rate for cruise ships is uncertain, and it could be argued that it would be better to assume a utilisation rate of 80-90%. If this was the case, the value of flexibility for the ammonia ready design would be less sensitive to loss of cabins due to larger fuel tanks.

Some may say that the value of flexibility for the LNG dual fuel design is underestimated in our analysis. The reason for this is that the option of rebuilding the LNG dual fuel design into an ammonia design has not been accounted for. However, note that this option requires that materials with the ability to handle the corrosive nature of ammonia have been used in the LNG system (Wartsila, 2020). Including the ammonia option for the LNG dual fuel design is therefore proposed in further work. Furthermore, by giving the LNG dual fuel design, one more option will only increase the value of flexibility for this design.

In the analysis, the baseline cruise ship is allowed to switch to HVO or e-diesel for 95% zero-emission compliance. Some may argue that this makes the analysis to underestimate the value of flexibility for the flexible designs, and especially for the ammonia ready design. The availability of HVO and e-diesel is highly uncertain, and some may say that it is a significantly higher probability of ammonia to be a widely available fuel for cruise ships than HVO or e-diesel. However, at this point in time, the availability for all of the low- and zero-emissions fuels for ships are highly uncertain.

10.3 Modelling the Future by Epoch-Era Analysis

Generating the Eras

Eras can be generated with different methods, and the one used in this case study was the narrative approach. Advantages of the narrative method are that it is simple, and the decision maker and the maritime experts are allowed to test specific futures they believe can happen. However, the eras can quickly become biased, resulting in that eras we want to occur instead of realistic eras are modelled. To solve the problem of biased eras, a simulation approach could have been used. In this approach, simulations are used to generate the eras by following assigned transition rules and probabilities between each epoch. The results for the case study show that the eras have a high impact on the performance of the cruise ship designs. Thus, having the ability to test a wider range of eras generated by a simulation process could give us the opportunity of investigating the robustness of the cruise ship designs in even more detail. The simulation approach is, therefore, mentioned in further work.

The length of the epochs is another aspect of the epoch-era analysis that could be discussed. In the case study, the length of the epochs was set to five years. Some may argue that five years is too much, as a lot may occur over five years. However, the future is highly uncertain, and we do not have the ability to predict it 100%. Together with maritime experts, it was, therefore, decided that using epochs with five years in length was adequate in this case study.

Environmental Regulations

The main focus in this case study is GHG emissions, as this is expected to be the main challenge for cruise ships to reduce during the years. Both the IMO and regional authorities as the EU are currently investigating measures for reducing GHG emissions from ships, but concrete measures are still highly uncertain. In the case study, five different epoch variables concerning GHG emissions were included: local zero-emission regulation, global zero-emission regulation, local CO_2 tax, global CO_2 tax and the EPI. These were obtained by investigating political action plans from the Norwegian Government, reports from the EU commission, IMO's GHG Strategy, and by speaking to experts within the cruise industry and environmental regulations for ships.

It can be argued that the approach regarding environmental regulations in this thesis is relatively strict, as we are using zero-emission requirements instead of speed reduction or energy efficiency measures. The reason that zero-emission requirements are used is that we assume only reducing cruising speed, e.g., not will be enough to comply with the expectations from the cruise passengers. Thus, we believe that cruise passengers in the coming years will select cruise ships also based on the cruise ships environmental performance.

The term zero-emission has several interpretations. There is, for example, an ongoing discussion in the Norwegian world heritage fjords these days, on whether zero-emission should mean "no emissions at all" or 95% reduction in GHG, NO_x Tier III and SO_x 0.1% (DNV GL, 2020). In this thesis, it was chosen to interpret the zero-emission term as 95% reduction in GHG, NO_x Tier III and SO_x 0.1%. As a result of this, were solutions like hydrogen or ammonia in fuel cells, or fully electric operations with batteries scoped out of this thesis. These are all solutions that potentially will fulfil a 100% zero-emission regulation (DNV GL, 2020), and including 100% zero-emission regulations and technology in the valuation model is proposed in further work.

It can be argued that to require global zero-emission operations for all cruise ships from epoch 4 (2038-) in the baseline era is very strict and optimistic. However, a lot is expected to occur during the coming years, and several papers report that shipping will have to take zero-emission fuels into use from 2030 to be able to meet the 2°C Paris Agreement (e.g. (Lloyd's Register and UMAS, 2020)). It has also to be mentioned that the Norwegian Shipowner's Association recently published their GHG strategy, where it was emphasised that their members should only invest in ships with zero-emission technology from 2030 (NSA, 2020). Thus, taking the strict approach related to emissions as done in this thesis is maybe acceptable due to this.

10.4 Other Aspects

Safety and Technological Maturity for the Ammonia Ready Cruise Ship

Safety is one of the main issues with ammonia and needs to be taken care of with seriousness. In the case study, it was assumed that the safety aspect of ammonia was resolved when the technology was mature, and ammonia as a fuel was available. This assumption was emphasised by maritime experts to be reasonable, as it is expected that ammonia can play a key role for decarbonising shipping in the coming years.

Another issue that needs to be addressed for the ammonia ready cruise ship is the technological aspect. Research projects are currently under development investigating ammonia in internal combustion engines. However, when the technology is commercialised is still uncertain (DNV GL, 2020). It is in this thesis assumed that the technology for ammonia to be used in four-stroke engines would be commercialised within the next 8-10 years.

Lay-Up Option

The cruise ship is given three options if a local zero-emission regulation is introduced, where one of these is ”avoid to sail that route”. This option is the same as a temporarily ”lay-up option”, as the cruise ship is losing the same amount as it would have gained if it was able to sail the route.

It can be argued that it would have been more realistic to model the ”avoid to sail that route”, as a ”sail another route” option instead of a ”lay-up” option. The cruise ship can, for example, sail another route, but to a lower revenue than the initial route. Furthermore, if the ”sail another route” option actually will create lower revenues is another question. The option of sailing another route instead of laying up the cruise ship is, therefore, mentioned in further work.

Production of the Alternative Fuels

The IMO is expected to increase its focus on life cycle emissions from fuels in the years to come (DNV GL, 2019c). Thus, having a life cycle perspective when evaluating alternative fuels will become more and more important. For the alternative fuels investigated in this case study to have a positive effect on the environment, they must be produced as environmentally friendly as possible. It is, for example, favourable if ammonia is produced from an electrolysis process by renewable electricity, and not from natural gas. For e-diesel and e-methane, to have a positive effect on the environment, it is required that the carbons used in the production come from CCS and the electricity from clean and renewable sources.

Biofuels are currently one of the most disputed fuels on the market, and it is widely discussed whether they shall be characterised as carbon-neutral or not. Furthermore, biofuels should not be produced from sources that could have been used as food, or use land that could have been used for food production. In this thesis, LBG and HVO, have been assumed to be produced sustainable.

Are Cruise Owners using Flexibility Today?

The first LNG powered cruise ship, AIDAnova, came in 2018.[1] Today, LNG as a fuel for cruise ships have become increasingly popular, and around 35 LNG power cruise ships are in operation and on order.[2] It can because of this be argued that cruise owners have

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[1] https://carnivalsustainability.com/highlights/pioneering-liquefied-natural-gas/

[2] https://afi.dnvgl.com/

seen the value in being fuel flexible, for complying with ECA zone requirements, always selecting the cheapest fuel, and to prepare for the future.

Changeability Instead of Flexibility?

It can be argued that the term changeability instead of flexibility should have been used about the flexible designs in the case study. The reason for this is that the LNG dual fuel design is more an adaptable design than a flexible design, according to the definitions given by Fricke and Schulz (2005). Thus, by definition, only the ammonia ready design can be called a flexible design. However, as flexibility generally is better understood by non-technical stakeholders, than changeability, it was decided to stick to the flexibility term in this thesis.

COVID-19

The tourism sector in general and cruise ships more specifically are suffering large losses these days due to the outbreak of the worldwide pandemic *COVID-19*. All cruise ships are today in port, and many ask how long it will take before we will travel with cruise ships again. In the case study, it was assumed that the cruise market remains stable and robust for over 30 years. However, based on what we see in the cruise market today, it can be discussed whether this was an adequate assumption or not.

Chapter 11

Conclusion

In this thesis, we have investigated the value of future-proofing cruise ships by designing for flexibility. To value flexibility in cruise ship design has a generic flexibility analysis framework been proposed. This framework builds on epoch-era anlysis and real options analysis with Monte Carlo simulation and aims to be a structured step-wise approach for valuing flexibility in ship design. Furthermore, to facilitate dialogue between a maritime expert and a technical or non-technical decision maker.

