SHIP DESIGN FOR UNCERTAINTY

A Real Options Approach to determine the Value of Design-for-Conversion under Uncertainty

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TU Delft

Royal IHC

Thesis for the degree of MSc in Marine Technology in the specializations of
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Performed at

Royal IHC

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Abstract

The maritime industry faces a lot of uncertainty, and the energy transition has only increased this uncertainty. Ships will probably have to be converted to an alternative fuel during their lifetime and methanol seems to be the fuel with the most potential for offshore ships. By preparing for this, Design-for-Conversion to methanol, the costs of changes can be significantly reduced with only minor investments during the new building phase. The added design preparations pay for themselves only if they are being used in the future. However, due to large uncertainties, it is unclear whether a ship is actually converted to methanol in the future. Therefore, an answer had to be found to the main research question: *"How to determine the value of Design-for-Changeability under uncertainty to find the optimal DFC level when preparing for conversion to methanol?"*

From the literature is concluded that Design-for-Changeability principles can help to deal with uncertainty during a ship's lifetime. Moreover, Real Options Analysis is selected from the literature, as a method to deal with decisions and uncertainty when designing for conversion to methanol. By means of a combination of these methods, a methodology is established which is used in a case study.

In the case study, it was found that waiting with the execution of conversion to methanol results in decreasing added value of Design-for-Conversion. Moreover, it was found that the Discount Rate used for Net Present Value calculation significantly impacts the choice of whether to prepare a ship for methanol. It can be concluded that an instigator is needed so that ships are converted to methanol. Two instigators have been researched, a carbon pricing measure and a ban on CO_2 emissions. It can be concluded that a carbon pricing measure is only effective if the right price is established, while a CO_2 ban is highly effective as ships are converted instantly.

The combination of methods, the Design-for-Changeability principles together with a Real Options Decision Tree, provides a suitable framework to quantify the impact of Design-for-Conversion to methanol under uncertainty.

Preface

Dear reader,

During my graduation project, I had the opportunity to further develop my research skills. By combining theoretical knowledge from TU Delft with the experience from Royal IHC, I was able to set up my research, of which I am very proud.

First of all, I would like to thank Jesper Zwaginga for being my daily supervisor. We had nice, in-depth discussions about the theory and how to tackle certain problems. It was a pleasure working together. In addition, I would like to thank Ken van Schie for being my company supervisor. By sharing his knowledge and experience in ship conversions I learned a lot during my thesis about how things are done in practice, and what the differences are between theory and practice. Moreover, through Ken I was able to speak to many people within IHC, which was very helpful throughout my thesis.

In addition to my daily supervisors, I would like to thank Jeroen Pruyn for providing his knowledge and feedback of which I learnt a lot. Certainly, on the broad outlines of doing research and the economic part of my thesis, I have been given the opportunity to learn new aspects. Moreover, I would also like to thank Henk Polinder for completing my graduation committee.

In addition, I would like to thank Royal IHC for giving me the opportunity to include relevant experience from the industry in my research. My colleagues at the Life Cycle Engineering department have given me a warm welcome within the company, and have always shown their interest in my research. Special thanks to those who contributed directly to my research by sharing their knowledge and experience. First of all Dirk Vullings and Kevin Runge for providing knowledge regarding cost estimation. Moreover, special thanks to Benny Mestemaker for sharing all his knowledge regarding methanol. In addition, I would like to thank Bertin Mayer for his experience in the field of ship conversions.

Lastly, I would like to thank my family and friends who supported me during my thesis. Especially in the period that my research was paused due to my accident, you have been of great help to me.

M.G. Minderhoud
Delft, January 2023

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Nomenclature

Abbreviations

Chapter	Abbreviation	Explanation
Ch. 1	LNG	Liquefied Natural Gas
	GHG	Greenhouse Gas
	DFC	Design-for-Changeability
Ch. 2	DFX	Design-for-X
	NPV	Net Present Value
	DCF	Discounted Cash Flow
	FOD	Filtered outdegree
	FPT	Fuzzy Pareto Trace
	NFPT	Normalized Fuzzy Pareto Trace
	MCV	Multi-Criteria Valuation
	TISM	Total Interpretive Structural Model
	IRP	Interpretive Ranking Process
	B-S	Black-Scholes
	EEA	Epoch-Era Analysis
	ROA	Real Options Analysis
	MDP	Markov Decision Process
Ch. 3	LFO	Light Fuel Oil
	MDO	Marine Diesel Oil
	DAC	Direct Air Capture
	DFR	Design-for-Retrofit
	DP	Dynamic positioning
	ETS	Emissions Trading System
	IMO	International Maritime Organisation
	VOYEX	Voyage Expenditures
Ch. 4	DTA	Decision Tree Analysis
Ch. 5	COG	Centre of Gravity
	LCG	Longitudinal Centre of Gravity
	TCG	Transverse Centre of Gravity
	VCG	Vertical Centre of Gravity
	ER	Engine Room
	TR	Thruster Room
	SR	Storage Room
	WR	Winch Room
	CAPEX	Capital expenditures
	OPEX	Operational expenditures
	ROE	Return on Equity

