Master's thesis

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

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Retrofit Preparations of Liquid Natural Gas Carriers to Handle Future Uncertainty

Master's thesis in Marine Technology
Supervisor: Stein Ove Erikstad
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Kunnskap for en bedre verden

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Master Thesis in Marine Systems Design

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Background

The environment is the primary driver of the ongoing changes in the shipping business. Emissions need to be reduced, and strict regulations force shipowners to adapt. To be able to decrease emissions, new power, and fuel solutions are being developed. Zero-emission solutions are not ready for commercial use. It makes it difficult to order new ships. Even ships delivered today could be facing retrofits in 10-15 years to be able to meet stricter regulations.

Overall aim and focus

The main objective of this thesis is to investigate how a shipowner can prepare a new Liquid Natural Gas carrier for retrofit in the future and if the preparation should be done.

Scope and main activities

1. *Define the challenges regarding emissions for ships in the coming years.*
2. *Research industry expectations of the future and how uncertainty in ship design has been handled before.*
3. *Identify emission reduction solutions available for LNG carriers.*
4. *Present and discuss methodologies for analyzing and evaluating the emission reduction solutions.*
5. *Present a realistic case study where the decision framework is tested.*
6. *Discuss and conclude if the suggested preparations should be done and the value of the decision method.*

Modus operandi

Professor Stein Ove Erikstad will be the responsible advisor at NTNU.

The work shall follow the guidelines given by NTNU for the Master thesis work.

Preface

This thesis was done as the final part of the Master of Science degree in Marine Technology with a specialization in Marine Systems Design at the Norwegian University of Science and Technology (NTNU). The thesis was written during the spring of 2022, and the workload corresponds to 30 ECTS.

The master thesis builds upon the work done in the project thesis "Design of ships with options for retrofits", written in the fall of 2021.

I would like to thank my supervisor Stein Ove Erikstad for providing relevant literature and valuable discussion and advice throughout the semester. I would also like to thank Serge Schwalenstocker and the team at BW LNG for helping me understand the important functions and operational aspects of LNG carriers.

Abstract

Shipowners currently face a significant problem when ordering ships. New, stricter regulations force older ships to reduce power or do expensive retrofits. The regulations will get stricter and stricter every year. It creates uncertainty for shipowners ordering ships today. New regulations can lead to early retrofit needs. This study aims to determine how a ship can be prepared for a future retrofit. It investigates the lifetime cost savings of such a preparation. In this context, we primarily focus on preparations done during the construction of large Liquid Natural Gas (LNG) carriers.

Different aspects of LNG carriers and the LNG trade are researched to find the most critical aspects. The market expectations and available technology for the retrofits are then identified. Real options theory is used together with Epoch-Era Analysis for analyzing and valuing retrofit options.

The results suggest that if the ship is prepared for a retrofit, it should be for a fuel switch from LNG to ammonia. However, the long time until a retrofit makes a preparation unfavorable. The ship will likely be able to run on LNG for at least ten years before the switch. The present value of potential savings ten years into the future is insufficient to justify today's excess investment into retrofit preparations.

Sammendrag

Skipseiere står i dag overfor et betydelig problem når de bestiller skip. Nye utslippsreguleringer tvinger eldre skip til å redusere motorkraften eller gjøre kostbare ombygginger. Reguleringene vil bli strengere og strengere for hvert år. Det skaper usikkerhet for redere som bestiller nye skip i dag. Plutselige endringer i utslippsreguleringene kan føre til ombyggingsbehov for skipene. Denne studien tar sikte på å finne ut hvordan et skip kan forberedes for en mulig fremtidig ombygging. Den undersøker de økonomiske besparelsene ved å forberede skipet på en slik ombygging. Oppgaven fokuserer på forberedelser gjort under bygging av store flytende naturgass (LNG)-skip.

Ulike aspekter ved LNG-skip og LNG-frakt undersøkes for å finne de mest kritiske aspektene. Markedets forventninger og tilgjengelig teknologi for ombyggingene identifiseres deretter. Opsjonsteori brukes sammen med Epoch-Era Analyse for å analysere og finne verdien av de ulike ombyggingsalternativene.

Resultatene tyder på at dersom en skal forberede skipet for en ombygging, bør det være for et drivstoffbytte fra LNG til ammoniakk. Den forventede tiden fra bygging til ombygging av skipet gjør imidlertid besparelsene av forberedelse små. Skipet vil sannsynligvis kunne kjøre på LNG i minst ti år før ombygging. Nåverdien av mulige besparelser ti år frem i tid er ikke store nok til å rettferdiggjøre de økte bygge kostnadene for å forberede skipet til en ombygging. Da er det bedre å ta hele kostnaden ved den eventuelle ombyggingen.

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Abbreviations

C	=	Certified for ammonia
CCS	=	Carbon Capture and Storage
CII	=	Carbon intensity indicator
CO_2	=	Carbon dioxide
D	=	Design ready
DCF	=	Discounted cash flow
DFDE	=	Dual Fuel Diesel Engine
EEA	=	Epoch-Era Analysis
EEDI	=	Energy efficiency design index
EEXI	=	Energy efficiency existing ship Index
ENPV	=	Expected net present value
EV	=	Expected value
FAME	=	Fatty acid methyl ester
GHG	=	Green house gas strategy
HFO	=	Heavy fuel oil
HVO	=	Hydrotreated vegetable oil
IMO	=	International maritime organization
ICE	=	Internal Combustion Engines
LBG	=	Liquefied bio gas
LNG	=	Liquid natural gas
LNG-380e	=	LNG with energy equivalent to one ton of IFO380 bunker
NPV	=	Net present value
MATE	=	Multi-Attribute Tradespace Exploration
MEc	=	Main engine convertible
MEGI	=	M-type, Electronically Controlled, Gas Injection
MDO	=	Marine diesel oil
MGO	=	Marine gas oil
NOx	=	Nitrogen oxides
OPEX	=	Operating expenses
OSV	=	Offshore service vessel
P	=	Piping
PTI	=	Power take-in
PTO	=	Power take-off
Q-Max	=	Qatar max
R	=	Reliquefaction

ROA	=	Real options analysis
RSC	=	Response Systems Comparison
S	=	Structural preparations
TEU	=	Twenty-foot equivalent unit
Ti	=	Tanks installed
SOx	=	Sulphur oxides
VLSFO	=	Very low sulfur fuel oils

Chapter 1

Introduction

1.1 Background

Ships are the cornerstone of international trade and transportation. More than 80% of the international trade in goods are transported by sea (UNCTAD, 2021). It makes ships a significant contributor to the world's emissions. Shipping emissions contributed 2,89% of the global emissions in 2018 (IMO, 2021). The emissions from shipping are still increasing. Action must be taken to meet the Paris agreement and reduce emissions from shipping.

The Initial International maritime organization (IMO) Green House Gas (GHG) Strategy contributes to the global fight against climate change. It leads to new regulations and mandatory emissions reduction for the whole shipping fleet. The initial strategy envisages a reduction of the total annual GHG emissions by at least 50% by 2050 compared to 2008. The Energy Efficiency Design Index (EEDI) and Carbon Intensity Indicator (CII) are implemented to reach these targets.

Shipowners face high unexpected costs when the Energy Efficiency Existing ship Index (EEXI) and Carbon Intensity Indicator (CII) are implemented in 2023. A significant part of the world fleet will need retrofits or reduced speed to comply. 10-year-old ships can be affected. It has led to significant uncertainty for shipowners ordering ships today. A new Liquid Natural Gas (LNG) carrier costs more than 200 million USD. An expensive retrofit after only ten years can have a turning impact on the lifetime economics of a ship.

1.2 Objective of the report

This thesis starts with the assumption that a retrofit will be needed during a ship's lifetime to meet stricter emission regulations in the future. It leads to the question:

What should a shipowner ordering an LNG carrier do to prepare the ship for a retrofit in the future?

The uncertainties of the LNG and shipping markets must be defined and methods for handling these uncertainties need to be identified.

Which retrofits improve the ship and which of these are relevant to prepare for?

A more technical insight is then needed. The effect of each solution must be researched. Then the effect of not preparing the ship for retrofit must be identified.

What will the implications be for the shipowner if he chooses not to prepare for a retrofit?

A method is needed for finding the solution(s) with the most potential. Then the solution(s) must be tested and evaluated.

How should the identification and evaluation be done, and what is a suitable method for doing this?

1.3 Structure of the report

Chapter 2 presents the previous research on flexibility and the path to zero-emission. It includes expectations and suggestions for the pathway to zero-emission in shipping. Then the value of changeability facing uncertainty is analyzed.

Chapter 3 introduces the Liquid Natural Gas carrier. It presents ship development and the last engine solutions. Essential technical and commercial aspects of the ship and trade are introduced. Then there are new regulations, finishing with the LNG market outlook and recent fuel prices.

Chapter 4 introduces fuel and energy solutions. Hydrogen, ammonia, methanol, and biofuels are compared. Then important part of LNG to ammonia retrofit is described. Other emission reduction solutions are introduced as well.

Chapter 5 describes different evaluation methods. It gives an introduction to real options. Different methods for valuing real options are then described. It illustrates a method for options identification. Epoch-Era Analysis is the primary simulation method.

Chapter 6 is a case study on a newbuilt LNG carrier. The earlier described methods are used for analyzing and evaluating options for flexibility. Screening finds the most promising options. Epoch-Era Analysis estimates the economic benefit of the options.

Chapter 7 discusses the findings of the report and the case study.

Chapter 8 sets a conclusion on the objective of the report.

Chapter 2

Literature review

The literature presented in this chapter has helped solve the objective of the report. It can be categorized into different segments; paths to emission reduction and zero-emission shipping, changeability and uncertainty in ship design, and simulation and evaluation methods.

The best way to reach zero-emission is not decided yet. All parts of the industry are trying to figure out the solution. DNV (2021), ITF and FIT (2018), Mallouppas and Yfantis (2021) and Maersk (2021) provides an outlook on regulatory and commercial drivers for decarbonization in shipping, ship technology and fuels, and an estimated timeline. Then describes potential pathways for reaching emission targets. New energy sources and carriers are needed to meet the emission reduction targets. DNV (2021) gives an outlook on the expected energy demand and sources. Shell (2022) gives an outlook focused on the LNG market. DNV (2019b) provides a further comparison of different fuels. Kim et al. (2020) has done a study on alternative ammonia propulsion systems. It tests different propulsion systems against a conventional engine running on Heavy Fuel Oil (HFO). MAN Energy Solutions (2022) and Wärtsilä (2020) are working on new engine solutions, and many of the engines on the market today will be possible to retrofit.

IMOs emission reduction target of 50% by 2050 requires new solutions. 12% of current new builds are ordered with alternative fuel systems, mainly LNG. LNG as a shipping fuel is a step in the right direction, but the reduction is not significant enough to meet the target. Balcombe et al. (2021) has analyzed how LNG-fuelled ships can reach these targets. LNG is used in different engines available today and compared to HFO, Marine Diesel Oil (MDO), and methanol. High-pressure dual fuel 2-stroke and low-pressure dual fuel 2-stroke engines running on LNG show the best results with GHG emission reduction up to 28% and 18% compared to HFO. This reduction is not enough to meet IMOs target. A combination of solutions is needed to reach these targets. Traditional low-pressure engine efficiency is in the 45 to 48% range. The new two-stroke gas engines reach efficiencies up to 55%. It limits the potential for higher efficiency. Zero/low emission fuels or/and alternative energy savings solutions are needed to reach the emission target.

Increased ship efficiency or renewable energy solutions are other solutions for reducing emissions. Waste heat recovery (WHR) systems produce heat energy that otherwise would be lost to the surroundings. It can lead to fuel savings of 5% - 15% (Singh and Pedersen, 2016), (Baldi and Gabrielii, 2015). Hull coatings reduce drag and energy use. However, large ships will usually have modern hull coatings already. Air lubrication is an additional solution. It can reduce fuel consumption up to 8% (Fotopoulos and Margaris, 2020). The hull needs regular cleanings to keep its efficiency. The economic and environmental impacts and efficiency of hull cleanings are analyzed in Pagoropoulos et al. (2018) and Adland et al. (2018). Hull cleanings have been done manually in drydock or by divers. Different types of robots are developed for this purpose. They are getting smaller and better and taking an increased part of the hull cleanings (Song and Cui, 2020). Wind-assisted energy solutions are another option. Sails, kites, and rotor sails used for generating energy are evaluated in Lu and Ringsberg (2020) and Ammar and Seddiek (2021). Speed reduction is one of the most efficient ways of reducing emissions but greatly impacts the operation. The speed has generally gone down in the last 10-15 years, and it has greatly reduced emissions. Speed limits have been suggested, but that is not a solution shipowners can implement (Psaraftis, 2019). The Energy Efficiency Design Index was introduced in 2015 to improve the efficiency of new ships. All new LNG carriers at the time did meet the new index (Ekanem Attah and Bucknall, 2015).

Design for changeability is analyzed by Fricke and Schulz (2005). Its principle is that a system can not only be designed for today's requirements. Changes must be able to meet the requirements of the ship throughout the ships's lifecycle. Flexibility, agility, robustness, and adaptability are the key aspects of changeability. They can be described as (Schulz and Fricke, 1999):

- *Robustness* characterizes a system's ability not to be affected by changing environments. The system is still functional without being changed.
- *Flexibility* characterizes a system's ability to change easily. The system has to be changed externally. It does not change itself.

- *Agility* characterizes a system's ability to be changed fast. The system has to be changed externally.
- *Adaptability* characterizes a system's ability to change itself. It adapts to new environments without external change.

Ross et al. (2008) discuss robustness and changeability. They divide changeability into three core aspects: change agents, change effects and change mechanics. Change agents are the force that makes the change occur. It includes humans, weather, and software. If the change agent is external to the system, it is a flexible change. An adaptable change happens when the change agent is internal in the system. The change effect is the difference in states before and after a change. Change effects can be divided into robustness, scalability, and modifiability. A robust system is constant during a change of states. The system is scalable if it can scale up or down a part of the whole system. A system is modifiable if it can change function or form.

The maritime industry is affected by high market uncertainty and expensive projects with long time horizons. Shipowners must make decisions based on uncertain parameters. Ship design under uncertainty has been researched by Rehn (2018) and Agis (2020). Changeability is investigated in regards to improved profitability and reduced risk. The most important uncertainties in conceptual ship design are uncovered. Both studies focus on offshore ships.