This framework was successfully tested in a case study, where two flexible cruise ship designs were investigated, an LNG dual fuel design and an ammonia ready design. In the case study, Monte Carlo simulation excelled as a proper tool for valuing more complex real options ”in” projects, and the epoch-era analysis turned out as a structured way of modelling the future.

The results from the case study illustrate that flexibility in cruise ship design generally has a high value and that it significantly improves the performance of the design. However, the results and the sensitivity analysis also show that flexibility comes with a cost, and if this cost becomes too high, the value of flexibility may disappear. Results from the case study show that the value of flexibility is highly dependent on how the future evolves. The ammonia ready design performed best in the era we believed was the most likely one, while the LNG dual fuel design performed best when evaluated over all eras. It is, therefore, difficult to say which of the flexible designs that will be the best investment decision. Thus, which flexible design to invest in is more related to which of the future scenarios the decision maker believes in most.

At this moment in time, there are many unanswered questions related to environmental requirements for cruise ships. However, new and stricter environmental requirements will arrive, there is no doubt about that. Thus, results from this thesis, show that future-proofing cruise ships by designing for flexibility generally has a high value.

11.1 Further Work

This thesis shows that flexibility in cruise ship design for handling uncertainty regarding environmental requirements, technological innovations and alternative fuels is an attractive topic and something that should be further investigated.

Several assumptions had to be made for valuing flexibility in the cruise ship designs in the case study. It would, therefore, be of high interest to further develop the valuation model, for generating even more realistic valuation estimates of having flexibility in the design. In the following, some recommendations for further work are presented.

- Generate eras by using simulation instead of the narrative approach. As the narrative approach quickly becomes biased. Furthermore, by generating eras with simulation, more eras can potentially be created meaning that the robustness of the flexible designs can be even more thoroughly tested. This would most likely create target curves that moves over both negative and positive NPV values, which makes it possible to illustrate that downside risk is reduced by flexibility. It could also be interesting to decrease the intervals of the epochs, from five years to two years e.g.
- Include more costs in the flexibility analysis, e.g. crew costs, in order to obtain even more realistic NPV values. The target curve will then create both positive and negative NPV results, which makes it possible to give a better picture of the reduction in downside risk provided by a flexible design.
- Include 100% zero-emission regulations (both local and global) in the model. This will require that also fuel cell technology is included as flexible design alternatives.
- Improve the designs already included in the valuation model, by including more realistic data and by giving the cruise designs more retrofit options. For example, giving the LNG dual fuel cruise ship design the option to switch to ammonia.
- Improve the ”on” options. By, for example, including a ”sail another route” option in the valuation model, as a complement to the ”avoid to sail that route”/”Lay-up” option.
- Investigate the availability of the alternative fuels even more, as it is possible that the eras used in the case study are too optimistic on the timing of the availability of the fuels.

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Appendix A

Map of EU Ports That Differentiate Port Fees

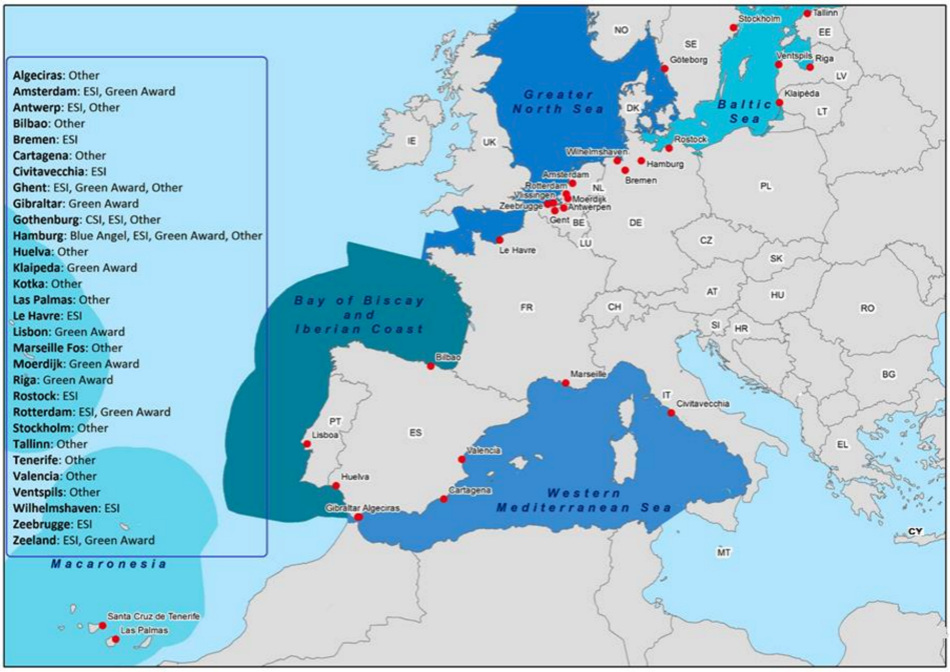
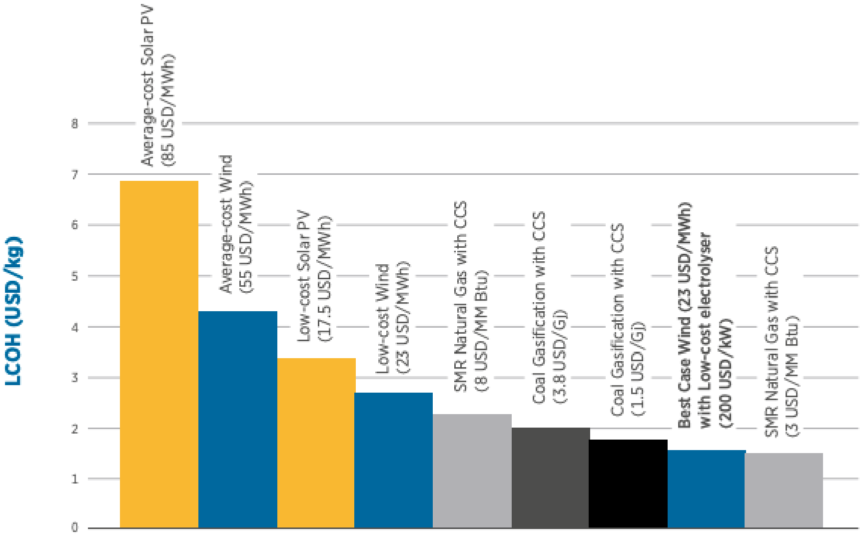


Figure A.1: Map of EU ports that differentiate charges based on environmental criteria (adopted from (Bragadin and Pititto, 2017))

Appendix B

Production Cost of Hydrogen

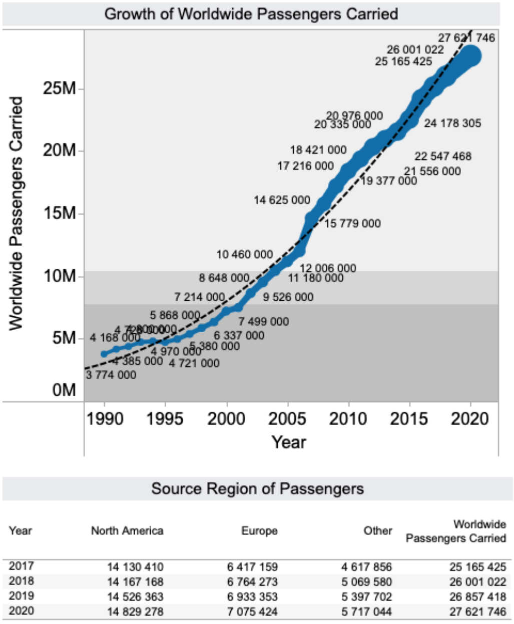


Notes: Electrolyser capex: USD 840/kW; Efficiency: 65%; Electrolyser load factor equals to either solar or wind reference capacity factors. For sake of simplicity, all reference capacity factors are set at 48% for wind farms and 26% for solar PV systems.
Source: IRENA analysis

Figure B.1: Costs of producing hydrogen from renewables and fossil fuels today (adopted from (IRENA, 2019))

Appendix C

The Cruise Market Development



Source Region of Passengers

Year	North America	Europe	Other	Worldwide Passengers Carried
2017	14 130 410	6 417 159	4 617 856	25 165 425
2018	14 167 168	6 764 273	5 069 580	26 001 022
2019	14 526 363	6 933 353	5 397 702	26 857 418
2020	14 829 278	7 075 424	5 717 044	27 621 746