Symbols

Chapter	Subject	Symbol	Unit	Explanation
Ch. 1		CH_3OH	[-]	Chemical composition of methanol
		CO_2	[-]	Chemical composition of carbon dioxide
		H_2	[-]	Chemical composition of hydrogen
Ch. 2	Net Present	NPV	[€] or [$]	Time value of money
	Value	R_t	[€] or [$]	Cash flow during period t
		i	[%]	Interest rate
		t	[-]	Amount of time periods
	Black-Scholes	C_0	[€] or [$]	Call price
	Formula	S_0	[€] or [$]	Price of the underlying asset
		$N(d_i)$	[-]	Normal distribution of d_i
		X	[€] or [$]	Strike price of an option
		r	[%]	Risk free interest rate per year
		T	[years]	Time until the expiration of the option
		σ	[-]	Volatility
	Markov	$S\{s\}$	[-]	States
	Decision	$A\{a\}$	[-]	Actions
	Process	$T(s'\|s,a)$	[-]	Transitions
		$R(s,a)$	[-]	Rewards
Ch. 3	Greenhouse	NO_x	[-]	Nitrogen Oxides
	gases	SO_x	[-]	Sulphur Oxides
		PM	[-]	Particulate matter
		CO	[-]	Carbon monoxide
	Fuel properties	ρ	$[kg/m^3]$	Density
		LHV	[MJ/kg]	Lower Heating Value
Ch. 4	Decision	exp_{value}	[€] or [$]	Expected value at an uncertainty node
	Tree	$\text{payoff}_{value,\ N}$	[€] or [$]	Payoff value of an option
	Analysis	prob_N	[€] or [$]	Probability of occurrence of an option
Ch. 5	General ship	L_{oa}	[m]	Length overall
	parameters	B	[m]	Beam
		T	[m]	Draught
		D	[m]	Depth
		C_B	[-]	Block coefficient
	Decks	x_{start}	[-]	Frame at which the deck starts in x-direction
		x_{stop}	[-]	Frame at which the deck ends in x-direction
		y_{start}	[m]	Location at which the deck starts in y-direction x-direction
		y_{stop}	[m]	Location at which the deck ends in y-direction
		z_{loc}	[m]	Vertical location of the deck
	Double Shell	x_{start}	[-]	Frame at which the double shell starts in x-direction
		x_{stop}	[-]	Frame at which the double shell ends in x-direction
		W_{shell}	[m]	Width of the double shell