The trade-off between versatility and retrofit ability on offshore vessels is studied by Rehn et al. (2018). It investigates the ability to satisfy diverse needs with or without a physical change. Pettersen and Erikstad (2017) does an assessment on flexible offshore construction vessels. A model for maximizing the expected net present value is presented. Zwaginga et al. (2021) explores market uncertainty in early ship design. The study focuses on offshore wind installation vessels. The study results create a robust design that handles uncertainty without retrofits. Lagemann et al. (2022) has developed a model for finding the optimal ship lifetime fuel and power system. The model favors LNG today and retrofits for ammonia when emission reductions are needed.

The traditional methods for option pricing include the Black-Scholes pricing model, binomial option pricing, and simulation. These are financial option pricing methods. The traditional valuation of options using Black and Scholes (1973) is often not suitable in real options. There are several methods for valuing flexibility in ship design. Sødal et al. (2008) uses a real options model for valuing the flexibility to switch between wet and dry cargo for a combination carrier. The value of flexibility is based on the historical prices of combination carriers and oil tanker rates. The switch depends on switching costs and spreads between rates in the wet and dry bulk markets.The spread is modelled as an Ornstein-Uhlenbeck process. Wang and de Neufville (2009) and Perlitz et al. (1999) are looking at real options in physical systems and the application in R&D project evaluation. Cox et al. (1979) gives a simplified approach for options pricing. Real options are hard to evaluate. All the methods have different flaws. Schachter and Mancarella (2016) does a critical analysis of real options methods for evaluating flexible systems.

There are several methods for evaluating system performance. Epoch-Era is used and described further in this thesis. It is used for evaluating a system's robustness in Ross and Rhodes (2008). Schaffner et al. (2014) and Schaffner et al. (2013) have developed a model of the Epoch-Era method aiming for affordability. The method is used for selecting affordable systems concepts. It gets tested on a case regarding naval ship design. The Responsive Systems Comparison Method (RSC) is another method for comparing systems using Epoch-Era (Ross et al., 2009). The RSC-method is used by Pettersen et al. (2018) on an ill-structured commercial ship design problem. It focuses on the issue of evaluating system performance and trade-offs early in the design phase.

Chapter 3

Liquid Natural Gas Carrier

This chapter will give an introduction to Liquid Natural Gas (LNG) carriers. The ship technology and development are introduced. Essential technical and commercial aspects are presented. The regulations introduced in section 1.1 are further discussed together with fuel prices and market outlook.

3.1 LNGC technical aspects

Liquid natural gas carriers are vessels that transport liquid natural gas. They are built specifically for this purpose. The volume of natural gas is about 600 times lower in liquid form compared to gas. For this reason, the gas needs to be carried in liquid form. It requires a temperature of -162 °C to keep it liquid. The low temperature sets specific design and operation requirements for the ship.

The cargo containment system is an essential part of the LNG carrier. It is the full system for containing the cargo. The system must be gas tight and insulate the LNG to minimize boil-off. The cargo containment system is built as part of the hull structure. Cargo tanks are placed forward of the engine space and deckhouse. It keeps the dangerous gas areas separated from the crew accommodation spaces.

Because of the characteristics of LNG, it will always be boil-off gas. The tanks are not capable of keeping all the LNG liquefied for an extended period. It leads to a constant boil off of the LNG. The cooling systems on new LNG carriers have improved the recent years. Boil off rate has drastically been improved on new ships compared to older steam ships. It is close to 0,1% per day on new vessels. Older ships with lower efficiency could use all the boil-off gas as fuel.

It was the standard for all steam LNG carriers. New ships have higher efficiency than older ships. Their fuel consumption is usually lower than the boil-off rate. A reliquification system is, therefore, an essential part of new ships. Depending on the size, it can either be used for partly or fully reliquefaction. New ships designed for using LNG boil-off as fuel will usually have reliquefaction systems sized for the excess boil-off gas, ships designed for using fuel oils instead of LNG need 100% reliquefaction (Kukuljan et al., 2012).

3.2 Development in LNG trade

LNG carriers stayed quite similar for many years. Ships with the Moss Type design presented in 1970 are still operating today. Steam turbines powered all LNG carriers until about 15 years ago. Then Dual Fuel Diesel Engines were ordered. These lasted a short decade before today's engines were introduced.

The steam turbines are powered by boil-off gas. It was an excellent solution when introduced, but they are inefficient compared to new engines. The EEXI and CII will be a problem for the ships with steam engines. Which is a significant part of the total fleet.

The Dual Fuel Diesel Engine (DFDE) improved efficiency compared to steam engines. They are efficient enough to meet the EEDI and EEXI baseline but can get in trouble due to methane slip. The unburnt methane emissions of the DFDE can increase the GHG emission index value up to 115% (Ekanem Attah and Bucknall, 2015).

Two-stroke engines are the preferred solution for orders today. Two manufacturers dominate this market: MAN Energy Solution with the M-type, Electronically Controlled Gas Injection (MEGI) high-pressure gas injection system, and Win-GD with the low-pressure X-DF engine (RINA, 2019). These two-stroke engines operate on a combination of HFO or MDO and natural gas. They are some of the most fuel-efficient engines of all engines on the market today.

The capacity has increased over the years. It appears that the market has settled for ships between 174-180,000 m^3. The vessel size is primarily driven by terminal capacity. Some yards are looking at designing a 200,000 m^3 because of the increased capacity of the Panama canal (RINA, 2019). The Q-Max LNG carrier (Qatar Max) is the largest LNG carrier operating today. They are sized after the Qatar terminal and have a capacity of 266,000 m^3.

3.3 LNGC commercial aspect

Natural gas is an essential part of the world's energy consumption. The LNG market is closely connected to the global energy supply and demand. The market for LNG carriers is mainly driven by differences between supply and demand in different geographical locations. Gas from Qatar can be sold to Japan for consumption. Then LNG carriers are needed to transport the gas. Prices of gas have skyrocketed in the last year due to great demand. It is reflected in charter rates for LNG ships and fuel prices 3.2.

LNG ships have usually been chartered on long contracts. 10-year time charters have been typical. It has started to change recently. Five to seven-year contracts are more common. Spot cargoes regular in tanker and dry bulk shipping. These contracts have not been regular in LNG shipping. Spot cargoes have now started to be utilized as the charter periods are getting shorter.

The market is mainly consisting of larger specialized players. LNG is more expensive and complex than tankers and dry bulk. The extended contract periods make it a little different from traditional shipping. It also reduces the potential for asset plays.

3.4 Regulations

Regulation is an essential driver for change in shipping. It has been hard to force regulations on all shipowners earlier due to international trade and different flag states. Shipowners have been able to wait and see how regulations affect them before following them. It is no longer possible.

The coming regulations, Energy Efficiency Existing ship Index (EEXI) and Carbon Intensity Indicator (CII), will drastically affect older ships. EEXI is an addition to the Energy Efficiency Design Index (EEDI). EEDI is a baseline for how energy efficient a vessel's design needs to be when constructed. The EEXI is a certification for the energy efficiency of existing ships. It is a one-time certification. All vessels need this approved to keep trading. Actions have to be taken for vessels not compliant with the regulation. The CII measures operational efficiency and is subject to annual assessment. Ships will receive a rating from A to E. Ships with a rating under C will have to approve their operating efficiency. These regulations will affect a large part of the total LNG fleet.

3.5 LNG market outlook

The fast recovery of the economy after the pandemic accelerated the demand for LNG last year. The Ukrainian war has led more countries and the European Union to focus on energy security. European countries are looking to be less dependent on energy from Russia. LNG will have a significant part of this. It is a good choice for transition fuel until zero-emission fuels are ready. A Floating Storage Regasification Unit (FSRU) is one of the quickest ways to provide the country with an independent energy source. Renewable energy is rising, but the supply is far from enough. Stability is another problem. Backup fossil fuels are often needed. Even with the rapid technological improvements, we see in renewable energy; the LNG market is expected to be higher in 2040 than today (DNV, 2021).

LNG as a ship fuel is rising in popularity. LNG is a natural choice for many ship types with stricter emission regulations. There are few options for significant reductions in emissions available for deep sea shipping today. The rise in vessels ordered with LNG propulsion is shown in Figure 3.1.

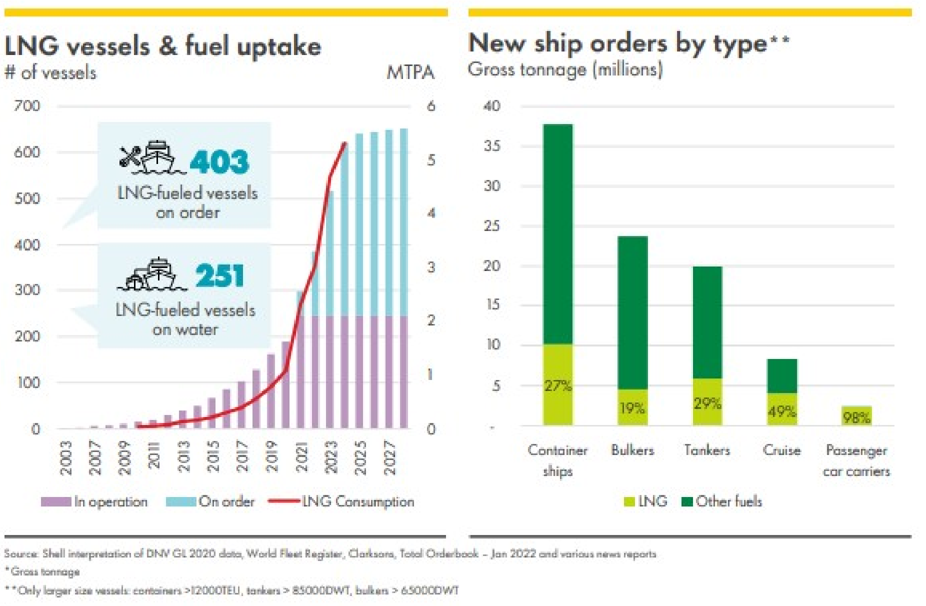

Figure 3.1: Vessel orders with LNG as a fuel. Source: (Shell, 2022).

3.6 Fuel prices

Fuel is a significant part of a ship's lifetime cost. It is also impossible to predict. Figure 3.2 shows the prices for the LNG-380e bunker in Rotterdam from November 2020 to May 2022. It ranges from 320 $ per ton to 2600 $ per ton. It illustrates the problem of predicting fuel prices. LNG carriers with dual fuel engines can run on MGO as well. Switching between fuels can decrease fuel costs but will increase emissions compared to only running on LNG. Oil and gas prices and energy prices, in general, are correlated. It limits the economic possibilities of fuel switching.

Figure 3.2: LNG-380e fuel prices from Ship & Bunker (2022).

DNV has a case study using different fuels in DNV (2021). Their price estimates are illustrated in Table 3.1. It reflects a scenario with high availability of low-cost renewable electricity used for the production of carbon-neutral electrofuels. The carbon tax is not considered. These estimates include distribution costs.

	Fuel	**Price (USD/toe)**
Fossil	MGO	578
	VLSFO	502
	LNG	327
	LPG	427
Carbon-neutral	Ammonia	959
	Methanol	1248
	MGO	1675
	LNG	1285

Table 3.1: Carbon-neutral electrofuels prices estimates from DNV (2021).

Chapter 4

Fuel and energy solutions

There are numerous solutions for emission reduction. New LNG carriers are being built with the most efficient engines today, but it is not enough to reach IMOs emission targets. This chapter will look into the potential of fuels and alternative solutions. Hydrogen, ammonia, methanol, and biofuels are discussed. Then alternative energy savings solutions are presented. The hydrogen, methanol and biofuels parts are partly collected from the project thesis written in the last fall.

4.1 Fuel selection

4.1.1 Hydrogen

Hydrogen can be divided into three parts. Green, blue and grey hydrogen. Renewable energy sources create green hydrogen. The long-term goal is to produce all hydrogen green. Blue hydrogen is the second best and can be used in the transition face to green hydrogen. Non-renewable energy sources make blue hydrogen. Carbon capture technologies are then used to reduce emissions. Hydrogen itself is carbon free and only emits pure water (DNV, 2021). The energy source decides the emissions. Grey hydrogen is hydrogen created by fossil fuels without carbon capture. It will usually lead to higher emissions than using fossil fuel itself because of the energy loss in the conversion. The conversion from hydrogen to energy can be done in either a combustion engine or fuel cells. Hydrogen fuel cells are the greenest way to generate power from hydrogen. It is not available to use yet as the primary energy source in deep sea shipping. The most viable solution for hydrogen is to use it in combustion engines.

There are different problems regarding hydrogen as a potential fuel. Hydrogen is the lightest of all atoms. It makes it harder to contain and requires other materials for tanks and equipment than when oil and gas are used. It requires different types of steel, and it ignites more easily than natural gas DNV (2021). New infrastructure is then needed to use hydrogen. The low volumetric energy density is another problem in deep sea shipping. The fuel volume and weight are critical. Low energy density leads to lower cargo capacity. Hydrogen boils at -252 °C. It makes it hard to transport and store. All these together reduce the potential for hydrogen as the main ship fuel for long distances. This makes it more suitable for short-sea shipping. Car ferries are already being delivered with hydrogen power. The short distances make it possible.

4.1.2 Methanol

Methanol is the simplest alcohol with the lowest carbon content. It is produced mainly by natural gas and coal today but can be produced by different renewable sources. Methanol is a liquid fuel and can be stored in standard tanks with some minor modifications.

The infrastructure is not fully developed yet. Most ports offering methanol bunkering have built infrastructure to support a specific project or vessel. The demand for methanol as a ship fuel is still low but slowly increasing. The current methanol production is large enough to cover the growing methanol demand until at least 2030. It includes methanol produced from fossil fuels. Another downside is the low energy density. It requires about 2,5 times larger tanks compared to oil for the same amount of energy, (DNV, 2019a).

The emissions from methanol produced from coal are about twice as high as if it is produced from natural gas. Methanol from renewable energy is needed to cut greenhouse gas emissions. The possibility of using methanol from natural gas makes the transition to methanol easier (DNV, 2019a). It reduces the risk of ordering methanol powered vessels. Maersk has already ordered a new set of ships with methanol duel fuel engines. They come with a two-stroke engine running on methanol or VLSFO.