Figure C.1: The cruise market development from 1990-2020 (Cruise Market Watch, 2020)

Appendix D

Estimates of Fuel Production Costs for Alternative Fuels

Table D.1: Production cost estimates for the different alternative fuels (Brown et al., 2020; Brynolf et al., 2018; IRENA, 2019; NCE Maritime CleanTech, 2019; Lloyd's Register and UMAS, 2020)

Fuel types	**Production cost (min - max)**
Blue hydrogen	3000 - 5300 USD/tonne
Blue ammonia	500 - 800 USD/tonne
E-methane	3800 - 6200 USD/tonne
E-diesel	5600 - 8900 USD/tonne
Green hydrogen	6200 - 11000 USD/tonne
Green ammonia	1000 - 1700 USD/tonne
HVO	800 - 900 USD/tonne
LBG	1100 - 1200 USD/tonne

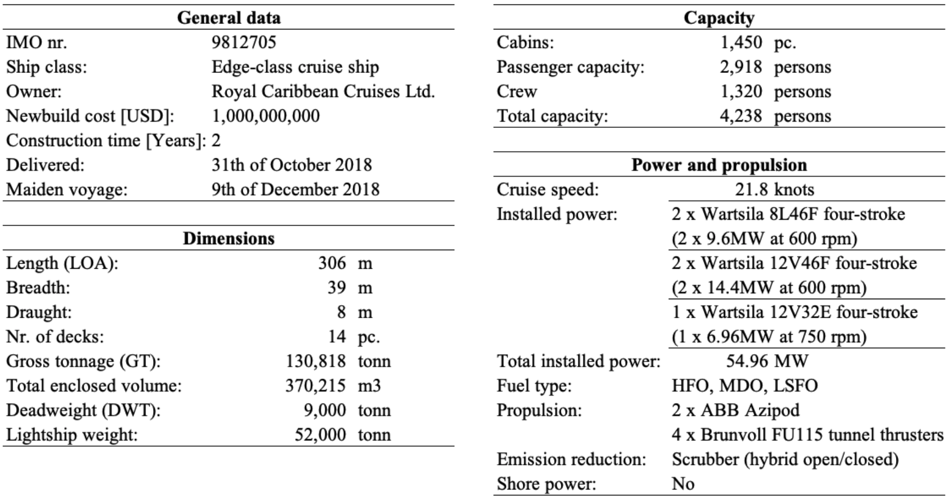
Appendix E

Case Study

E.1 The Cruise Ship - Celebrity Edge

The cruise ship Celebrity Edge is a part of the Royal Caribbean Cruises and is the first of fours ships delivered in the new Edge-class. The newbuild cost of the Celebrity Edge is estiated to be 1,000 mUSD.[1] Table E.1 below, presents information about the Celebrity Edge.[2]

Table E.1: Data about the Celebrity Edge cruise ship



General data	
IMO nr.	9812705
Ship class:	Edge-class cruise ship
Owner:	Royal Caribbean Cruises Ltd.
Newbuild cost [USD]:	1,000,000,000
Construction time [Years]:	2
Delivered:	31th of October 2018
Maiden voyage:	9th of December 2018

Dimensions		
Length (LOA):	306	m
Breadth:	39	m
Draught:	8	m
Nr. of decks:	14	pc.
Gross tonnage (GT):	130,818	tonn
Total enclosed volume:	370,215	m3
Deadweight (DWT):	9,000	tonn
Lightship weight:	52,000	tonn

Capacity		
Cabins:	1,450	pc.
Passenger capacity:	2,918	persons
Crew	1,320	persons
Total capacity:	4,238	persons

Power and propulsion	
Cruise speed:	21.8 knots
Installed power:	2 x Wartsila 8L46F four-stroke (2 x 9.6MW at 600 rpm)
	2 x Wartsila 12V46F four-stroke (2 x 14.4MW at 600 rpm)
	1 x Wartsila 12V32E four-stroke (1 x 6.96MW at 750 rpm)
Total installed power:	54.96 MW
Fuel type:	HFO, MDO, LSFO
Propulsion:	2 x ABB Azipod 4 x Brunvoll FU115 tunnel thrusters
Emission reduction:	Scrubber (hybrid open/closed)
Shore power:	No

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[1] https://www.cruisemapper.com/wiki/759-how-much-does-a-cruise-ship-cost

[2] https://vesselregister.dnvgl.com/VesselRegister/vesseldetails.html?vesselid=34827

E.2 Operational Data for the Celebrity Edge

From AIS data is operational data from the 2019 cruise season for the Celebrity Edge obtained. In Figure E.1, the annual speed distribution is shown.

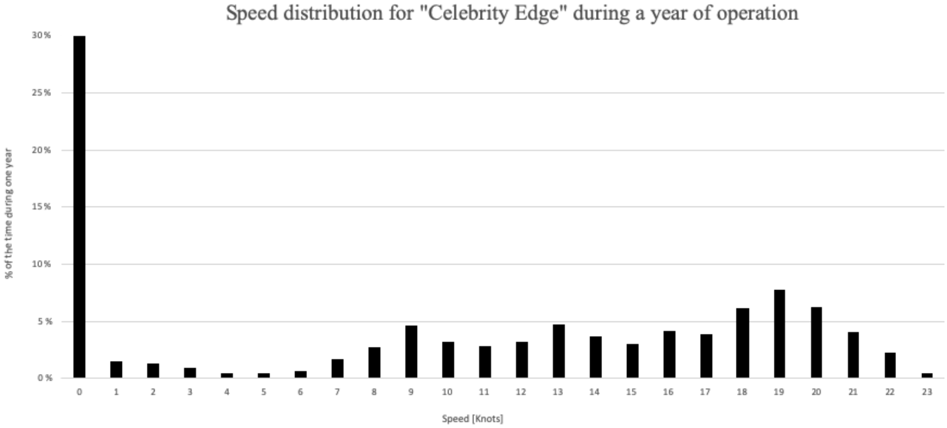


Figure E.1: Speed distribution for the Celebrity Edge during a year of operation (from AIS data) (Mjelde, 2020)

In Table E.2, estimates of the annual fuel consumption and CO_2 emissions of the Celebrity Edge are shown. These estimates are based on AIS data and provided by a maritime expert in DNV GL.

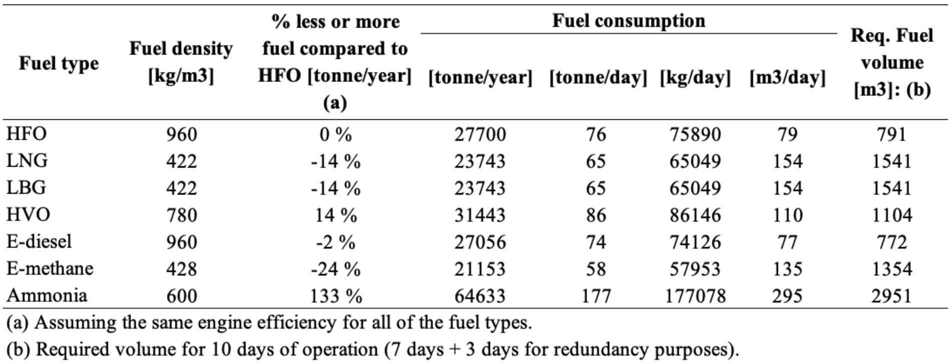
Table E.2: Fuel consumption and CO_2 emissions from AIS data (Mjelde, 2020)

	Fuel consumption	**CO_2 emissions**
Celebrity Edge	27700 tonne/year	88400 tonne CO_2/year

E.3 Fuel Tank Estimation

The annual fuel consumption and the fuel tank size for each alternative fuel are estimated based on the operational data for the Celebrity Edge. The results are presented in Table E.3 below.

Table E.3: Estimating the fuel tank capacity for the alternative fuels



Fuel type	Fuel density [kg/m3]	% less or more fuel compared to HFO [tonne/year] (a)	Fuel consumption				Req. Fuel volume [m3]: (b)
			[tonne/year]	[tonne/day]	[kg/day]	[m3/day]	
HFO	960	0 %	27700	76	75890	79	791
LNG	422	-14 %	23743	65	65049	154	1541
LBG	422	-14 %	23743	65	65049	154	1541
HVO	780	14 %	31443	86	86146	110	1104
E-diesel	960	-2 %	27056	74	74126	77	772
E-methane	428	-24 %	21153	58	57953	135	1354
Ammonia	600	133 %	64633	177	177078	295	2951

(a) Assuming the same engine efficiency for all of the fuel types.