4.1.3 Ammonia

Ammonia will likely play an essential role in the energy transition. According to (Maersk, 2021), it can account for half of the fuel composition in 2050. The main reasons are that it could be the only relevant blue fuel and potentially the cheapest e-fuel.

Blue ammonia can be important if high renewable energy cost leads to high e-fuels cost or the scale-up of renewable energy sources is delayed. Blue ammonia is dependent on Carbon Capture and Storage (CCS) on a large scale. To be able to do this, an industry standard for the performance of CCS and a solution for methane emissions needs to be solved (Maersk, 2021).

Optimal ship lifetime fuel and power system selection has been evaluated by (Lagemann et al., 2022). The most robust solution of the fuels available today is LNG. Biofuels are a potential solution for low emission fuels, but it is not likely to meet the expected demand. A ship ordered today will probably need to reduce emissions in the next 15 years. The most robust solution will likely be LNG and retrofit to ammonia when it is ready and needed.

Several engine manufacturers are developing ammonia engines. The manufacturers are seeing promising results when running ammonia in Internal Combustion Engines (ICE) (Wärtsilä, 2020). The first ammonia-ready engines are expected to hit the market in a couple of years. A number of properties need further investigation before the engines are ready for commercial use. It is toxic and corrosive, which sets a higher requirement for safe handling and storage. Ammonia ignites and burns poorly compared to fuels used today. Burning it can lead to higher NOx emissions without after-treatment or optimizing the combustion process. The regulatory framework is still not ready for use as a marine fuel (Wärtsilä, 2020).

4.1.4 Bio fuels

Biofuels are produced by converting biomass into liquid or gaseous fuels. The most promising ones are Hydrotreated Vegetable Oil (HVO), Fatty Acid Methyl Ester (FAME), and Liquefied Bio Gas (LBG), (DNV, 2019a). The main reason for using biofuels is to reduce greenhouse gases. Biofuels are considered CO2 neutral fuels even though they still emit CO2 to the atmosphere during combustion. This CO2, however, is captured from the atmosphere by the feedstock plants as they grow.

Biofuels are still in the development phase, and the market is minimal. The cost is higher than fossil fuels today, but regional variations exist. The infrastructure is only built out in some ports in the world. It makes use of biofuels in shipping limited. The same systems can mostly use HVO as MGO and HFO. FAME is more challenging and should not be stored for more than six months. LGB could easily blend with LNG and use its infrastructure, (DNV, 2019a).

4.1.5 Comparison of fuels

Fuel property	Unit	LNG	Liquid Hydrogen	Liquid Ammonia	Methanol
Boiling temperature at 1atm	°C	-162	-253	-33	65
Volumetric energy density	Mj/m3	23.400	8.500	12.700	15.800
Lower heating value	Mj/kg	48,6	120,0	18,8	19,9
Auto ignition temperature	°C	600	560	650	440

Table 4.1: Fuel properties sources:(Toolbox, 2003), (Kim et al., 2020), (DNV, 2019b), (DNV, 2021).

There are benefits and negatives of all the fuels. Industry experts have different opinions about the different fuels. There is a large agreement that ammonia will play an important role as long as its issues are solved. Methanol engines have already been ordered. They could be the best solution if ammonia is not usable. Some key takeaways:

- Biofuels are compliant with most of the infrastructure already built, but the availability is low in most of the world. It requires large areas of agricultural land to produce.
- Ammonia and hydrogen are the only ones that can be regarded as "zero-emission". Methanol is a low emission fuel.
- The low energy density of hydrogen is a problem for long distances.
- The low boiling temperature of hydrogen is a disadvantage for storage and handling.
- Ammonia has higher volumetric hydrogen content than liquid hydrogen.
- Ammonia has a toxicity problem and a strong smell. The toxicity problem needs to be solved, but the strong smell makes it easier to detect.
- Methanol and ammonia are easier to store than hydrogen.

4.2 Ammonia ready

Several issues with ammonia still need to be solved before commercial use onboard ships. Ships built today can then be prepared for retrofit to ammonia in the future. It can be done in several degrees. DNV has created a class notation called Fuel Ready for ships prepared for retrofit (DNV, 2021). Fuel Ready notation includes different levels of readiness. The design is compliant with current rules for ammonia (D). The main engine can be converted to ammonia (MEc). Structural preparations are done to support the future ammonia containment system (S), and tanks that can be used for ammonia are installed (Ti).

4.2.1 Engine

Engine manufacturers are working on developing engines compliant with the next-generation fuel. The low-speed dual fuel engines are the preferred choice for LNG. Maersk has already ordered container vessels with dual fuel diesel/methanol engines. Ammonia engines are not possible to order today. MAN is working towards being able to deliver retrofits of existing vessels to ammonia from 2025 (MAN Energy Solutions, 2022). New LNG carriers are mostly built with either MEGI or X-DF engines today. Figure 4.1 shows some of the engines on the market today that is possible to retrofit. It will make the retrofit easier than the need for a complete engine switch. The engines that can be converted to ammonia are compliant with the Fuel Ready notation for main engines (MEc).

Fuel types	MC	ME-B	ME-C	ME-GI	ME-GA	ME-GIE	ME-LGIM	ME-LGIP
0-0.50% S VLSFO	Design	Design	Design	Design	Design	Design	Design	Design
HFO	Design	Design	Design	Design	Design	Design	Design	Design
Biofuels	Design	Design	Design	Design	Design	Design	Design	Design
LNG	-	-	Retrofit	Design	Design	Retrofit	Retrofit	Retrofit
LEG (Ethane)	-	-	Retrofit	Retrofit	-	Design	Retrofit	Retrofit
Methanol	-	-	Retrofit	Retrofit	-	Retrofit	Design	Retrofit
LPG	-	-	Retrofit	Retrofit	-	Retrofit	Retrofit	Design
Ammonia	-	-	Retrofit	Retrofit	-	Retrofit	Retrofit	Retrofit

Figure 4.1: Retrofittability of different fuels provided by MAN Energy Solutions (2022).

4.2.2 Tank system and piping

The standard LNG tank and the piping system will not be sufficient for ammonia use. Ammonia is more corrosive and less volumetric energy dense than LNG. The fuel tank notation (T) and pipe notation (P) means that the tanks and piping installed can be used for ammonia. The tanks must be able to carry both fuels. Right now, only stainless steel is suitable for both fuels. Ammonia has about half the energy by volume compared to LNG (DNV, 2021). It either reduces operating range or requires the installation of additional tanks.

4.2.3 Structure and design

Ammonia is about 36% heavier than LNG (DNV, 2021). The structural preparations (S) must be able to handle this extra weight. If the vessel needs extra tanks for ammonia, then the structure can also be prepared for this. The design notation (D) implies that the design followed all ammonia regulations when it was built.

4.2.4 Ammonia tested

The ship's emissions must be tested and approved by class when it is built. It is a standard procedure, and all new builds have to do it. Engines are tested on a test rig before being installed on the ship. It does not need further testing onboard the ship to receive its certificates. Engines are harder to test for emission onboard the ship after installation. Certificates of rebuilt engines can be expensive to get. A potential solution for this is to buy the retrofit kit together with the engine. The engine is tested and certified for regular use and retrofit. After certification, it will be placed in storage until needed for retrofit.

4.3 Energy savings solutions

Fuel is the most crucial decision for emission reduction, but there are other alternatives. Most of them can be used both alone and together with fuel improvement.

4.3.1 Speed reduction

Speed reduction is a well-known method for emission and fuel reduction. Slow steaming was implemented after the financial crisis in 2008. It has been used to reduce fuel consumption when the rates are low, or bunker prices are high. Slow steaming was a more straightforward fix earlier when some ships, like container vessels, sailed at 25 knots. The effect is much lower at lower speeds. A large part of the steam-LNG fleet will have to reduce emissions next year when the new EEXI and CII regulations are implemented. A speed limit has been suggested earlier as a way to reduce emissions. It is not as easy as it seems because speed optimization includes many factors. If it only were regarding fuel per tonne mile, it would favor a very low service speed (Psaraftis, 2019). It will not be economically possible.

4.3.2 Hydrodynamics

Hull coating is used by most larger vessels to reduce fouling. The coating is usually redone every time the vessel is in drydock. Air lubrication systems are a method for reducing hull friction. It reduces the friction between the wet surface of the ship and the seawater. Computational analysis on a 154,800 m^3 LNG carrier was performed by Fotopoulos and Margaris (2020). The analysis is done using a vessel speed of 20 knots, with four dual fuel Wartsila 13,740 kW engines running on LNG. The results show a fuel reduction of 8 % and 12 tons per day. Silverstream's air lubrication has delivered systems to Carnival, Maersk, MSC, and others. Their systems give a net savings of 6% to 9% for LNG carriers. The payback time of the system usually ranges between two and six years (Silverstream, 2022), (Ship & Bunker, 2021).

Hull cleaning is a method to remove fouling. It is usually done some years after the last docking to reduce resistance on the vessel. The fuel savings from hull cleanings is characterized by diminishing returns. Regular hull cleanings will lead to less fouling and less improvement from each hull cleaning. Low fuel prices and frequent cleanings can outweigh the savings (Pagoropoulos et al., 2018). The energy efficiency effect of hull cleanings is considered significant by (Adland et al., 2018). A fleet of Aframax tankers is analyzed. The results show a fuel reduction of 9 % from cleaning after only 45 days. The effects of a dry dock are higher at 17 % fuel reduction.

4.3.3 Machinery

A shaft generator can be used as a tool to optimize the emission profile of a propulsion system. It can help reduce emissions from the ship and lower its EEDI values. The shaft generator ensures that the main engine always runs at optimal fuel efficiency. It will switch between power take-in (PTI) and power take-off (PTO). When the main engine has excess power, the shaft generator charges batteries for later use. Then it is used later when the main engine needs excess power (Perez and Reusser, 2020).

4.3.4 Wind-assisted propulsion

Wind-assisted commercial ships have become an alternative after 100 years without them. There are several different technologies. An Aframax tanker and a Handysize bulk carrier have been used in a performance study testing three wind-assisted propulsion technologies (Lu and Ringsberg, 2020). Fuel savings for actual routes were estimated for Flettner rotors, wingsails, and the DynaRig concept.

Flettner rotors were the most efficient solution. It leads to fuel savings of 8,9% in the case study.

Another case study on flettner rotors is done on a 229-meter bulk carrier by (Ammar and Seddiek, 2021), suggests fuel reductions of 16,2%, 8,5% and 10,9%. The ship is equipped with 4 Flettner rotors and has been tested on three routes. The payback period for the investment is 7, 13, and 11 years with an HFO fuel price of 300 $/ton bunker.

Chapter 5

Decision method

A method for valuing and modeling the future is needed to analyze different alternatives. This chapter will give an introduction to real options in projects. It is followed up by a discussion of different valuations and simulation methods. Then the preferred method is decided.

5.1 Real Options

The most promising solutions for achieving zero-emission from shipping are not ready yet. The technology must be developed, tested, and approved on board ships before it can be used. Options for retrofit are the closest possibility. Real options theory is introduced for valuing opportunities.

Real options use the financial option theory for valuing real investment projects. Real options allow an investor to take an upfront cost to potentially reduce costs or increase earnings later. It can help the investor face future uncertainties. It opens for flexibility in future investments. Flexibility is represented as options in Real Options Analysis (ROA), and different types of flexibility have been identified (Perlitz et al., 1999):

Option	Description
Option to defer	The possibility to wait until more favorable circumstances.
Time-to-build	Carry out an investment in several stages gives the opportunity to abandon an investment before all cost are sunken.
Option to expand	Expand the scale of production if market conditions are more favourable then expected.
Option to abandon	Abandon operation in bad market conditions.
Option to switch	Switch product or market if demand changes.
Growth option	Research and development is opening future opportunities.

Table 5.1: Different types of options (Perlitz et al., 1999)

Financial option

The definition of an option is "An option is a security giving the right to buy or sell an asset, subject to certain conditions, within a specified period of time" (Black and Scholes, 1973). It is traditionally related to finance. The pricing and value of the financial option are based on the underlying security. The option owner has the "right" to sell or buy the option, but he is not obligated to do so. The price of this flexibility is the option premium. It gives the buyer of an option a potentially unlimited upside with a limited downside. The most used option types is *American* options and *European* options. An American option can be exercised any time before the option's maturity. The European option is only possible to exercise at maturity. A *Call* option is the right to buy the underlying security at the given strike price. *Put* option is the right to sell the underlying security at the given strike price. Perpetual options are options without an expiration date. The use of perpetual options in finance is limited, and they are not listed on any options exchanges.

Real options in and on systems

Real options are project dependent and often unique. They are not as well-defined as financial options. Real options can either be categorized as "on" projects or "in" projects (Wang and de Neufville, 2009). The possibility of selling a ship is an option the shipowner has on the ship. The shipowner has the option to sell the ship whenever he wants. It makes it similar to a financial option. Real options in projects are often more complex and harder to value. They are changes to the actual project. An "in" option on the ship can be the option to switch fuel. It is impossible to sell this individual option to an outsider at any time. Several difficulties need to be regarded when analyzing real options "in" projects Wang and de Neufville (2009):

- Information and knowledge about the option and technology is essential. It is impossible to evaluate the system without a deep understanding of the technology. The economic assessment is the only one needed in financial options. An option for retrofit for a new fuel requires knowledge about the risks and uncertainties and the economic aspect.

- Real options are likely path dependent. The value of an option for retrofit to a new fuel is dependent on technology improvements, fuel prices, availability, and regulations. The development of external factors is often hard to predict.

- The valuation metrics of financial options are more set than for real options. The exercise price, time to exercise, and volatility are important factors when using Black-Scholes for valuation. These are usually uncertain for real options "in" projects. The exercise price and time to exercise are often path-dependent. The volatility can not be regarded in the same way if it is impossible to sell the option.

- An option in a project is likely to depend on other options and parts of the project. It creates compound options and is more complicated to value.

5.2 Options in physical systems

Options "in" projects are complex. It is likely many potential options and a combination of options in a project. The process for analysis of real options "in" projects described by (Wang and de Neufville, 2009) is illustrated in Figure 5.1.