(b) Required volume for 10 days of operation (7 days + 3 days for redundancy purposes).

E.4 Epoch Variables

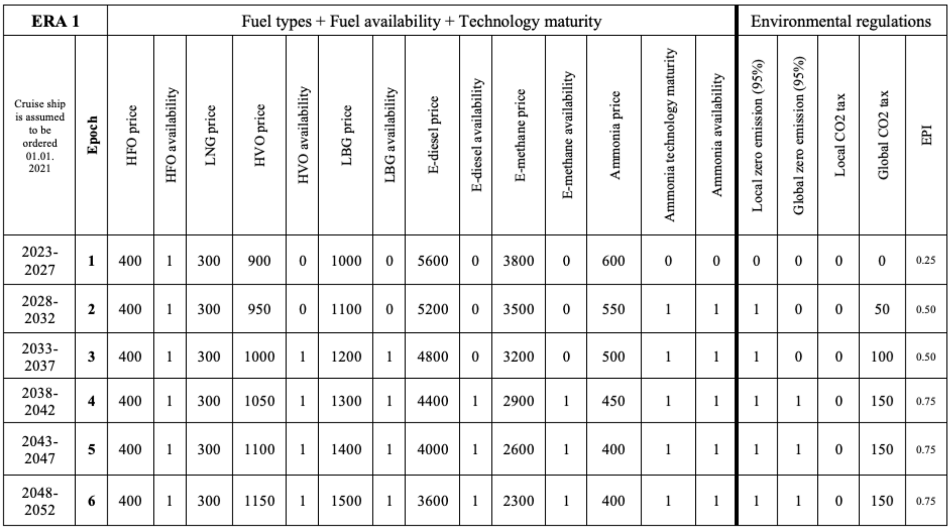
Table E.4: Epoch variables

	Epoch variables	**Range (min-max)**	**Step length**	**Nr. of steps**
Technology space	HFO fuel price	200 - 700	50	11
	HFO fuel availability	0 - 1	1	2
	LNG fuel price	200 - 700	50	11
	HVO fuel price	800 - 4000	50	65
	HVO fuel availability	0 - 1	1	2
	LBG fuel price	1100 - 4800	100	38
	LBG fuel availability	0 - 1	1	2
	E-diesel fuel price	3500 - 9000	100	56
	E-diesel fuel availability	0 - 1	1	2
	E-methane fuel price	2300 - 6000	100	38
	E-methane fuel availability	0 - 1	1	2
	Ammonia fuel price	400 - 1700	50	26
	Ammonia technology maturity	0 - 1	1	2
	Ammonia fuel availability	0 - 1	1	2
Regulatory space	Local zero-emission (95%)	0 - 1	1	2
	Local zero-emission (100%)	0 - 1	1	2
	Local CO_2 tax	50 - 200	50	4
	Global CO_2 tax	50 - 250	50	5
	Environmental port index (EPI)	0.25 - 1	0.25	4

E.5 Quantitative Description of the Eras

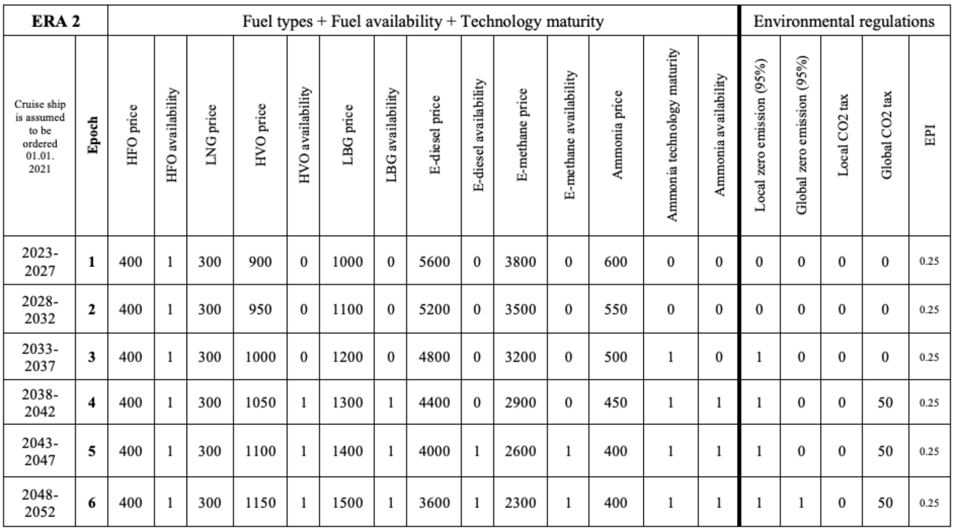
Note: 1 = yes and 0 = no.

Table E.5: Quantitative description of era 1



ERA 1		Fuel types + Fuel availability + Technology maturity														Environmental regulations				
Cruise ship is assumed to be ordered 01.01. 2021	**Epoch**	HFO price	HFO availability	LNG price	HVO price	HVO availability	LBG price	LBG availability	E-diesel price	E-diesel availability	E-methane price	E-methane availability	Ammonia price	Ammonia technology maturity	Ammonia availability	Local zero emission (95%)	Global zero emission (95%)	Local CO2 tax	Global CO2 tax	EPI
2023-2027	**1**	400	1	300	900	0	1000	0	5600	0	3800	0	600	0	0	0	0	0	0	0.25
2028-2032	**2**	400	1	300	950	0	1100	0	5200	0	3500	0	550	1	1	1	0	0	50	0.50
2033-2037	**3**	400	1	300	1000	1	1200	1	4800	0	3200	0	500	1	1	1	0	0	100	0.50
2038-2042	**4**	400	1	300	1050	1	1300	1	4400	1	2900	1	450	1	1	1	1	0	150	0.75
2043-2047	**5**	400	1	300	1100	1	1400	1	4000	1	2600	1	400	1	1	1	1	0	150	0.75
2048-2052	**6**	400	1	300	1150	1	1500	1	3600	1	2300	1	400	1	1	1	1	0	150	0.75

Table E.6: Quantitative description of era 2



ERA 2		Fuel types + Fuel availability + Technology maturity														Environmental regulations				
Cruise ship is assumed to be ordered 01.01. 2021	**Epoch**	HFO price	HFO availability	LNG price	HVO price	HVO availability	LBG price	LBG availability	E-diesel price	E-diesel availability	E-methane price	E-methane availability	Ammonia price	Ammonia technology maturity	Ammonia availability	Local zero emission (95%)	Global zero emission (95%)	Local CO2 tax	Global CO2 tax	EPI
2023-2027	**1**	400	1	300	900	0	1000	0	5600	0	3800	0	600	0	0	0	0	0	0	0.25
2028-2032	**2**	400	1	300	950	0	1100	0	5200	0	3500	0	550	0	0	0	0	0	0	0.25
2033-2037	**3**	400	1	300	1000	0	1200	0	4800	0	3200	0	500	1	0	1	0	0	0	0.25
2038-2042	**4**	400	1	300	1050	1	1300	1	4400	0	2900	0	450	1	1	1	0	0	50	0.25
2043-2047	**5**	400	1	300	1100	1	1400	1	4000	1	2600	1	400	1	1	1	0	0	50	0.25
2048-2052	**6**	400	1	300	1150	1	1500	1	3600	1	2300	1	400	1	1	1	1	0	50	0.25

Table E.7: Quantitative description of era 3

ERA 3		Fuel types + Fuel availability + Technology maturity														Environmental regulations				
Cruise ship is assumed to be ordered 01.01. 2021	**Epoch**	HFO price	HFO availability	LNG price	HVO price	HVO availability	LBG price	LBG availability	E-diesel price	E-diesel availability	E-methane price	E-methane availability	Ammonia price	Ammonia technology maturity	Ammonia availability	Local zero emission (95%)	Global zero emission (95%)	Local CO2 tax	Global CO2 tax	EPI
2023-2027	**1**	400	1	300	900	0	1000	0	5600	0	3800	0	600	0	0	0	0	100	0	0.25
2028-2032	**2**	400	1	300	950	1	1100	1	5200	0	3500	0	550	1	1	1	0	0	150	0.50
2033-2037	**3**	400	1	300	1000	1	1200	1	4800	1	3200	1	500	1	1	1	0	0	200	0.50
2038-2042	**4**	400	1	300	1050	1	1300	1	4400	1	2900	1	450	1	1	1	1	0	200	0.75
2043-2047	**5**	400	1	300	1100	1	1400	1	4000	1	2600	1	400	1	1	1	1	0	250	0.75
2048-2052	**6**	400	0	300	1150	1	1500	1	3600	1	2300	1	400	1	1	1	1	0	250	0.75