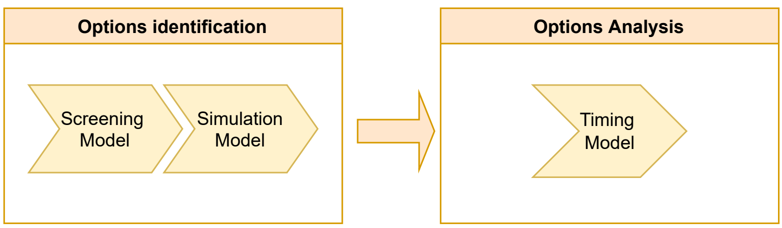

Figure 5.1: Framework for options analysis based on Wang and de Neufville (2009).

The first part of the process is to identify the option. The terms (European, American, expiration day, and exercise price) are clearly defined in financial options. It is not the case for options in projects. They must be identified and more clearly defined before they can be analyzed. A screening model is used to identify different options in the project. Then a simulation model is used for testing the candidates. The second part of the process is to analyze the options. A model for valuing the options and finding a strategy for exercise is then needed (Wang and de Neufville, 2009).

5.2.1 Screening model

The screening model is used for identifying options. A project has many potential options. They are usually complex, and the valuation is not straightforward. The screening model works as a quick tool to identify which options are most promising and justifies further study. The screening model can be fully quantitative to entirely qualitative. It depends on the screened parameters. An alternative to a screening model based on (Wang and de Neufville, 2009) can be:

$$Max : \sum_j (\beta_j * X_j - c_j * X_j) \tag{5.1}$$

s.t

$$T * X > t \tag{5.2}$$

$$E * X > e \tag{5.3}$$

X_j are the design parameters, β_j are the benefit coefficients, and c_j are the cost coefficients. The objective function 5.1 calculates the net benefit. Constraints 5.2 and 5.3 illustrate technological and economic limitations of the system. All of the parameters can be uncertain. It can be a method for uncovering uncertainties for the later options analysis.

Figure 5.2 shows a qualitative approach for screening the options or options classes. Equation 5.1 maximizes for one key metric. It can be easier to highlight several metrics with a qualitative approach.

	Price	GHG Reduction	Zero Emission
Ammonia	Medium	High	Yes
Hydrogen	High	High	Yes
Air Lubrication	Low	Low	No

Figure 5.2: Example of a screening approach.

5.2.2 Simulation

The next step is to test the most promising option candidates. Two potential methods here are Monte Carlo simulation and Epoch-Era Analysis.

5.2.3 Monte Carlo simulation

Monte Carlo simulation is a method for simulating random variables. It is used to predict probabilities of different outcomes when uncertain variables are involved. A random value is assigned to the uncertain value, and the result is stored. Then this process is repeated many times. The results are averaged together to give an estimate of the result. The process is illustrated in Figure 5.3.

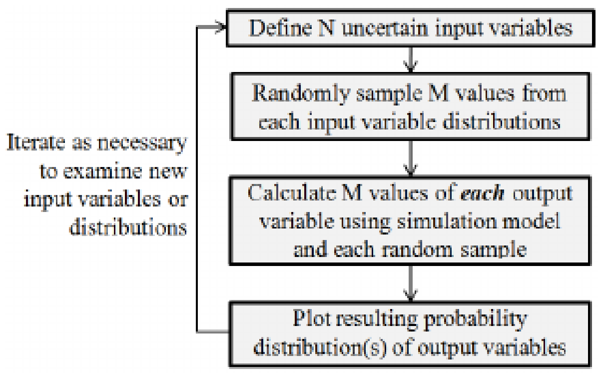

Figure 5.3: Monte Carlo simulation process illustrated by (Rader et al., 2010).

Monte Carlo simulation makes it possible to estimate various problems that otherwise would be hard to solve using standard methods. An advantage of Monte Carlo simulation is that all possible outcomes are visible. It can illustrate large upsides and large downsides. It makes Monte Carlo simulation a valuable method for simulating uncertainties.

5.2.4 Epoch-Era Analysis

Epoch-Era analysis (EEA) evaluates how a system provides value to stakeholders over time. EEA captures the value of flexibility and changeability over time (Ross et al., 2008).

EEA can be used for estimating how a ship will perform during its lifetime. The full lifetime is referred to as *System Era*, which is divided into *Epochs* (Ross and Rhodes, 2008). Each epoch is static. Market, technology, design, and regulations are constant during an epoch. The switch of these attributes starts the change to a new epoch. It makes the system era and evaluation system dynamic. EEA is especially valuable for testing changeability and how a ship performs in an uncertain future.

Figure 5.4 illustrates how a fixed system performs in different epochs. The expectation is given in a range from the minimally acceptable to the highest expectations. The system performs far above expectations in epoch 1. There is a switch in the context in epoch 2, but the expectations are unchanged. The performance has decreased but is still above expectations. Epoch 3 has higher expectations without change in context. The high performance considering changes shows robustness in the system. A potential change in the system is illustrated in epoch 5. It makes it possible to meet expectations if a change is possible.

Switching cost is an essential part of the evaluation. A stable but sound system will often be better than a system that needs costly changes and perform very well in some scenarios.

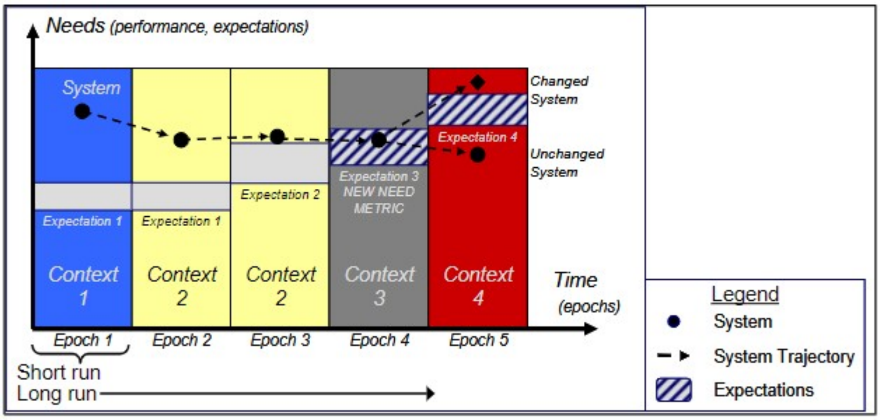

Figure 5.4: System needs vs expectations across epochs of the system era (Ross and Rhodes, 2008).

5.2.5 Responsive Systems Comparison method

The Responsive Systems Comparison (RSC) method is a potential step by step process of using the Epoch-Era analysis. It consists of 7 processes. These are illustrated in Figure 5.5.

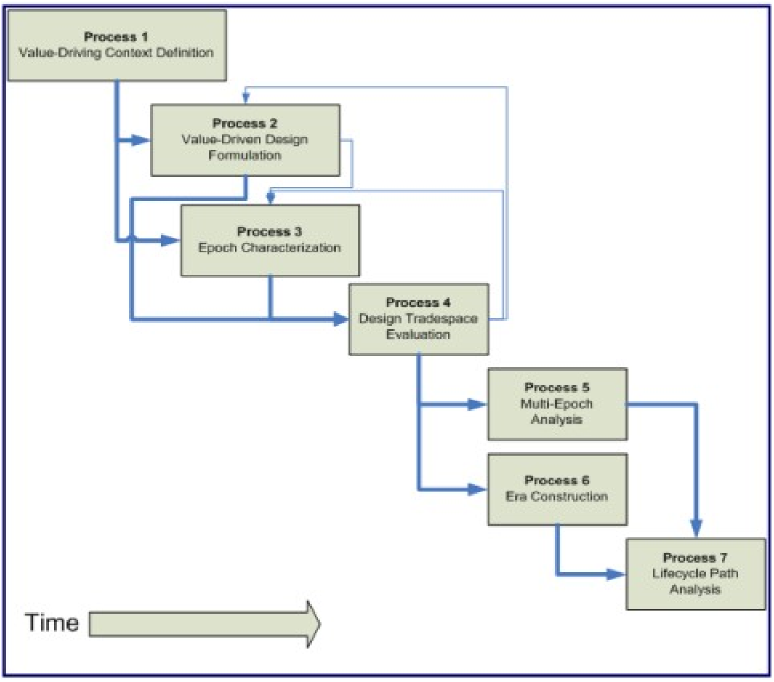

Figure 5.5: Responsive Systems Comparison method process flowchart (Ross et al., 2009).

The Responsive Systems Comparison method is a structured method for analyzing how changes in context and preferences impact the performance of a system. RSC uses Multi-Attribute Tradespace Exploration (MATE) together with Epoch-Era Analysis. Then the user is guided through a step-by-step process for designing and evaluating different system concepts (Ross et al., 2009).

Process 1: Value-Driving Context Definition
The first process of the RSC is to define the basic problem, stakeholders involved, and other important factors. Then the overall value proposition for the case study is formed.

Process 2: Value-Driven Design Formulation
The second process starts with defining stakeholders' needs. A set of attributes reflects the system's performance according to the stakeholders' preferences. Then a set of concepts that meets those attributes are developed. The different concepts are decomposed into design variables of the system.

Process 3: Epoch Characterization

The different uncertainties are parameterized as epoch variables. The epoch variables are divided into different categories. The combination of different epoch variables creates epochs. These will also reflect the change in stakeholders' preferences.

Process 4: Design Tradespace Evaluation

The system solutions are simulated in each of the different epochs. The range of how a system performs in the different epochs defines a design tradespace. The trade space is typically illustrated in a graphic representation.Figure 5.6 shows an illustration of a utility versus lifecycle cost tradespace. The systems plotted on top to the left are the preferred solutions.

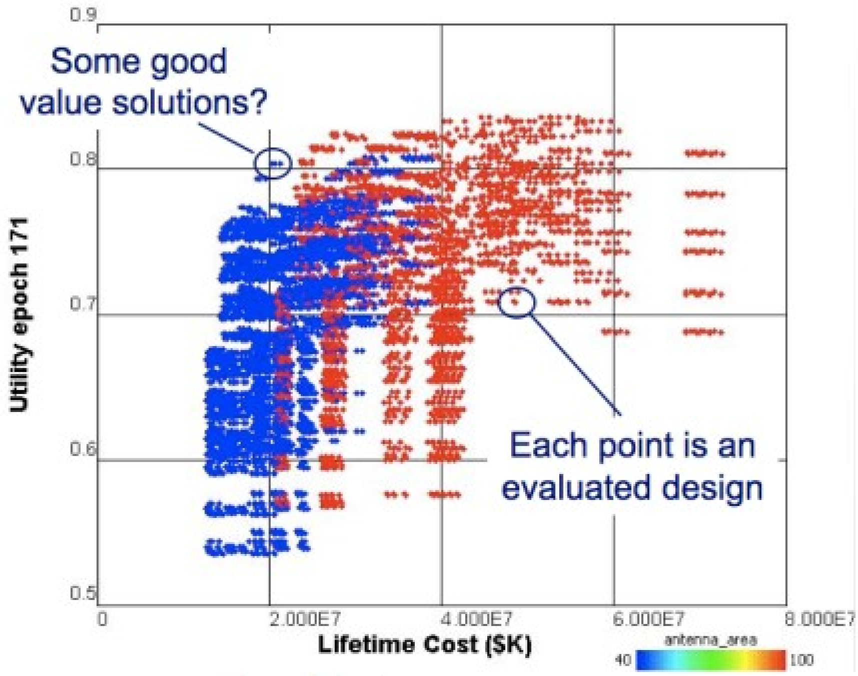

Figure 5.6: Static Tradespace (Ross et al., 2009).

Process 5: Multi-Epoch Analysis

The different systems solutions are tested across multiple epochs. It gives an insight into the robustness and flexibility of the system and how it is affected by uncertainties.

Process 6: Era Construction

Each era is constructed by combining a set of fixed duration epochs. Eras are long-term descriptions of possible futures for the systems (Schaffner et al., 2013). The eras can be constructed automatically or manually. It can be done using Monte Carlo simulation or stakeholder and expert opinions.

Process 7: Life Cycle Path Analysis

The last process is analyzing how a system performs in different eras. A static system can be used as a benchmark. Then flexible systems with options for retrofits can be tested against the benchmark.

5.2.6 Valuation model

The last part of the option evaluation is to find the value of the option.

5.2.7 Binomial option pricing model

Binomial option pricing provides a straightforward approach for valuing financial options. It uses an iterative numerical method and assumes binomial price movements of the stock price over a given time period. The price can either go up or down. The return of the stock after a given period is either u-1 or d-1 with a probability of q and 1 - q. The stock price is then uS or dS after a time period (Cox et al., 1979). The value of option S can be found by working backward in the binomial tree in Figure 5.7.

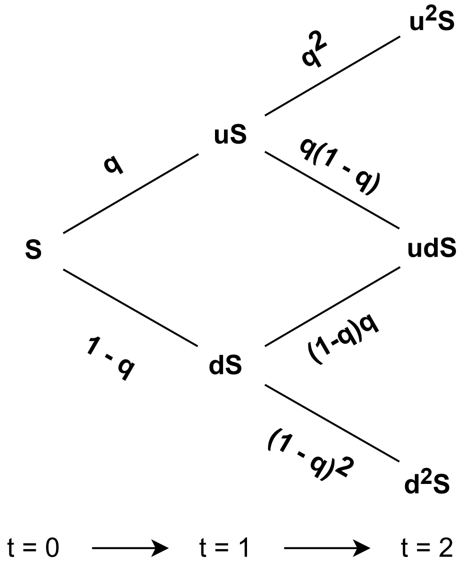

Figure 5.7: Binomial tree based on (Cox et al., 1979).

5.2.8 Net present value

Net Present Value (NPV) is the difference between the value of cash inflow today and the present value of cash outflow over a given period of time. It is used to find the present value of a future cash flow. NPV can be used for investment decisions in projects. The investment meets the demand for return if the NPV is positive. The cash flow from each period is discounted with a given discount rate. The discount rate should represent the return achieved through alternative investments. Net Present Value can be calculated by using:

$$NPV = \sum_{t=0}^{N} \frac{R_t}{(1+r)^t} \tag{5.4}$$

In Equation 5.4, *R* is the net cash flow in a period *t*, **r** is the discount rate.
The Expected Net Present Value (ENPV) can be found using the probability of the expected cash flow in each period.

5.3 Decision process

The decision method must be made considering the individual project. A screening is a valuable start for identifying potential options. Next is the simulation. Emission regulations will get stricter, but technology development is uncertain. Monte Carlo simulation is suitable for testing uncertain variables with randomness. Epoch-Era Analysis provides a method for simulating the shipowners' concerns and expectations.

Epoch-Era analysis can be done in different ways. It ranges from "quantitative" to "qualitative". It is possible to generate all potential combinations and then evaluate them. Similar to a Monte Carlo simulation. The opposite way of doing it is to create a smaller set of potential epochs and eras based on expert and stakeholders' expectations. The duration of each epoch and era can be randomly decided or specifically chosen based on the given project. Epoch-Era Analysis is a flexible method for simulating performance in an uncertain future. It will be the method used for the simulation.

The next step is the valuation model. Exercise of the option(s) will likely happen far into the future (5 - 15 years). Some of the technology solutions are not ready yet. A ship will usually be retrofitted close after it is built. The net present value is better than the Binomial option pricing method in this case. The binomial option pricing method better fits real options "on" projects. The problems of using financial option pricing methods "in" projects have been presented in Table 5.1. NPV will be used in the RSC-method's life cycle analysis to find the options' value.

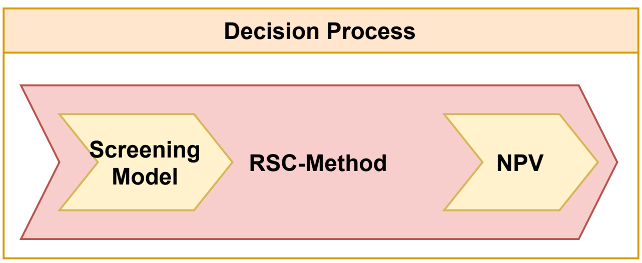

Figure 5.8: Decision process

Chapter 6

Case study

The case study will test and illustrate the models suggested earlier on an LNG carrier. The screening method illustrated in Figure 5.2 and the responsive systems comparison method is used together with NPV to analyze the problem. The responsive system comparison method will include steps from 1-3 and 4-7.

6.1 Value-Driven Context Definition

A shipowner has been awarded a 10-year contract for gas transportation. There are uncertainties regarding emission regulations, fuel prices, and available technology. It means that it can be necessary to retrofit the ship to get a new favorable contract after ten years. The shipowner wants to know what he can do during the vessel's construction to prepare for a potential retrofit and if he should do it.

6.1.1 Stakeholders in the project

Stakeholders' needs set the groundwork for the project. The shipowner is the most important stakeholder in this project. Then comes the customer of the shipowner and the shipyard building it. All of these are important when making decisions regarding the ship. They have different needs and priorities. Risk and time period are different for them. All of these considerations can affect the decision process. Some of them are illustrated in Figure 6.1. How each makes money will define many of their interests, wants, and needs. Shipyards is a low-margin business. The price is agreed upon before building. Exceeds will usually lead to a profit reduction for the shipyard. Shipyards will then prefer a series of standard ships. Shipowners will, on the other hand, often have specialized ships to be able to meet the fluctuating demands of their customers. The shipowner wants to be able to adapt if suddenly the customer wants a more specialized ship.

Description	Shipyard	Shipowner	Customer
Role	The ship builder	Owner and operator	Charters the vessel
Time periode	2 to 5 years	25 years	Days to 10 years
Risk	Takes the risk of construction	Risk of ownership	Dependent on charter period
Economic upside	Limited upside, contract price	High with good rates	High with bad rates
Economic downside	Large downside with to low contract price	High with bad rates	High with good rates
Specialization	Wants standard ships	Flexible ships	Fluctuating

Figure 6.1: Stakeholders needs.

6.2 Value-Driven Design Formulation

The stakeholders involved in the project have been introduced in Figure 6.1. The primary stakeholder is the shipowner. It means that the needs of the shipowner are the main target. The shipowner will be the decision maker. Assumptions of the main stakeholder are introduced:

6.2.1 Assumptions of the shipowner

- The ship will be built to run on LNG. It will be equipped with a dual fuel MEGI engine.
- The length and size of the ship are predetermined by infrastructure and contract. It is not possible to optimize size. It is built as a standard 174,000 cubic meter LNG carrier.
- The potential retrofit of the vessel will be done during a special survey. The logistics of ship position, routes, and shipyard availability make this the most likely solution.
- The ship will only run on LNG until the potential retrofit. Ammonia will be the only available fuel after the retrofit.

6.2.2 Stakeholders needs

The next step is to define the shipowner's needs and preferences. It will be used to find and define the potential solutions that fit the shipowners' expectations. The most important needs and parameters for the shipowner is:

- *Price* is always an important factor. The target of this case is to find solutions that help reduce the lifetime cost of the ship. The installation cost is still an important part. Low upfront costs are preferred.

- *GHG reductions*. It is important to be able to meet stricter regulations. High reduction solutions will therefore be preferred.

- *Zero-emission* is the final IMO target. Many companies have already set zero-emission targets for 2050. The ship can have a lifetime of 30 years. It means that zero-emission solutions are needed to meet this target.

- *Standard today*. Some solutions are standard on the ship today. Will the ship use this solution from the start?

- *Available today*. Is the technology for this solution developed?

6.2.3 Screening model

There are many potential options for an LNG carrier. Screening is needed to find the options with the best potential. These will then be further evaluated. This thesis focuses on fuel and energy solutions. Potential solutions discussed in chapter 4 will be evaluated. The qualitative approach from Figure 5.2 will be used because of the uncertainty in the numbers. The goal is to find solutions according to stakeholders' needs.

	Price	GHG Reduction	Zero Emission	Standard Today	Available Today
Ammonia	High	High	Yes	No	No
Hydrogen	High	High	Yes	No	No
Methanol	High	High	No	No	Yes
Air Lubrication	Medium	Low	No	No	Yes
Shaft Generator	Medium	Low	no	No	Yes
Hull Cleaning	Low	Low	No	Yes	Yes
Rotor Sails	Medium	Low	No	No	Yes

Figure 6.2: Screening of options.

Screening of potential options is done on essential parameters. Figure 6.2 illustrates the results. Assumptions for the screening are made in appendix section A.

Options are divided into two categories; fuel and energy saving solutions. The target is to find solutions where the economic benefit of the options are positive. The most critical parameter for this is "available today". It will have a large impact on the total life cycle economy of the solutions. Regular hull cleanings are performed on all larger vessels today. An option for hull cleaning tools is then excessive. Air lubrication, shaft generator, and rotor sails are available today. The net economic benefit of these systems is dependent on payback time. It favors building them during construction instead of in 10 years. A rapid decrease in technology prices can change the estimate. A net present value estimate can be used for the calculations.

New fuel solutions are needed for considerable emission reduction as noted in Figure 6.2. Methanol is available as a fuel today. Maersk has ordered ships with dual fuel methanol engines. However, only a tiny part of the methanol produced today is low emission fuel. Ammonia and hydrogen are then the only way toward zero CO_2 emission. These solutions are not ready yet. An option for retrofit gives the option to install it cheaper later if needed.

6.2.4 Design concepts

The ship can be designed with an endless number of different configurations. Based on the screening, hydrogen and ammonia are the only solutions capable of zero CO2 emissions. Other emission reduction solutions are ready today. Their lifetime value depends on how many years they are used. It makes it favorable to install the systems as early as possible. The findings from section 4.1 and chapter 2 must be considered. Ammonia's characteristics are favorable over hydrogen in deep sea shipping. Hydrogen will likely not be possible in deep sea shipping in the near future. The only relevant option preparation for zero-emission will then be for ammonia.

Retrofit preparation can be done in several degrees. DNV has created a new standard for ships ready for retrofit called "Fuel ready" (DNV, 2021). DNVs fuel ready notation includes design (D), engine possible to be converted (MEc), structural requirements (S), and tanks (T). Other essential aspects are reliquefaction (Re) and piping (P). The notations are discussed in section 4.2. They give different levels of readiness.

LNG carriers are carrying and running on gas. They have to comply with gas regulations. It makes them compliant with the design-ready notation as a standard. Most new large LNG carriers are built with the MAN MEGI engine. This engine is compliant with a retrofit for ammonia. It means that these vessels are built with design (D) and engine (MEc) as a standard. Even though the ship is installed with the right engine, it needs certification for ammonia. A conversion kit for ammonia is then needed. The engine is tested and certified (C) for ammonia use simultaneously as the regular testing. It is further discussed in subsection 4.2.4.

Five additional options can be installed during construction to make a retrofit easier. Design (D) and engine (MEc) are "free". Reliquefaction (R) system increases the reliquefaction capacity to 100%, piping (P) makes the pipe system compliant with ammonia, structure (S) handles the increased weight of ammonia, and certified (C) are the conversion kit for ammonia and certification. Tanks (T) are tanks capable of both ammonia and LNG. A large combination of options is possible. All combinations are not necessary to test. Prices of each option at newbuild and the price of each retrofit are illustrated in Table 6.1.

	Piping	Structure	Certified	Reliquefaction	Tanks	Unit
Newbuild	1	2	6	15	15	m USD
Retrofit	3	4	10	18	12	m USD
Savings	2	2	4	3	-3	m USD
Savings	67	50	40	17	-25	%

Table 6.1: Building prices as new build and retrofit, based on estimates from BW LNG.

Option combinations are dependent on price savings and total price. Significant percentage savings and small installation costs are preferred. Piping gives savings of 67% with only 1 million in sunk cost. A larger reliquefaction plant gives in comparison 17% with 15 million USD upfront cost. The options with low prices and high returns are selected first. Six design alternatives are then available. The design alternatives are illustrated in Table 6.2. This combination assumes that an improved structure is not needed for piping.

Design nr.	Piping	Structure	Certified	Reliq	Tanks
Design 1					
Design 2 (P)	x				
Design 3 (PS)	x	x			
Design 4 (PSC)	x	x	x		
Design 5 (PSCR)	x	x	x	x	
Design 6 (PSCRT)	x	x	x	x	x

Table 6.2: Design options.

Quantifying the option of flexibility

Each design's new build and retrofit cost are presented in Table 6.3. Each design is possible to retrofit, but at a different cost. The option price is paid at construction, and the retrofit cost is paid at retrofit.

Design nr.	Option price [m USD]	Retrofit cost [m USD]
Design 1	0	47
Design 2 (P)	1	44
Design 3 (PS)	3	40
Design 4 (PSC)	9	30
Design 5 (PSCR)	24	12
Design 6 (PSCRT)	39	0

Table 6.3: Options and retrofit cost.

6.3 Epoch characterization

A set of epoch variables is created based on stakeholders' needs. The epoch variables are divided into different categories and illustrate uncertainties in the future. The target is to test how the different concept designs perform in the future. The most critical uncertainties that affect the design performance are; fuel prices, greenhouse gas taxation, available technology, and infrastructure. Fuel prices are a large part of ships operating expenses. Emission regulations are getting stricter and stricter. It is not yet sure what the preferred low emission fuel will be and when it will be ready. Infrastructure is essential for fuel availability. The epoch variables are presented in Table 6.4. The value of each epoch variable is either; Low, Medium, or High.

Epoch variables		**Value**	**Unit**
Fuel price	LNG	Low, Medium, High	[-]
	Ammonia	Low, Medium, High	[-]
	Bio LNG	Low, Medium, High	[-]
Regulation	GHG tax	Low, Medium, High	[-]
Technology	Ammonia ready	Low, Medium, High	[-]
Infrastructure	LNG availability	Low, Medium, High	[-]
	Ammonia availability	Low, Medium, High	[-]
	Bio LNG availability	Low, Medium, High	[-]

Table 6.4: Epoch variables.

Fuel prices

Industry experts and financial analysts are always trying to predict fuel prices. The problem is that fuel prices are impossible to predict. Anybody capable of doing it would quickly be a rich. The prices used in this case study are based on findings from section 3.6. Table 6.5 is given as averages from different periods in the last 18 months. Prices are given in USD per ton of LNG-380e.

Fuel prices		
Value	Quantification	Description
Low	500	Average Nov. 20 to Sep. 21
Medium	900	Average Feb. 21 to Feb. 22
High	1400	Average Jan. 22 to May. 22

Table 6.5: Quantification of fuel prices.

Green house gas taxation

A greenhouse gas tax is expected to be implemented. The European Commission has a plan for it, but some countries are against the tax. It will likely start as a small tax based on CO_2 emissions. Suggestions start at about 25 USD per ton of LNG. Prices will then increase in steps to phase out fossil fuels. Based on different estimates, prices can range from 100 USD/ton to 400 USD/ton (Blanton and Mosis, 2021), (Maersk, 2021), (Liu et al., 2021). The GHG tax in this case study is set as a base, then multiplied by the tax factor for finding taxes per ton of fuel for different fuels. A base case tax of 100 USD/ton is used for the case study. Equation 6.1 shows how the tax for a ton of a given fuel is estimated.

$$\textit{Total tax [USD/ton]} = \textit{GHG tax factor} * \textit{Base GHG tax} \tag{6.1}$$

GHG tax factor		
Value	Tax factor	Description
Zero	0	No GHG tax for zero-emission solutions
Low	1	Base tax factor
Medium	1,5	Increased taxes
High	2	High case tax factor

Table 6.6: GHG tax factor.

Ammonia technology

The available technology is essential for being able to use a particular fuel. New technology is developed fast. It leads to lower prices of "old" technology. Equipment installed today can be a lot cheaper in 10 years. Price decreases are happening to every type of technology. Lithium-ion battery technology is an example. The prices have decreased by 97% in the last three decades (Ziegler and Trancik, 2021).

Ammonia technology		
Value	Quantification	Description
Low	3	Not available technology or not competitive priced
Medium	1,2	Available technology, upper range of price
High	1	Regularaly used, competitive pricing

Table 6.7: Ammonia technology availability.

Infrastructure

Infrastructure is needed to use a particular fuel. Fuels like MGO/HFO are the most used ones and are available in all ports. LNG is less used. It is not available in all ports, but the infrastructure is being built out. However, the general LNG infrastructure is not relevant for LNG carriers. They run on boil off from the tanks and always have access to LNG. It is possible to build infrastructure for new fuels if it is not ready, but this comes at a higher price.