Table E.8: Quantitative description of era 4

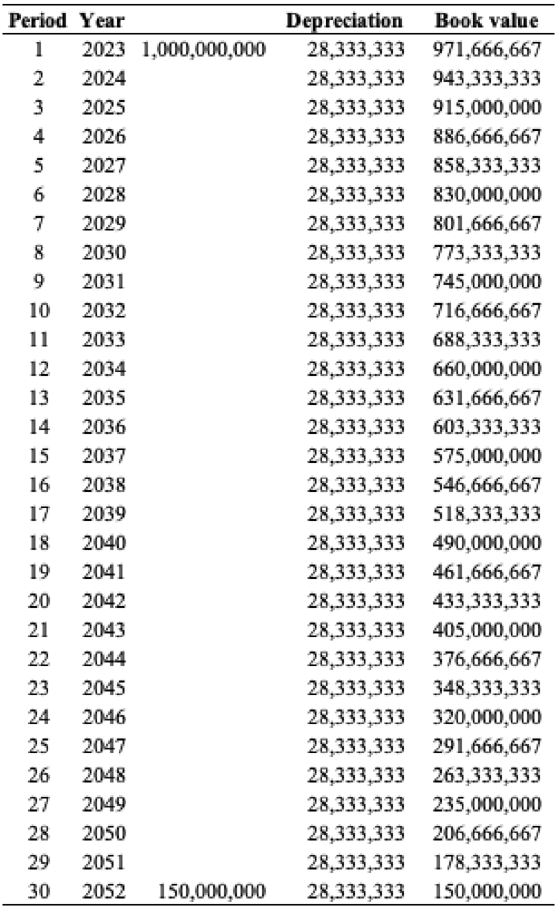
ERA 4		Fuel types + Fuel availability + Technology maturity														Environmental regulations				
Cruise ship is assumed to be ordered 01.01. 2021	**Epoch**	HFO price	HFO availability	LNG price	HVO price	HVO availability	LBG price	LBG availability	E-diesel price	E-diesel availability	E-methane price	E-methane availability	Ammonia price	Ammonia technology maturity	Ammonia availability	Local zero emission (95%)	Global zero emission (95%)	Local CO2 tax	Global CO2 tax	EPI
2023-2027	**1**	700	1	600	1000	0	1300	0	8900	0	6000	0	900	0	0	0	0	100	0	0.25
2028-2032	**2**	700	1	600	1500	1	1800	1	8200	0	5500	0	850	1	1	1	0	0	150	0.5
2033-2037	**3**	700	1	600	2000	1	2300	1	7500	1	5000	1	800	1	1	1	0	0	200	0.5
2038-2042	**4**	700	1	600	2500	1	2800	1	6800	1	4500	1	750	1	1	1	1	0	200	0.75
2043-2047	**5**	700	1	600	3000	1	3300	1	6100	1	4000	1	700	1	1	1	1	0	250	0.75
2048-2052	**6**	700	0	600	3500	1	3800	1	5400	1	3500	1	650	1	1	1	1	0	250	0.75

E.6 Sell Option Estimation

After being in contact with experts in DNV GL, it was emphasised that estimating the value of a cruise ship after a given set of years generally is very challenging. However, for modelling purposes, it was suggested that the book value could give an adequate estimate. The book value is, therefore, used to estimate the value (selling price) of the cruise ship designs during their lifetime.

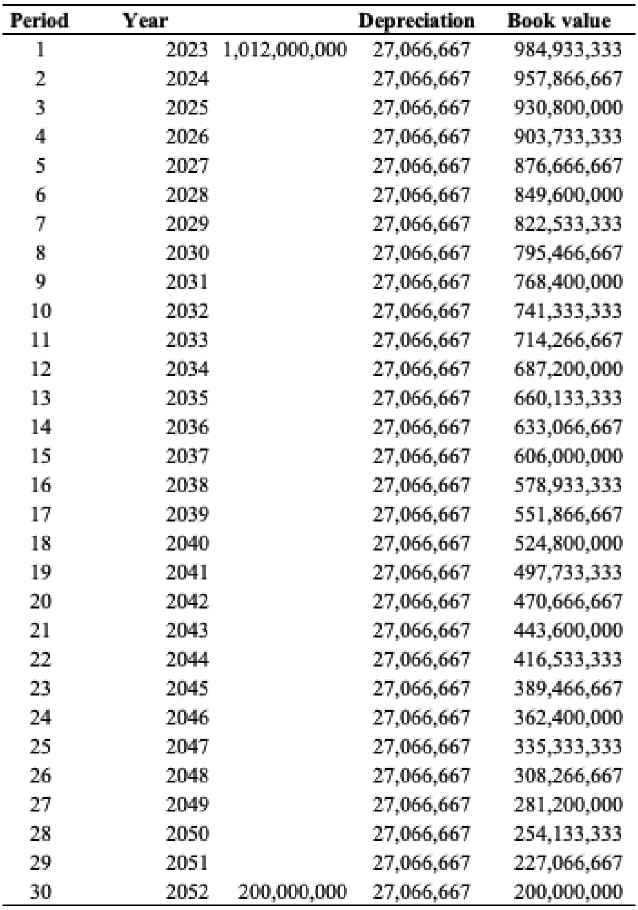
To find the yearly book value of the cruise ship, it was highlighted that normal practice is to linearly depreciate the initial value (newbuild cost) down to 15% of the newbuild cost of the cruise ship after 30 years (Hermundsgård, 2020). For the flexible cruise ships, approximately 20% was used instead of 15%, as the value of the flexible cruise ships is assumed to remain higher. In the figures below, the spreadsheets used to model the value of the cruise ships are shown.

Table E.9: Value of the baseline cruise ship



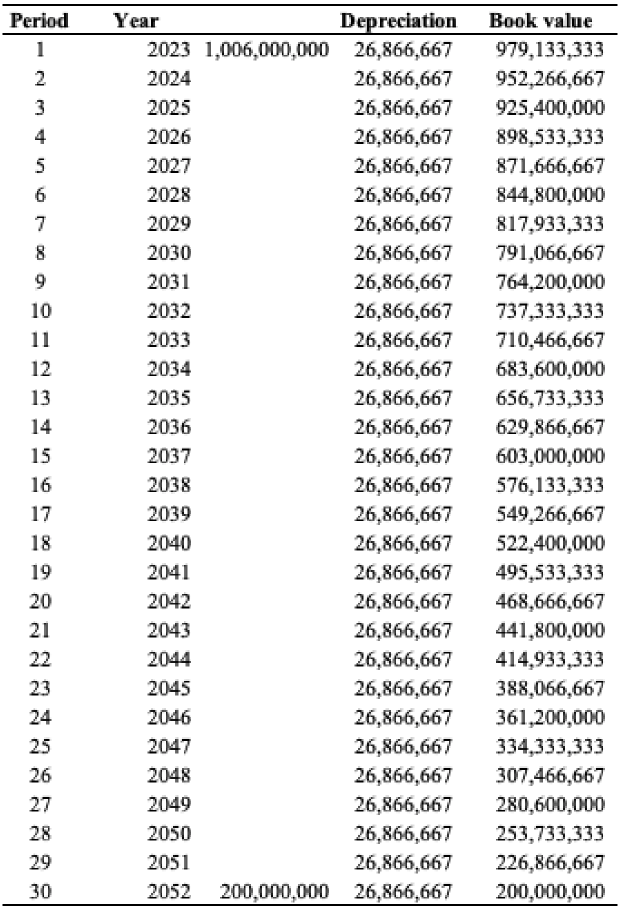
Period	Year		Depreciation	Book value
1	2023	1,000,000,000	28,333,333	971,666,667
2	2024		28,333,333	943,333,333
3	2025		28,333,333	915,000,000
4	2026		28,333,333	886,666,667
5	2027		28,333,333	858,333,333
6	2028		28,333,333	830,000,000
7	2029		28,333,333	801,666,667
8	2030		28,333,333	773,333,333
9	2031		28,333,333	745,000,000
10	2032		28,333,333	716,666,667
11	2033		28,333,333	688,333,333
12	2034		28,333,333	660,000,000
13	2035		28,333,333	631,666,667
14	2036		28,333,333	603,333,333
15	2037		28,333,333	575,000,000
16	2038		28,333,333	546,666,667
17	2039		28,333,333	518,333,333
18	2040		28,333,333	490,000,000
19	2041		28,333,333	461,666,667
20	2042		28,333,333	433,333,333
21	2043		28,333,333	405,000,000
22	2044		28,333,333	376,666,667
23	2045		28,333,333	348,333,333
24	2046		28,333,333	320,000,000
25	2047		28,333,333	291,666,667
26	2048		28,333,333	263,333,333
27	2049		28,333,333	235,000,000
28	2050		28,333,333	206,666,667
29	2051		28,333,333	178,333,333
30	2052	150,000,000	28,333,333	150,000,000