Infrastructure		
Value	Quantification	Description
Low	2	Low availability, needs to be improved to be able to use
Medium	1,2	Available some places, depending on ports
High	1	Available in all ports

Table 6.8: Infrastructure availability.

6.3.1 Epoch description

The epochs can be constructed automatically or manually. A large number of epochs are available by using all combinations of the epoch variables. The epochs are manually constructed in this case to reflect different market developments and stakeholders' expectations.

Epoch 1

LNG prices are stable, and the vessel will keep running on LNG. Both ammonia and Bio LNG are still too expensive to use. GHG taxes have not yet been implemented. LNG is available in the ports the ship is bunkering in but still not available everywhere. Ammonia is not approved for use on ships yet. Bio LNG is only available in some places at high prices.

Epoch 2

Ammonia is available for use, but fuel is still expensive. LNG and bio LNG is cheaper and similarly priced. Emission taxes have been implemented for LNG. It is possible to bunker LNG in all ports. Bio LNG and ammonia are available in larger ports.

Epoch 3

Energy prices have decreased. LNG is cheap, and ammonia is available in most places at affordable prices. LNG tax increases the total price of LNG. Biofuels are expensive and less used.

Epoch 4
It is impossible to solve the problems regarding ammonia toxicity for use onboard ships. Methanol and bio LNG is the preferred fuel options for low emission fuels. LNG has become more expensive, and bio LNG is cheap. It is possible to bunker both LNG and bio LNG everywhere.

Epoch 5
Ammonia technology has been used for years. Fuel prices are lower for ammonia than LNG, and bio LNG is still expensive. LNG tax and bio LNG tax are high and medium. LNG is available in all ports, bio LNG is only available in some places, and ammonia is available in all ports.

Epoch description					
	Epoch 1	Epoch 2	Epoch 3	Epoch 4	Epoch 5
LNG price	Medium	Medium	Low	High	Medium
Ammonia price	High	High	Medium	High	Low
Bio LNG price	High	Medium	High	Low	High
LNG tax	Zero	Low	Medium	High	High
Bio LNG tax	Zero	Low	Low	Low	Medium
Ammonia tech	Low	Medium	High	Low	High
LNG availability	High	High	High	High	High
Ammonia availability	Low	Medium	Medium	Low	High
Bio LNG availability	Low	Medium	Medium	High	Low

Table 6.9: Epoch characterization.

6.4 Multi-Epoch analysis

The multi-epoch analysis aims to test the designs in various situations. It gives a better understanding of the robustness of the system. Two sets with multiple epochs are tested. The combination of these represents a potential development in the industry.

Bio LNG multi-epoch

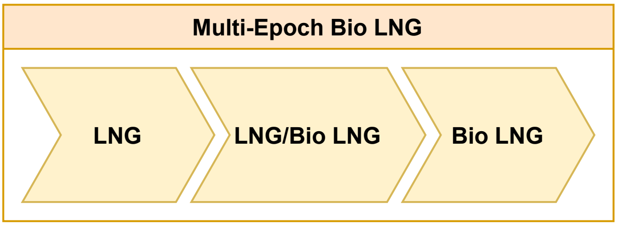

Figure 6.3: Multi-Epoch analysis including epoch 1, 2 and 4.

The multi-epoch illustrated in Figure 6.3 goes toward adopting Bio LNG as a fuel. Each epoch characteristic can be seen in Table 6.9. The preferred fuel will start as LNG, then gradually switch to Bio LNG as the availability increases and the prices decreases. The high ammonia prices and low availability make a switch to ammonia unlikely. The ship will not be retrofitted to ammonia in this scenario. Options are regarded as a sunk cost, and the investment is lost.

Design.nr	Value	Unit
Design 1	0	m USD
Design 2 (P)	- 1	m USD
Design 3 (PS)	- 3	m USD
Design 4 (PSC)	- 9	m USD
Design 5 (PSCR)	- 24	m USD
Design 6 (PSCRT)	- 39	m USD

Table 6.10: Option value of each design in multi-epoch 1, 2, 4.

Ammonia multi-epoch

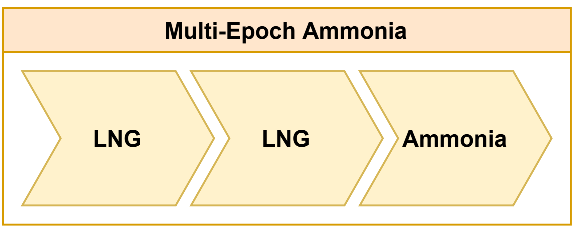

Figure 6.4: Multi-Epoch analysis including epoch 2, 3 and 5.

The multi-epoch illustrated in Figure 6.4 goes toward ammonia adoption. Prices and availability make ammonia expensive at the start, then it decreases. LNG is cheaper than ammonia in the first two epochs, then switches in the last. A retrofit to ammonia will then be done before the last epoch. The option will then only provide value on the last epoch. Each design is displayed in Table 6.11. Yearly savings are dependent on the spread between ammonia and the combined LNG fuel and tax cost. The value shown is the cumulative savings after x years into the epoch. The designs are compared to a standard ship without an option for retrofit, running on LNG for the whole period. The calculations do not adjust for the present value.

Design nr.	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**	**Year 10**	**Unit**
D1	- 36,2	-25,4	-14,6	-3,8	7	61	m USD
D2 (P)	-34,2	-23,4	-12,6	-1,8	9	63	m USD
D3 (PS)	-32,2	-21,4	-10,6	0,2	11	65	m USD
D4 (PSC)	-28,2	-17,4	-6,6	4,2	15	69	m USD
D5 (PSCR)	-25,2	-14,4	-3,6	7,2	18	72	m USD
D6 (PSCRT)	-28,2	-17,4	-6,6	4,2	15	69	m USD
Base case	0	0	0	0	0	0	m USD

Table 6.11: Option value after x years into the last epoch.

6.5 Era construction

Each epoch has been constructed, and a multi-epoch analysis has been performed. It indicates how the designs perform in different scenarios. The next step is to analyze how they perform in a longer changing period. Each era is constructed as a set of epochs with fixed time periods. It models a possible long-term future. The epoch and era period have to be decided. The eras are then constructed.

Each epoch runs for a given period. It can range from seconds to years, depending on the type of analysis. A retrofit is both expensive and time-consuming. The ship must go out of trade to a yard for the retrofit. The best way to decrease the opportunity cost is to do the retrofit during a special survey. Then it is only "possible" to retrofit every fifth year. A ship with the newest technology should not need a retrofit after five years. Will therefore, use ten year period for each epoch.

The number of epochs decides the era period. A ship will likely have a lifetime between 20 and 30 years. It argues for either two or three epochs in each era. Cost and prices expected in the future have to be discounted to find the present value.

The discounted value will almost eliminate costs and savings happening 20 years into the future. This, together with the high uncertainty, a period of 20 years is reasonable.

Eras can either be constructed manually or randomly. Each epoch has been constructed manually based on market research and stakeholders' expectations. The eras will therefore also be constructed manually. Epochs 1 and 2 are similar to the market environment today and in the coming years. This is used for the first epoch in each era. Then the following epoch illustrate different directions. Ammonia can either be adapted or flop, similar to bio LNG, and the effect of increased CO_2 tax is illustrated. The eras show possible market developments. They are presented in Table 6.12.

Era construction		
	First epoch	Second epoch
Era 1	Epoch 1	Epoch 3
Era 2	Epoch 1	Epoch 5
Era 3	Epoch 2	Epoch 3
Era 4	Epoch 2	Epoch 4
Era 5	Epoch 2	Epoch 5

Table 6.12: Era construction.

6.6 Life Cycle Path Analysis

The eras are constructed to simulate the long-term future of the system. It is used for a life cycle path analysis. Similar to in section 6.4 a base case design is used for a benchmark. Net present value is used to estimate each design's value. The results are then displayed. The expected value of each design is discussed.

The six different design alternatives are tested over 20 years. They will be operating with LNG fuel for the first ten years, then retrofit for ammonia use. It is assumed that the ship will only operate on ammonia after the retrofit. There are two additional benchmark designs. Design 7 is an LNG benchmark running on LNG the whole period, and design 8 is a Bio LNG benchmark running on Bio LNG the whole period. These two will not have an option for retrofit and will not be retrofitted.

	Description
i	Sets of vessel designs
j	Sets of fuels
F	Daily fuel consumption
O	Operation days per year
G	GHG base tax
E	Epoch time peroid
r	Discount rate
C_i^O	Option cost of design i
C_i^R	Retrofit cost of design i
C_j^F	Fuel cost of fuel j
G_j^F	GHG tax factor for fuel j
C_j^T	Technology cost of fuel j
A_j	Availability cost of fuel j
C_i^C	Combined cost of vessel i
r	Discount rate
R	Time until retrofit

Table 6.13: Vessel cost.

The analysis includes four cost parts for the different designs. The designs are indexed (i).

Option cost C_i^O is the cost of buying and installing the extra equipment during the construction of the vessel.

$$\textbf{Option cost} = C_i^O \tag{6.2}$$

Fuel cost is dependent on fuel prices, operating days, and daily consumption. Low availability of fuel leads to an increased cost. The fuel cost is discounted over the two-stage era.

Fuel tax is dependent on operating days, daily consumption, base GHG tax, and GHG tax factor for each fuel.

$$\textbf{Fuel and tax} = \sum_{t=0}^{E} \frac{FO(C_j^F A_j + GG_j^F)}{(1+r)^t} + \sum_{t=E}^{2E} \frac{FO(C_j^F A_j + GG_j^F)}{(1+r)^t} \tag{6.3}$$

Retrofit cost is discounted because of the time period. It is also adjusted for the extra price of available technology.

$$\textbf{Retrofit cost} = \frac{C_i^R C_j^T}{(1+r)^E} \tag{6.4}$$

The combined cost of the vessel is then:

$$C_i^C = C_i^O + \frac{C_i^R C_j^T}{(1+r)^E} + \sum_{t=0}^{E} \frac{FO(C_j^F A_j + GG_j^F)}{(1+r)^t} + \sum_{t=E}^{2E} \frac{FO(C_j^F A_j + GG_j^F)}{(1+r)^t} \tag{6.5}$$

6.6.1 Probability and expected net present value

The whole analysis aims to give the shipowner helpful input when ordering a new vessel. Epochs and eras are constructed based on expectations and market outlook. The NPV of the different solutions is estimated. The last step is actual probabilities for finding the expected net present value (ENPV) based on stakeholders' future expectations. Probabilities of each era are presented in Table 6.14.

Era nr.	Probability
Era 1	20 %
Era 2	20 %
Era 3	15 %
Era 4	20 %
Era 5	25 %

Table 6.14: Probability of each era.

6.6.2 Results

Results of the analysis are displayed in Table 6.15, Table 6.16, Table 6.17 and Table 6.18. The life cycle cost includes installation, retrofit, and fuel costs. The prices are discounted to present value. The expected value (EV) of each design is calculated based on expected probabilities presented Table 6.14. The significant differences between the eras are mainly from changes in fuel cost. The results will mainly illustrate the effect of changing fuel, not the option's value. The option value is better illustrated in Table 6.19.

Total cost with standard switch

The results in this section present the total cost with a switch to ammonia after ten years for designs 1 to 6. The six designs are being rebuilt to ammonia and will run with ammonia fuel for the last ten years.

Design nr.	Era 1	Era 2	Era 3	Era 4	Era 5	EV	Unit
Design 1	177	154	190	259	167	188	m USD
Design 2 (P)	177	154	190	259	167	188	m USD
Design 3 (PS)	177	154	190	259	167	188	m USD
Design 4 (PSC)	179	156	192	261	169	190	m USD
Design 5 (PSCR)	187	164	200	269	177	199	m USD
Design 6 (PSCRT)	197	174	210	280	187	208	m USD
Design 7	142	159	155	193	172	165	m USD
Design 8	431	477	222	175	269	317	m USD

Table 6.15: Results with discount rate of 10% and base GHG tax of 100 USD/ton.

Design nr.	Era 1	Era 2	Era 3	Era 4	Era 5	EV	Unit
Design 1	255	209	286	421	241	280	m USD
Design 2 (P)	254	208	285	421	240	279	m USD
Design 3 (PS)	254	208	285	420	240	279	m USD
Design 4 (PSC)	253	208	285	420	239	279	m USD
Design 5 (PSCR)	257	212	289	424	243	282	m USD
Design 6 (PSCRT)	265	219	296	432	251	290	m USD
Design 7	204	243	235	315	275	256	m USD
Design 8	587	683	348	256	444	468	m USD

Table 6.16: Results with discount rate of 5% and base GHG tax of 200 USD/ton.

Total cost with optimal switch

This section illustrates the total cost of a more optimal switch, compared to section 6.6.2 that illustrates the total cost of a "forced" switch. Table 6.17 and Table 6.18 presents the results of a more realistic switch. The ship will only get retrofitted for the next period if it saves money. Figure 6.5 illustrates the best fuel solutions in each era for minimizing total cost.

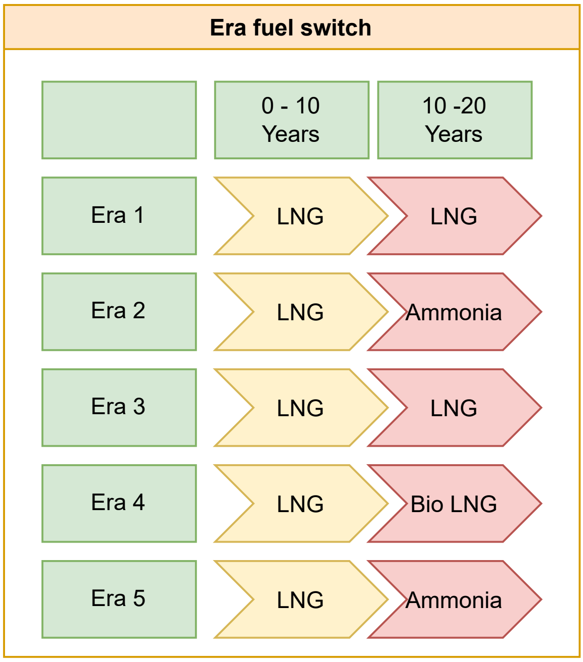

Figure 6.5: Optimal fuel solutions in each era.

Design nr.	**Era 1**	**Era 2**	**Era 3**	**Era 4**	**Era 5**	**EV**	**Unit**
Design 1	142	154	155	153	241	154	m USD
Design 2 (P)	143	154	156	154	240	155	m USD
Design 3 (PS)	145	154	158	156	240	156	m USD
Design 4 (PSC)	151	156	164	162	239	161	m USD
Design 5 (PSCR)	166	164	179	177	243	172	m USD
Design 6 (PSCRT)	181	177	194	192	251	185	m USD
Design 7	142	159	155	193	275	165	m USD
Design 8	431	477	222	175	269	317	m USD

Table 6.17: Results with discount rate of 10% and base GHG tax of 100 USD/ton. Switching done for optimal cost.

Design nr.	Era 1	Era 2	Era 3	Era 4	Era 5	EV	Unit
Design 1	204	209	235	228	241	224	m USD
Design 2 (P)	205	209	236	229	240	224	m USD
Design 3 (PS)	207	208	238	231	240	225	m USD
Design 4 (PSC)	213	208	244	237	239	228	m USD
Design 5 (PSCR)	228	212	259	252	243	238	m USD
Design 6 (PSCRT)	243	220	274	267	250	250	m USD
Design 7	204	243	235	314	275	256	m USD
Design 8	587	683	348	256	444	468	m USD

Table 6.18: Results with discount rate of 5% and base GHG tax of 200 USD/ton. Switching done for optimal cost.

6.6.3 Option value

It is possible to retrofit all the suggested designs to ammonia. Design 1 is a standard ship retrofitted later on. It will be the benchmark for valuing the options when doing a retrofit. The total cost of each option includes option cost and exercise cost. It is ten years from investment to exercise. The discount rate will have a large effect. Figure 6.6 illustrates the large effect of various discount rates. It illustrates the present value of installation and retrofit for the different design alternatives. Design 1 installs all the equipment during the retrofit in 10 years. It gives a higher cost with 0 discount rate, but large savings with high rates. Design 6 installs all the equipment during construction. It means that the discount rate does not affect the price.

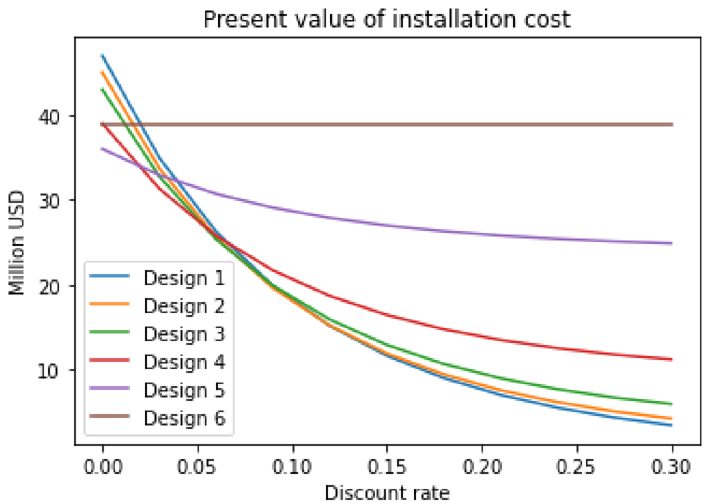

Figure 6.6: Present value of installation and retrofit cost based on discount rate and 10 years until retrofit.

The discount rate is significant for the total cost. It means that time until retrofit also is essential. The present value of installation and retrofit cost dependent on time is presented in Figure 6.7. It is calculated with a discount rate of 5%. Design 5 is the optimal choice for retrofits earlier than four years in the future. It is not very likely to happen. A new ship with new technology should not need a retrofit this early.

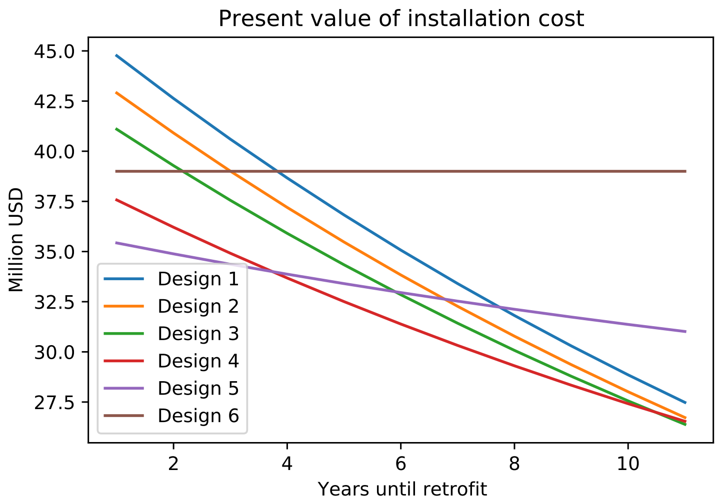

Figure 6.7: Present value of installation and retrofit cost dependent on years until installation with a discount rate of 5%.

The option value of the different designs based on the discount rate is presented in Table 6.19. It illustrates the option value based on the discount rate of the different designs, assuming it is retrofitted in 10 years. At just 10%, there is practically no value in any of the options.

Design\Discount rent	**0 %**	**5 %**	**10 %**	**15 %**	**Unit**
Design 1	0	0	0	0	m USD
Design 2 (P)	2,0	0,8	0,1	-0,2	m USD
Design 3 (PS)	4,0	1,2	-0,2	-1,2	m USD
Design 4 (PSC)	8,0	1,4	-2,5	-4,8	m USD
Design 5 (PSCR)	11,0	-2,6	-10,5	-15,4	m USD
Design 6 (PSCRT)	8,0	-10,2	-21,9	-27,4	m USD

Table 6.19: Option value based on discount rate. Retrofit is done after 10 years.

Chapter 7

Discussion

This chapter will include a discussion of the case study results, the weaknesses of the assumptions and simplification, and a discussion of the suggested method and how the case study highlights its strengths and weaknesses.

Discounted cash flow significantly affects the results of the study presented in Table 6.18 and Table 6.17. The discount rate's effect is illustrated in Figure 6.6. Design 1 is the best solution based on the results. It is a standard vessel that is retrofitted when needed. The present value of the savings from the cheaper retrofit gets low when it happens in 10 years. None of the eras in Table 6.12 illustrates a scenario when ammonia is ready immediately. An era with ammonia retrofit in the first epoch could have been created, but it would not have accurately illustrated the near future. Ammonia is not ready to be used yet.

Assumptions and simplifications have been made for the case study that impacts the calculations. An important consideration is that ammonia has a lower energy density than LNG. If the ammonia tanks are the same size as the LNG tanks, it will lead to a lower range. The reduced range will likely harm the ship's earnings. A reinforced structure is another problem. It will increase the weight of the ship and reduce the loading capacity. A problem with the option valuations and the values seen in Table 6.19 is that they only consider ammonia. The expected value of each option would increase if they also considered retrofitting to other fuels. An example is the reliquefaction system; it can be used on all retrofits. It will increase the probability of using the option and increase the expected value.

It was assumed that the ship could only run on ammonia when it was retrofitted to ammonia. It is not necessarily technically correct. A solution using both LNG and ammonia is potentially possible. However, for practical reasons, it is probably correct. A switch to ammonia is likely driven by force due to regulations, high prices, or customer demand. If regulations drive it, it will be impossible to switch back even if the shipowner wants to.

The epoch and era generation was done manually. It was done to make it reflect the market and stakeholders' expectations. If a shipowner uses the model for part of the decision process, it must be understandable and easy to use. Analysis and research are wasted time if the shipowner does not understand and is willing to use them. The decision-maker needs to be on board with the process. However, there are several negatives of manually constructing them as well. One of the reasons for doing a simulation is to find out how a system handles uncertainty and unexpected events. Detecting unexpected events is more unlikely with manually constructed epochs and eras. Automatically generated epochs and eras are likely better for discovering unexpected events.

Each epoch was set to an extended time period. It will lower the accuracy of the model. When looking at technology and expensive retrofits, long periods make sense. These decisions are taken with a long-time perspective. The fuel prices will, on the other hand, be inaccurate. The fluctuations in just the last two years have been enormous. Nevertheless, fuel prices are impossible to predict. The epoch characterization for technology and infrastructure is case-dependent. The quantifications used in the case study are meant for illustrative use and are not based on any particular research. It will likely give a wrong estimate on how much extra it costs for technology and infrastructure in the different epochs.

Savings from each option is essential. The percentage savings are highest for the cheapest options in the case study. It partly illustrates the labor cost. Piping and structure offer considerable percentage savings. It is because the installation is a significant part of the cost. The reliquefaction system is much more expensive. The installation cost of the reliquefaction system is a minor part of total costs. It illustrates the importance of finding the options where installation is a large part of the total costs.

There is uncertainty when a model is dependent on numbers that are either hard to find or hard to estimate. Different numbers can change the results of the study. It is essential to include this as a margin of error. Some solutions seem like no-brainers if the information is correct for the ship in question. An example is air lubrication. With more than 5% fuel savings and less than five years of payback time, it seems like no reason not to install it. In addition, the increased fuel prices in the last years will improve many of these investments.

A simulation dependent on fuel prices leads to uncertainties. Fuel prices have large price fluctuations and are impossible to predict. The prices used in the case study was based on prices from the last 1,5 year. The prices increase during this period has reduced the effect of the proposed GHG tax. The tax would considerably impact LNG fuel prices at 300 USD/toe. The price difference is lower at 1500 USD/toe. It will impact the percentage cost difference between ammonia-fueled and LNG-fueled ships more at lower fuel prices.

One considerable negative with this epoch-era simulation is that the six different designs all test for retrofit for ammonia. It is illustrated in section 6.4. It is only the time that separates the outcome of the different solutions. If the outcome of one of them is positive, then all will be positive if given enough time. The value of the option to retrofit is dependent on the fact that it is possible to retrofit a standard ship. If the standard ship were impossible to retrofit, the options would get a higher value.

It is easy to miss small critical details. The tank solutions illustrate this. Installation of tanks capable of both LNG and ammonia seems like a potential cost saver. The tanks are a large part of the vessel and can be expensive to switch. On a retrofit, however, tanks will not be switched. New ammonia tanks are most likely installed on deck instead. Then it is possible to use cheaper tanks that are not compliant with LNG and ammonia. It makes new tanks cheaper than duel-fuel tanks.

Design for changeability was introduced by Fricke and Schulz (2005). Robustness, flexibility, agility, agility, and adaptability are important aspects of changeability. Different types of changeability have been evaluated. On combination carriers by Sødal et al. (2008) and on offshore vessels by Rehn et al. (2018), Rehn (2018), Pettersen et al. (2018) and Agis (2020). It is concluded that flexibility can have value in certain types of designs. Combination carriers can switch to the market with the best rates (Sødal et al., 2008). Rehn et al. (2018) studies the relationship between economic performance and flexibility for non-transport vessels. Either retrofit ability or versatility achieves flexibility. Findings indicate that retrofit ability increases economic performance. Both studies indicate a value in increased flexibility. It is then interesting to ask if the suggested design solutions in the LNG case improve flexibility. Special for this case is that the ship is already compliant for retrofit. The standard ship can do the same retrofit as the retrofit prepared designs, just at a higher price. The design prepared for retrofit does not open any new markets or operation possibilities. This is different compared to the increased flexibility of the offshore vessels and the combination carriers. Their flexibility opens new markets and contracts. The flexibility provided in the LNG case is just easier retrofit.

A general problem with theoretical experiments and models is that many of the proposed solutions are impossible. Outside factors that are neither included nor easy to simulate can change promising results. For this case, it can be perfect timed retrofits. It would be possible to find the optimal retrofit time based on fuel prices. As discussed earlier, the logistics and alternative costs limit this solution. It is usually not possible to take the ship out of the trade in a short moment, and most shipyards do not have drop-in opportunities. Sødal et al. (2008) highlights this problem on combination carriers. Theoretically, these ships can switch loads on different routes and directions. It gives a "possibility" to carry dry cargo one way of the route, then liquid cargo on the way back. It is, in almost all cases, not possible. Usually because of the logistics.

The case study does not fully utilize the potential of the suggested method. All the six concept designs illustrate retrofit to ammonia. The value of all concept designs is dependent on the same variables. They will have value if the ship is retrofitted to ammonia within a given period, dependent on time and the discount rate used to calculate value.

Better use of the method with a similar case could potentially be to either go more or less into detail. A solution could be to test all the solutions in Figure 6.2 based on the stakeholder's needs. It is probably a more accurate use of the RSC method. The more complex solution is possible as well. Some of the concepts used for ammonia will also comply with other solutions. The reliquefaction system is needed for all fuel retrofits. It will then have a value on both hydrogen and ammonia retrofits. A more technical understanding of how all the parts and systems work is then needed.

Epoch-Era Analysis makes it possible to illustrate and simulate the market expectations of experts and stakeholders. It is a good method for testing the robustness of a system. Figure 5.4 illustrates this. The different concept designs in the case do not improve the system's robustness. A case design capable of operating on both ammonia and LNG could be compared to a standard system that is only LNG compliant. The method would then illustrate and test the robustness of the improved system in a better way.

The most critical assumption is time until retrofit and discount rate. Most other assumptions and simplifications will not matter as long as these are correct. The time value will neglect other mistakes.

Chapter 8

Conclusion

Several retrofits can be done to improve the ship. Additional solutions like air lubrication and shaft generators can be added for efficiency improvements. However, the ship should not be prepared for a retrofit to these. If the net present value of these solutions is positive or the shipowner thinks they will be needed, then they should be installed at construction. It will improve the value of the solutions compared to a retrofit for them in the future.

Fuel solutions are needed if zero-emission is the target. The relevant fuels to consider are ammonia, methanol, and hydrogen. The zero-emission fuels like ammonia and hydrogen are not ready yet. A preparation for retrofit is therefore possible. Methanol is possible to order today, but it is not zero-emission. A new efficient ship running on LNG will not need a retrofit for many years. A retrofit preparation should therefore be done to a zero-emission solution. The characteristics of hydrogen are likely not suitable for deep-sea shipping. A potential preparation should therefore be done for ammonia.