Table E.10: Value of the LNG dual fuel cruise ship



Period	Year		Depreciation	Book value
1	2023	1,012,000,000	27,066,667	984,933,333
2	2024		27,066,667	957,866,667
3	2025		27,066,667	930,800,000
4	2026		27,066,667	903,733,333
5	2027		27,066,667	876,666,667
6	2028		27,066,667	849,600,000
7	2029		27,066,667	822,533,333
8	2030		27,066,667	795,466,667
9	2031		27,066,667	768,400,000
10	2032		27,066,667	741,333,333
11	2033		27,066,667	714,266,667
12	2034		27,066,667	687,200,000
13	2035		27,066,667	660,133,333
14	2036		27,066,667	633,066,667
15	2037		27,066,667	606,000,000
16	2038		27,066,667	578,933,333
17	2039		27,066,667	551,866,667
18	2040		27,066,667	524,800,000
19	2041		27,066,667	497,733,333
20	2042		27,066,667	470,666,667
21	2043		27,066,667	443,600,000
22	2044		27,066,667	416,533,333
23	2045		27,066,667	389,466,667
24	2046		27,066,667	362,400,000
25	2047		27,066,667	335,333,333
26	2048		27,066,667	308,266,667
27	2049		27,066,667	281,200,000
28	2050		27,066,667	254,133,333
29	2051		27,066,667	227,066,667
30	2052	200,000,000	27,066,667	200,000,000

Table E.11: Value of the ammonia ready cruise ship



Period	Year		Depreciation	Book value
1	2023	1,006,000,000	26,866,667	979,133,333
2	2024		26,866,667	952,266,667
3	2025		26,866,667	925,400,000
4	2026		26,866,667	898,533,333
5	2027		26,866,667	871,666,667
6	2028		26,866,667	844,800,000
7	2029		26,866,667	817,933,333
8	2030		26,866,667	791,066,667
9	2031		26,866,667	764,200,000
10	2032		26,866,667	737,333,333
11	2033		26,866,667	710,466,667
12	2034		26,866,667	683,600,000
13	2035		26,866,667	656,733,333
14	2036		26,866,667	629,866,667
15	2037		26,866,667	603,000,000
16	2038		26,866,667	576,133,333
17	2039		26,866,667	549,266,667
18	2040		26,866,667	522,400,000
19	2041		26,866,667	495,533,333
20	2042		26,866,667	468,666,667
21	2043		26,866,667	441,800,000
22	2044		26,866,667	414,933,333
23	2045		26,866,667	388,066,667
24	2046		26,866,667	361,200,000
25	2047		26,866,667	334,333,333
26	2048		26,866,667	307,466,667
27	2049		26,866,667	280,600,000
28	2050		26,866,667	253,733,333
29	2051		26,866,667	226,866,667
30	2052	200,000,000	26,866,667	200,000,000

E.7 Cash Flow Calculation

In the following, the elements included in the cash flow calculation in the valuation model are described in more detail.

E.7.1 Revenue Calculation

Table E.12 presents a general description of the parameters used to calculate the revenue.

Table E.12: Revenue calculation

Parameter	**Symbol**	**Value**	**Unit**
Revenue per passenger	R_p	250	USD/passenger/day
Days of cruise	D_c	365	Days/year
Passenger capacity	P_c	2918	Passengers
Loss in passenger capacity[a]	$L_{p,d}$	-	Passengers
Loss in days of cruise[b]	$L_{c,d}$	-	Days/year

[a] The loss in passenger capacity for design d, due to larger tanks etc. after retrofit. (Specific numbers are presented in Table E.13).

[b] The loss in days of cruise for design d, due to 5 years maintenance in drydock or retrofit at shipyard. (Specific numbers are presented in Table E.14).

Equation E.7.1 presents the formula used to calculate the yearly revenue.

$$\text{Revenue [/year]} = R_p \times (D_c - L_{c,d}) \times (P_c - L_{p,d}) \tag{E.7.1}$$

In Table E.13, the estimated numbers of cabins lost due to larger fuel tanks for the flexible designs are presented.

Table E.13: Estimated decrease in the number of cabins and passenger capacity due to larger fuel tanks

Cruise Design	**Num. cabins lost**	**Num. passenger lost (1 cabin = 2 passengers)[a]**
Baseline	0	0
LNG dual fuel	0	0
Ammonia ready	0	0

[a] Assuming that there are in average 2 persons per cabin.

In Table E.14, the number of cruise days lost due to maintenance in drydock and retrofit for the ammonia ready design is presented.

Table E.14: Loss in days of cruise due to maintenance or retrofit

Cruise Design	Days for maintenance[a]	Days for retrofit
Baseline	14	0
LNG dual fuel	14	0
Ammonia ready	14	14

[a] Maintenance in drydock every 5 years.

E.7.2 CAPEX Calculation

In Table E.15, the newbuild and retrofit cost for the cruise ship designs are presented.

Table E.15: Newbuild and retrofit cost

Ship design	Newbuild cost [USD]	Retrofit cost [USD]
Baseline design	1,000,000,000	0
LNG dual fuel	1,012,000,000	0
Ammonia ready	1,006,000,000	2,000,000

Annuity Loan with Balloon Calculation

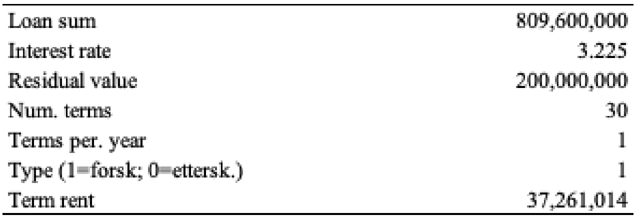
The repayment of the loan, including interests and instalments, is assumed for the modelling to be an annuity loan, as this is the most common type of loans used in the cruise industry. After being in contact with a cruise expert in DNV GL, it was given a general understanding that it was usual practice to assume a ”balloon” (or residual value of the cruise ship) of 15% of the newbuild cost after 30 years. As the ”balloon” will affect the annuity loan calculation, this will have to be included. Therefore, for the baseline cruise ship, a balloon of 15% (150,000,000 USD) was assumed. Moreover, as the flexible designs are expected to maintain a higher value during the years, a balloon of 20% (approx. 200,000,000 USD) of the initial newbuild cost was assumed for each of the flexible cruise ship designs.

Table E.16: The annuity loan with balloon for the baseline cruise ship

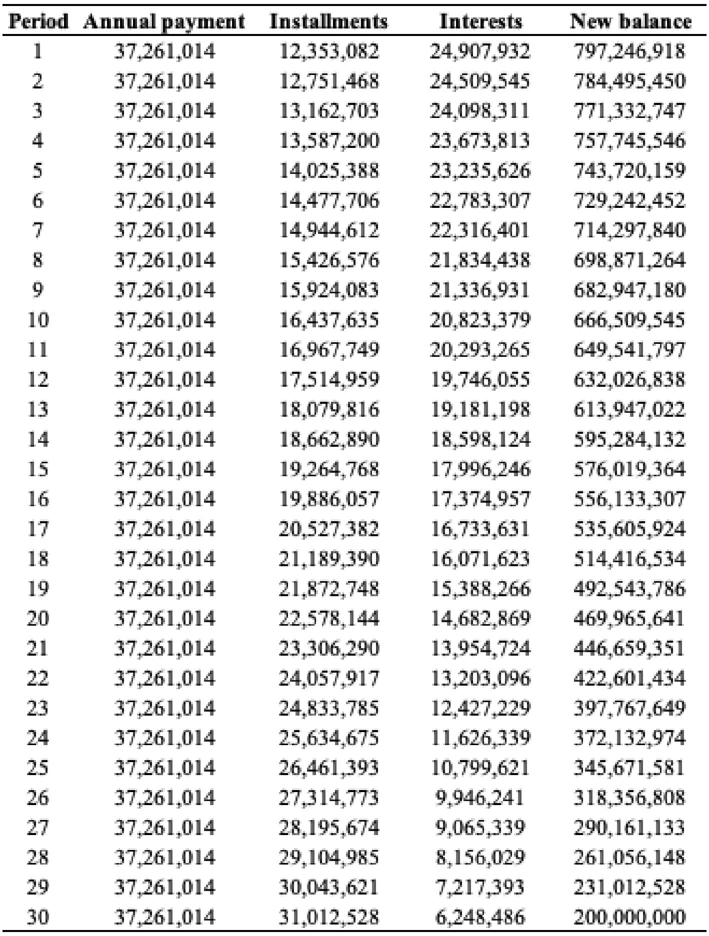
Loan sum	800,000,000
Interest rate	3.225
Residual value	150,000,000
Num. terms	30
Terms per. year	1
Type (1=forsk; 0=ettersk.)	1
Term rent	37,754,184

Period	Annual payment	Installments	Interests	New balance
1	37,754,184	13,171,757	24,582,428	786,828,243
2	37,754,184	13,596,546	24,157,638	773,231,697
3	37,754,184	14,035,035	23,719,150	759,196,662
4	37,754,184	14,487,665	23,266,520	744,708,998
5	37,754,184	14,954,892	22,799,293	729,754,106
6	37,754,184	15,437,187	22,316,997	714,316,919
7	37,754,184	15,935,036	21,819,148	698,381,883
8	37,754,184	16,448,941	21,305,243	681,932,942
9	37,754,184	16,979,420	20,774,765	664,953,522
10	37,754,184	17,527,006	20,227,179	647,426,517
11	37,754,184	18,092,252	19,661,933	629,334,265
12	37,754,184	18,675,727	19,078,458	610,658,538
13	37,754,184	19,278,019	18,476,165	591,380,519
14	37,754,184	19,899,735	17,854,449	571,480,784
15	37,754,184	20,541,502	17,212,683	550,939,282
16	37,754,184	21,203,965	16,550,219	529,735,317
17	37,754,184	21,887,793	15,866,392	507,847,524
18	37,754,184	22,593,674	15,160,510	485,253,850
19	37,754,184	23,322,320	14,431,864	461,931,530
20	37,754,184	24,074,465	13,679,719	437,857,065
21	37,754,184	24,850,867	12,903,318	413,006,198
22	37,754,184	25,652,307	12,101,877	387,353,891
23	37,754,184	26,479,594	11,274,591	360,874,297
24	37,754,184	27,333,561	10,420,624	333,540,737
25	37,754,184	28,215,068	9,539,116	305,325,668
26	37,754,184	29,125,004	8,629,180	276,200,664
27	37,754,184	30,064,285	7,689,899	246,136,379
28	37,754,184	31,033,859	6,720,326	215,102,520
29	37,754,184	32,034,701	5,719,484	183,067,820
30	37,754,184	33,067,820	4,686,365	150,000,000

Table E.17: The annuity loan with balloon for the LNG dual fuel cruise ship



Loan sum	809,600,000
Interest rate	3.225
Residual value	200,000,000
Num. terms	30
Terms per. year	1
Type (1=forsk; 0=ettersk.)	1
Term rent	37,261,014



Period	Annual payment	Installments	Interests	New balance
1	37,261,014	12,353,082	24,907,932	797,246,918
2	37,261,014	12,751,468	24,509,545	784,495,450
3	37,261,014	13,162,703	24,098,311	771,332,747
4	37,261,014	13,587,200	23,673,813	757,745,546
5	37,261,014	14,025,388	23,235,626	743,720,159
6	37,261,014	14,477,706	22,783,307	729,242,452
7	37,261,014	14,944,612	22,316,401	714,297,840
8	37,261,014	15,426,576	21,834,438	698,871,264
9	37,261,014	15,924,083	21,336,931	682,947,180
10	37,261,014	16,437,635	20,823,379	666,509,545
11	37,261,014	16,967,749	20,293,265	649,541,797
12	37,261,014	17,514,959	19,746,055	632,026,838
13	37,261,014	18,079,816	19,181,198	613,947,022
14	37,261,014	18,662,890	18,598,124	595,284,132
15	37,261,014	19,264,768	17,996,246	576,019,364
16	37,261,014	19,886,057	17,374,957	556,133,307
17	37,261,014	20,527,382	16,733,631	535,605,924
18	37,261,014	21,189,390	16,071,623	514,416,534
19	37,261,014	21,872,748	15,388,266	492,543,786
20	37,261,014	22,578,144	14,682,869	469,965,641
21	37,261,014	23,306,290	13,954,724	446,659,351
22	37,261,014	24,057,917	13,203,096	422,601,434
23	37,261,014	24,833,785	12,427,229	397,767,649
24	37,261,014	25,634,675	11,626,339	372,132,974
25	37,261,014	26,461,393	10,799,621	345,671,581
26	37,261,014	27,314,773	9,946,241	318,356,808
27	37,261,014	28,195,674	9,065,339	290,161,133
28	37,261,014	29,104,985	8,156,029	261,056,148
29	37,261,014	30,043,621	7,217,393	231,012,528
30	37,261,014	31,012,528	6,248,486	200,000,000

Table E.18: The annuity loan with balloon for the ammonia ready cruise ship

Loan sum	804,800,000
Interest rate	3.225
Residual value	200,000,000
Num. terms	30
Terms per. year	1
Type (1=forsk; 0=ettersk.)	1
Term rent	37,016,821

Period	Annual payment	Installments	Interests	New balance
1	37,016,821	12,255,813	24,761,008	792,544,187
2	37,016,821	12,651,063	24,365,758	779,893,124
3	37,016,821	13,059,060	23,957,761	766,834,064
4	37,016,821	13,480,215	23,536,606	753,353,849
5	37,016,821	13,914,952	23,101,869	739,438,898
6	37,016,821	14,363,709	22,653,112	725,075,189
7	37,016,821	14,826,938	22,189,882	710,248,251
8	37,016,821	15,305,107	21,711,714	694,943,143
9	37,016,821	15,798,697	21,218,124	679,144,447
10	37,016,821	16,308,205	20,708,616	662,836,242
11	37,016,821	16,834,144	20,182,676	646,002,098
12	37,016,821	17,377,046	19,639,775	628,625,052
13	37,016,821	17,937,455	19,079,365	610,687,597
14	37,016,821	18,515,938	18,500,883	592,171,659
15	37,016,821	19,113,077	17,903,744	573,058,581
16	37,016,821	19,729,474	17,287,347	553,329,107
17	37,016,821	20,365,749	16,651,071	532,963,358
18	37,016,821	21,022,545	15,994,276	511,940,813
19	37,016,821	21,700,522	15,316,299	490,240,291
20	37,016,821	22,400,364	14,616,457	467,839,927
21	37,016,821	23,122,776	13,894,045	444,717,152
22	37,016,821	23,868,485	13,148,336	420,848,667
23	37,016,821	24,638,244	12,378,577	396,210,423
24	37,016,821	25,432,827	11,583,994	370,777,596
25	37,016,821	26,253,036	10,763,785	344,524,560
26	37,016,821	27,099,696	9,917,125	317,424,864
27	37,016,821	27,973,661	9,043,159	289,451,203
28	37,016,821	28,875,812	8,141,009	260,575,391
29	37,016,821	29,807,057	7,209,764	230,768,334
30	37,016,821	30,768,334	6,248,486	200,000,000

E.7.3 OPEX Calculation

In Table E.19, the operational expenditures for using HFO, LNG and ammonia on board the cruise ship is estimated. The two main sources used for this price estimation are Hansson, Månsson, et al. (2019) and Hansson, Brynolf, et al. (2020).

Table E.19: Operational expenditures (Hansson, Månsson, et al., 2019; Hansson, Brynolf, et al., 2020)

Fuel type	**USD/MWh**	**MWh/year**	**USD/year**[a]
HFO ICE	5	330,000	1,700,000
LNG ICE	8.5	330,000	2,800,000
Ammonia ICE[b]	9	330,000	3,000,000

[a] The price estimates have been rounded off.
[b] Assumed to have slightly higher operational cost than LNG.

Note that the OPEX for LNG is always used for the LNG dual fuel cruise ship design, independently on what types of fuels it utilise.

E.7.4 VOYEX Calculation

The elements included in the annual voyage expenditure is presented in Table E.20.

Table E.20: VOYEX calculation

Variables	**Symbol**	**Unit**
Fuel cost	F_c	USD/year
Port cost	PO_c	USD/year
CO_2 cost	$CO2_c$	USD/year
Loss in days of cruise[a]	$L_{c,d}$	% reduction[b]

[a] The loss in days of cruise for design d, due to 5 years maintenance in drydock or retrofit at shipyard. (Specific numbers are presented in Table E.14).
[b] Note that this is a % reduction in total number of cruise days during one year.