With an expectation of being able to run on LNG for an extended period, uncertainty about ammonia, and a discount rate of between five and ten percent, a shipowner should not prepare the ship for ammonia. The main reason for this is the time and potential implications. New LNG ships are very efficient, and LNG is the fossil fuel with the lowest emissions. They will likely be the last to be phased out. It will probably take at least ten years until this happens. The present value of potential savings happening in ten years is small because of the discount rate. It eliminates most of the upside of the option. The implications of not preparing for retrofit is another essential aspect. The ship is already running on gas, and most new ships will be built with the MEGI engine compliant for a retrofit. A standard vessel is, therefore, possible to retrofit. The main implication of not preparing the ship is a higher cost in 10 years. The conclusion is dependent on the ship configurations, expectations of ammonia, discount rate, and time. Different expectations of the stakeholders can make a preparation valuable. Lower discount rates and shorter time will make the investment valuable. A standard configuration not suitable for retrofit will also change the conclusion. If the ship is prepared for retrofit, the options with low upfront costs are the preferred start. In this case, it will be the designs with piping and structure preparations.

Bibliography

Adland, R., Cariou, P., Jia, H., Wolff, F.C., 2018. The energy efficiency effects of periodic ship hull cleaning. Journal of cleaner production 178, 1–13.

Agis, J.J.G., 2020. Effectiveness in decision-making in ship design under uncertainty .

Ammar, N.R., Seddiek, I.S., 2021. Wind assisted propulsion system onboard ships: case study flettner rotors. Ships and offshore structures , 1–12.

Balcombe, P., Staffell, I., Kerdan, I.G., Speirs, J.F., Brandon, N.P., Hawkes, A.D., 2021. How can lng-fuelled ships meet decarbonisation targets? an environmental and economic analysis. Energy 227, 120462. URL: https://www.sciencedirect.com/science/article/pii/S0360544221007118, doi:https://doi.org/10.1016/j.energy.2021.120462.

Baldi, F., Gabrielii, C., 2015. A feasibility analysis of waste heat recovery systems for marine applications. Energy 80, 654–665. URL: https://www.sciencedirect.com/science/article/pii/S0360544214013784, doi:https://doi.org/10.1016/j.energy.2014.12.020.

Black, F., Scholes, M., 1973. The pricing of options and corporate liabilities. The Journal of political economy 81, 637–654.

Blanton, E., Mosis, S., 2021. The carbon-neutral lng market: Creating a framework for real emissions reductions.
https://www.energypolicy.columbia.edu/research/commentary/carbon-neutral-lng-market-creating-framework-real-em
_ednref73. (Accessed on 01.04.2022).

Cox, J.C., Ross, S.A., Rubinstein, M., 1979. Option pricing: A simplified approach. Journal of Financial Economics 7, 229–263. URL: https://www.sciencedirect.com/science/article/pii/0304405X79900151, doi:https://doi.org/10.1016/0304-405X(79)90015-1.

DNV, 2019a. Assessment of selected alternative fuels and technology. https://www.dnv.com/maritime/publications/alternative-fuel-assessment-download.html. (Accessed on 12.11.2021).

DNV, 2019b. Comparison of alternative marine fuels. https://safety4sea.com/wp-content/uploads/2019/09/SEA-LNG-DNV-GL-Comparison-of-Alternative-Marine-Fuels-2019_09.pdf. (Accessed on 20.04.2022).

DNV, 2021. Energy transition outlook 2021. https://eto.dnv.com/2021/about-energy-transition-outlook. (Accessed on 23.02.2022).

DNV, 2021. Five lessons to learn on hydrogen as ship fuel. https://www.dnv.com/expert-story/maritime-impact/Five-lessons-to-learn-on-hydrogen-as-ship-fuel.html. (Accessed on 02.11.2021).

DNV, 2021. Maritime forecast to 2050. https://eto.dnv.com/2021/maritime-forecast-2050/about. (Accessed on 02.03.2022).

Ekanem Attah, E., Bucknall, R., 2015. An analysis of the energy efficiency of lng ships powering options using the eedi. Ocean engineering 110, 62–74.

Fotopoulos, A.G., Margaris, D.P., 2020. Computational analysis of air lubrication system for commercial shipping and impacts on fuel consumption. Computation 8, 38.

Fricke, E., Schulz, A.P., 2005. Design for changeability (dfc): Principles to enable changes in systems throughout their entire lifecycle. Systems Engineering 8. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/sys.20039, doi:https://doi.org/10.1002/sys.20039, arXiv:https://onlinelibrary.wiley.com/doi/pdf/10.1002/sys.20039.

IMO, 2021. Fourth imo greenhouse gas study. https://unctad.org/system/files/official-document/rmt2021_en_0.pdf. (Accessed on 19.04.2022).

ITF, FIT, 2018. Decarbonising maritime transport: Pathways to zero-carbon shipping by 2035 .

Kim, K., Roh, G., Kim, W., Chun, K., 2020. A preliminary study on an alternative ship propulsion system fueled by ammonia: Environmental and economic assessments. Journal of marine science and engineering 8, 183.

Kukuljan, D., Bernecic, D., Orović, J., 2012. The lng reliquefaction plant - operating principle and justifiability of its installation on board ships 26, 215–226.

Lagemann, B., Lindstad, E., Fagerholt, K., Rialland, A., Stein-Ove Erikstad, S., 2022. Optimal ship lifetime fuel and power system selection. Transportation research. Part D, Transport and environment 102, 103145.

Liu, Y., Xin, X., Yang, Z., Chen, K., Li, C., 2021. Liner shipping network - transaction mechanism joint design model considering carbon tax and liner alliance. Ocean coastal management 212, 105817.

Lu, R., Ringsberg, J.W., 2020. Ship energy performance study of three wind-assisted ship propulsion technologies including a parametric study of the flettner rotor technology. Ships and offshore structures 15, 249–258.

Maersk, 2021. Industry transition strategy. `https://cms.zerocarbonshipping.com/media/uploads/documents/MMMCZCS_Industry-Transition-Strategy_Oct_2021.pdf`. (Accessed on 23.01.2022).

Mallouppas, G., Yfantis, E.A., 2021. Decarbonization in shipping industry: A review of research, technology development, and innovation proposals. Journal of marine science and engineering 9, 415.

MAN Energy Solutions, 2022. Dual-fuel retrofits of low-speed engines key in push towards decarbonisation. `https://www.man-es.com/docs/default-source/press-releases-new/dual-fuel-retrofits-and-newbuilding_en.pdf?sfvrsn=9048cdcf_6`. (Accessed on 08.01.2022).

Pagoropoulos, A., Kjaer, L.L., Dong, Y., Birkved, M., McAloone, T.C., 2018. Economic and environmental impact trade-offs related to in-water hull cleanings of merchant vessels. Journal of industrial ecology 22, 916–929.

Perez, J.R., Reusser, C.A., 2020. Optimization of the emissions profile of a marine propulsion system using a shaft generator with optimum tracking-based control scheme. Journal of marine science and engineering 8, 221.

Perlitz, M., Peske, T., Schrank, R., 1999. Real options valuation: the new frontier in rd project evaluation? R D management 29, 255–270.

Pettersen, S.S., Erikstad, S.O., 2017. Assessing flexible offshore construction vessel designs combining real options and epoch-era analysis. Ship technology research = Schiffstechnik 64, 76–86.

Pettersen, S.S., Rehn, C.F., Garcia, J.J., Erikstad, S.O., Brett, P.O., Asbjørnslett, B.E., Ross, A.M., Rhodes, D.H., 2018. Ill-Structured Commercial Ship Design Problems: The Responsive System Comparison Method on an Offshore Vessel Case. Journal of Ship Production and Design 34, 72–83. URL: https://doi.org/10.5957/JSPD.170012, doi:10.5957/JSPD.170012, arXiv:https://onepetro.org/JSPD/article-pdf/34/01/72/2205077/sna

Psaraftis, H.N., 2019. Speed optimization vs speed reduction: The choice between speed limits and a bunker levy. Sustainability (Basel, Switzerland) 11, 2249.

Rader, A., Ross, A., Rhodes, D., 2010. A methodological comparison of monte carlo simulation and epoch-era analysis for tradespace exploration in an uncertain environment, pp. 409 – 414. doi:10.1109/SYSTEMS.2010.5482433.

Rehn, C.F., 2018. Ship design under uncertainty .

Rehn, C.F., Garcia Agis, J.J., Erikstad, S.O., de Neufville, R., 2018. Versatility vs. retrofittability tradeoff in design of non-transport vessels. Ocean Engineering 167, 229–238. URL: https://www.sciencedirect.com/science/article/pii/S0029801818308515, doi:https://doi.org/10.1016/j.oceaneng.2018.08.057.

RINA, 2019. Lng carrier designs reflect continued market evolution. Naval architect , 32.

Ross, A., Mcmanus, H., Rhodes, D., Hastings, D., Long, A., 2009. Responsive systems comparison method: Dynamic insights into designing a satellite radar system doi:10.2514/6.2009-6542.

Ross, A.M., Rhodes, D.H., 2008. 11.1.1 using natural value-centric time scales for conceptualizing system timelines through epoch-era analysis. INCOSE International Symposium 18, 1186–1201.

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

Schachter, J., Mancarella, P., 2016. A critical review of real options thinking for valuing investment flexibility in smart grids and low carbon energy systems. Renewable and Sustainable Energy Reviews 56, 261–271. URL: https://www.sciencedirect.com/science/article/pii/S1364032115013386, doi:https://doi.org/10.1016/j.rser.2015.11.071.

Schaffner, M.A., Ross, A.M., Rhodes, D.H., 2014. A method for selecting affordable system concepts: A case application to naval ship design. Procedia Computer Science 28, 304–313. URL: https://www.sciencedirect.com/science/article/pii/S187705091400101X, doi:https://doi.org/10.1016/j.procs.2014.03.038. 2014 Conference on Systems Engineering Research.

Schaffner, M.A., Shihong, M.W., Ross, A.M., Rhodes, D.H., 2013. Enabling Design for Affordability: An Epoch-Era Analysis Approach.

Schulz, A., Fricke, E., 1999. Incorporating flexibility, agility, robustness, and adaptability within the design of integrated systems - key to success?, in: Gateway to the New Millennium. 18th Digital Avionics Systems Conference. Proceedings (Cat. No.99CH37033), IEEE. pp. 1.A.2–1.A.2.

Shell, 2022. Shell lng outlook 2022. https://www.shell.com/promos/energy-and-innovation/v1/lng-outlook-2022-report/_jcr_content.stream/1645378179742/3399fc5b65329ddf5fda80ad6cf2f6eab2abd9e5/shell-lng-outlook-2022.pdf. (Accessed on 23.02.2022).

Ship & Bunker, 2021. Air lubrication firm silverstream targets 500 sales by 2025. https://shipandbunker.com/news/world/170808-interview-air-lubrication-firm-silverstream-targets-500-
(Accessed on 15.05.2022).

Ship & Bunker, 2022. Rotterdam bunker prices. https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam#LNG-380e. (Accessed on 21.05.2022).

Silverstream, 2022. Silverstream system performance. https://www.silverstream-tech.com/what-is-air-lubrication/. (Accessed on 15.05.2022).

Singh, D.V., Pedersen, E., 2016. A review of waste heat recovery technologies for maritime applications. Energy Conversion and Management 111, 315–328. URL: https://www.sciencedirect.com/

science/article/pii/S0196890415011826, doi:https://doi.org/10.1016/j.enconman.2015.12.073.

Song, C., Cui, W., 2020. Review of underwater ship hull cleaning technologies. Journal of marine science and application 19, 415–429.

Sødal, S., Koekebakker, S., Aadland, R., 2008. Market switching in shipping — a real option model applied to the valuation of combination carriers. Review of financial economics 17, 183–203.

Toolbox, E., 2003. Fuels - higher and lower caloric values. https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html. (Accessed on 20.04.2022).

UNCTAD, 2021. Review of maritime transport 2021. https://unctad.org/system/files/official-document/rmt2021_en_0.pdf. (Accessed on 19.04.2022).

Wang, T., de Neufville, R., 2009. Building real options into physical systems with stochastic mixed-integer programming .

Wärtsilä, 2020. Wärtsilä advances future fuel capabilities with first ammonia tests. https://www.wartsila.com/media/news/25-03-2020-wartsila-advances-future-fuel-capabilities-with-firs utm_source=press-release&utm_medium=org&utm_term=marine&utm_content=1st+Ammonia+test&utm_campaign=Green+Ammonia+engine+tests. (Accessed on 20.04.2022).

Ziegler, M.S., Trancik, J.E., 2021. Re-examining rates of lithium-ion battery technology improvement and cost decline. Energy Environ. Sci. 14, 1635–1651. URL: http://dx.doi.org/10.1039/D0EE02681F, doi:10.1039/D0EE02681F.

Zwaginga, J., Stroo, K., Kana, A., 2021. Exploring market uncertainty in early ship design. International Journal of Naval Architecture and Ocean Engineering 13, 352–366. URL: https://www.sciencedirect.com/science/article/pii/S2092678221000212, doi:https://doi.org/10.1016/j.ijnaoe.2021.04.003.

Appendix

A Option screening

Most of the screening is done based on assumptions. Prices and GHG reductions are not certain early in the screening process. Zero emission is assumed tank-to-wake. Nothing is really zero-emission well-to-wake. The ranges for price and GHG emission are given in Table 8.1. Prices are based on assumed total installation cost. The net benefit is not certain yet.

	Price [m USD]	GHG Reduction [%]
Low	0 - 1	0 - 10
Medium	1 - 5	10 - 30
High	5 -50	30 - 100

Table 8.1: Price and GHG reduction assumptions

Ammonia, hydrogen and methanol are capable of high GHG reduction. Zero CO2 emissions are also capable with ammonia and hydrogenMallouppas and Yfantis (2021). Retrofit cost estimated by (Lagemann et al., 2022) for LNG to methanol, ammonia and hydrogen indicates cost of 7, 11 and 23 million. Air lubrication gives an net effect of 6% to 9% for an LNGC according to (Silverstream, 2022), (Ship & Bunker, 2021). Hull cleaning is an effective and low cost way of reducing fuel consumption. Flettner rotors have different effect based on ship and location. Will assume they can reduce emission by less than 10 % even though some studies shows better results.

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