In the valuation model, the VOYEX is calculated by using the formula presented in Equation E.7.2 below.

$$\text{VOYEX [/year]} = (F_c \times (1 - L_{c,d})) + (PO_c \times (1 - L_{c,d})) + (CO2_c \times (1 - L_{c,d})) \quad \text{(E.7.2)}$$

Fuel Cost Calculation

Table E.21 presents the variables used to calculate the annual fuel cost.

Table E.21: Fuel cost calculation

Variables	Symbol	Unit
Fuel price	F_p	USD/tonne
Fuel consumption	F_{cons}	Tonne/year

Equation E.7.3 presents the formula used to calculate the annual fuel cost in the valuation model.

$$F_c = F_p \times F_{cons} \tag{E.7.3}$$

The fuel price development within the epochs can be either deterministic or stochastic. If the deterministic approach is used, the fuel price will stay equal to the value of the fuel price epoch variables the whole epoch. In Figure E.2, the deterministic fuel price development for era 1 is illustrated. Note that we will have the same fuel price development in era 2 and era 3. The switching option for the LNG dual fuel design will not be properly valued with the deterministic approach, as Figure E.2 greatly illustrates.

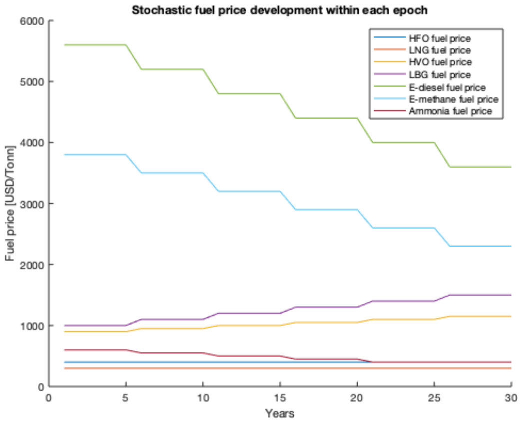


Figure E.2: Deterministic fuel price development

In the case study, the stochastic approach was used, and the fuel price was assumed to follow a geometrical Brownian motion process (often known as a ”Random walk” process) within the epochs. The idea in this approach is then to control the fuel price at the beginning of each epoch, but let the fuel price develop stochastic the rest of the epoch. By modelling it this way we both get stochastic development and it is possible to control the drift of the fuel price. In Figure E.3, the fuel price development over the total number of weeks during 30 years is shown.

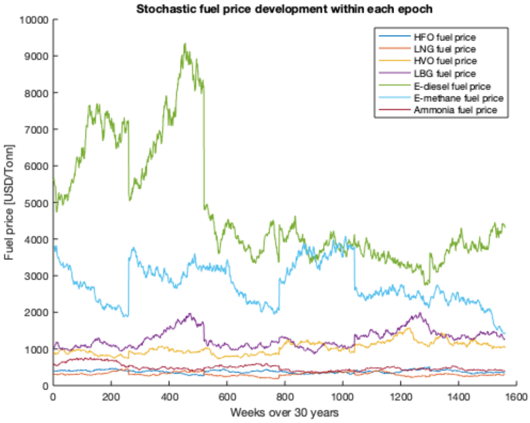


Figure E.3: Stochastic fuel price development

In Table E.22, the drift and the volatility used in the geometrical Brownian motion process is presented. As we have no or minimal data for many of the fuels, the parameters are obtained by tuning instead of using historical data. Note also that the same parameters are used for all fuel types.

Table E.22: Parameters in the geometrical Brownian motion process

Parameter	Value
Weekly drift [κ]	0.0002
Weekly volatility [σ]	0.02

Port Cost Calculation - Environmental Port Index (EPI)

The Environmental Port Index (EPI) was used in the valuation model to differentiate port costs between the cruise ship designs. Based on their environmental performance in port, is an EPI score calculated and a discount or extra cost based on this value is calculated from a formula. The discount or extra cost obtained from the EPI score will vary from port to port, and in this case study, the regime from the Port of Bergen was used. In the Port of Bergen, the EPI score affects the following four cost components in the port fee.[3]

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[3] https://bergenhavn.no/wp-content/uploads/2019/04/PRISLISTE-fra-01.05.2019_EN-1.pdf

Table E.23: Port Costs in the Port of Bergen

Parameters	Symbol	Cost	Unit
Fairway dues	Fd	0.26	NOK/GT/port call
Quay dues[a]	Qd	0.9	NOK/GT[b]
Passenger fees	Pf	5	NOK/passenger
ISPS charges	$ISPS$	17	NOK/passenger

[a] Charged per 24-hours period commenced.
[b] GT = Gross Tonnage of the cruise ship.

In Table E.24, the EPI scores used for each fuel in the valuation model is presented. It has to be emphasised that there is high uncertainty associated with the EPI scores as it was difficult to obtain proper information about these.

Table E.24: Assumed EPI scores for the different fuel types used by the cruise ships

Fuel type	EPI score [0-100]
HFO	0
LNG	60
HVO	60
LBG	60
E-diesel	60
E-methane	60
Ammonia	100

Based on the EPI scores presented in Table E.24 above, the discount or extra port cost given to the cruise ship design can be calculated, using Equation E.7.4 and Equation E.7.5.

$$\text{For a score blow 30:} \quad EPI = \frac{(30 - \text{EPI score}) \times 5}{100} \tag{E.7.4}$$

$$\text{For a score above 30:} \quad EPI = \frac{(30 - \text{EPI score})}{4 \times \text{EPI score}} \tag{E.7.5}$$

The port cost is calculated in the valuation model with the formula presented in Equation E.7.6 below.

$$Port_c = (Fd \times GT) + (Qd \times GT \times Num_{24}) + (Pf \times Num_p) + (ISPS \times Num_p) \quad \text{(E.7.6)}$$

Where GT is the gross tonnage of the cruise ships, Num_{24} is the number of commenced 24 hours in the port and Num_p is the number of passengers on board the cruise ship.

Table E.25: Variables in the port cost calculation

Variables	**Symbol**	**Unit**
Port cost	$Port_c$	USD/port call
EPI rebate[a]	EPI	%
EPI ratio[b]	EPI_r	%
Number of port calls[c]	Num_{pc}	Number/year

[a] Note that the EPI will increase the port costs for ships with low EPI scores.

[b] This ratio is decided by the eras.

[c] The number of port calls per year is presented in Table 8.5.

To calculate the annual port cost, and to account for the EPI in the calculation, the formula presented in Equation E.7.7 is used in the valuation model. Table E.25 above summarises the elements in the annual port cost calculation.

$$PO_c = (Port_c \times EPI \times Num_{pc} \times EPI_r) + (Port_c \times Num_{pc} \times (1 - EPI_r)) \quad \text{(E.7.7)}$$

CO_2 Cost Calculation

The exact size of the CO_2 tax is still uncertain, and is due to this included as an epoch variable in the eras. Furthermore, it is uncertain whether the CO_2 tax will be regulated by ”regional” authorities (EU etc.) or ”globally” by the IMO.

Table E.26: Variables in the CO_2 cost calculation

Variables	**Symbol**	**Unit**
CO_2 price	$CO2_p$	USD/tonne CO_2
CO_2 emissions[a]	$CO2_{e,d,f}$	Tonne CO_2/year

[a] The CO_2 emissions from each cruise ship design and for a given fuel type.

The CO_2 emissions from the different fuels used to generate power on board the cruise ships will vary. In Table E.27, the annual CO_2 emissions from each of the fuels are estimated. It has to be emphasised that there is much uncertainty related to these emission estimates. Note that the emissions are estimated in an LCA point of view, and HVO, LBG, e-diesel and e-methane are in this case study assumed as zero-carbon or carbon-neutral fuels in a tank-to-wake point of view.

Table E.27: Annual CO_2 emissions from each fuel type

Fuel type	**[Tonne CO_2/year]**[a]
HFO	88400
LNG	70720[b]
HVO	4420[c]
LBG	4420[c]
E-diesel	4420[c]
E-methane	4420[c]
Ammonia	0

[a] Emission in an LCA perspective.

[b] Assuming 20% reduction in CO_2 emissions compared to HFO.

[c] Assuming 95% reduction in CO_2 emissions compared to HFO.

The CO_2 cost is calculated by Equation E.7.8 below.

$$CO2_c = CO2_p \times CO2_{e,d,f} \tag{E.7.8}$$

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