Chapter	Subject	Symbol	Unit	Explanation
Ch. 5	Hull shape	$\mathrm{x_l}$	[m]	Lower boundary in x-direction
		$\mathrm{x_u}$	[m]	Upper boundary in x-direction
		$\mathrm{y_l}$	[m]	Lower boundary in y-direction
		$\mathrm{y_u}$	[m]	Upper boundary in y-direction
		$\mathrm{z_l}$	[m]	Lower boundary in z-direction
		$\mathrm{z_u}$	[m]	Upper boundary in z-direction
		order	[-]	Order of polynomial
		bilge	[m]	Radius of the bilge
		y_i	[m]	Transverse value of hull line
		a_i	[m]	Polynomial scaling factor
		x	[m]	Longitudinal value of hull line
		b_i	[m]	Polynomial shifting factor
	Volumes	V_{box}	[m^3]	Boxed volume of a rectangular space
		dx	[m]	Length of a space
		dy	[m]	Width of a space
		dz	[m]	Height of a space
	COGs	LCG	[m]	Longitudinal centre of gravity
		LCG_{box}	[m]	Longitudinal centre of gravity of boxed volume
		TCG	[m]	Transverse centre of gravity
		TCG_{box}	[m]	Transverse centre of gravity of boxed volume
		TCG_{trapz}	[m]	Transverse centre of gravity of curved part of corrected volumes
		TCG_{rect}	[m]	Transverse centre of gravity of rectangular part of corrected volumes
		$area_{trapz}$	[m^2]	Area of curved part of corrected volumes
		$area_{rect}$	[m^2]	Area of rectangular part of corrected volumes
		$area_{tot}$	[m^2]	Total area of corrected volume
		VCG_{box}	[m]	Vertical centre of gravity of boxed volume
		VCG_{actual}	[m]	Corrected vertical centre of gravity for corrected volumes
	Cofferdams	$m_{\text{cofferdam},i}$	[kg]	Mass of cofferdam i
		$A_{\text{plate},i}$	[m^2]	Area of cofferdam i
		$t_{\text{plate},i}$	[m]	Plate thickness of cofferdam i
		ρ_{steel}	[kg/m^3]	Density of steel
		$[adj_{area}]$	[m^2]	Adjacent area matrix
		$adj_{area,n,m}$	[m^2]	Adjacent area of space n to m
		$\overline{adj}_{air}$	[m^2]	Adjacent area to air vector
		$adj_{air,i}$	[m^2]	Adjacent area to air of space i
		$\overline{cpl}_{factor}$	[-]	Vector containing the complexity factors of all spaces
		$cpl_{factor,i}$	[-]	Complexity factor that scales the amount of work to place a cofferdam in space i
	Piping	L_{piping}	[m]	Total length of all pipes
		x_{ER}	[m]	Location of engine room in x-direction
		$x_{\text{aft tank}}$	[m]	Location of aft most tank in x-direction
		# of tanks	[-]	Total number of methanol tanks

Chapter	Subject	Symbol	Unit	Explanation
Ch. 5	Placement algorithm	r	[m]	Radius of baskets
		$\overline{X}_1$	[-]	Filling vector of spaces
		$\overline{X}_2$	[-]	Vector containing ones
		$\overline{V}_1$	[m^3]	Vector containing the volumes of all spaces
		$\overline{V}_2$	[m^3]	Vector containing the volumes of all usable spaces
		$[EXC]$	[-]	Exclusion matrix
		$C_{cofferdams}$	[€]	Costs based on steel weight cofferdams
		C_{piping}	[€]	Costs based on pipe length
		$C_{painting}$	[€]	Costs based on tank weight
		$C_{occupied\ spaces}$	[€]	Costs to prevent the model from choosing occupied spaces
		$W_{\text{cofferdam}}$	[m]	Distance between cofferdam and space plating
	Stability	GM_T	[m]	Distance between VCG and metacentric height
		KB	[m]	Distance between keel and centre of buoyancy
		BM_T	[m]	Distance between vertical centre of buoyancy and metacentric height
		KG	[m]	Distance between keel and centre of gravity
		TPI	[t/cm]	Tonne per cm immersion
		A_{WL}	[m^2]	Waterline area
		ρ_{sw}	[kg/m^3]	Density of seawater
		T_{new}	[m]	New draught
		I_{xx}	[m^4]	Moment of inertia
		∇	[m^3]	Displacement
		$I_{xx,\text{ aft ship}}$	[m^4]	Moment of inertia of the aft ship
		$I_{xx,\text{ midship}}$	[m^4]	Moment of inertia of the midship
		$I_{xx,\text{ foreship}}$	[m^4]	Moment of inertia of the foreship
		$I_{xx,\text{ moonpool}}$	[m^4]	Moment of inertia of the moonpool
		$m_{lightship}$	[t]	Mass of the lightship
	Costs and revenues	profit	[€]	Annual profit
		revenues	[€]	Annual revenues
		costs	[€]	Annual costs
		day rate	[€/day]	Daily income of the example ship
		up time	[days]	Number of operational days per year
		CAPEX	[€]	Capital expenditures
		OPEX	[€]	Operational expenditures
		VOYEX	[€]	Voyage expenditures
		C_{fuel}	[€]	Fuel costs
		$daily\ consumption$	[t/day]	Daily fuel consumption
		$fuel\ price$	[€/t]	Fuel price
		C_{carbon}	[€]	Costs of carbon
		$carbon\ price$	[€/t]	Carbon price
		$depreciation$	[€]	Annual depreciation of the vessel
		$debt_{interest}$	[€]	Annual paid interest over the debt
		C_{crew}	[€]	Costs for crew
		$C_{insurance}$	[€]	Costs for insurance
		$C_{maintenance}$	[€]	Costs for maintenance
		$C_{docking}$	[€]	Costs for docking
		$C_{management}$	[€]	Costs for ship management
		C_{other}	[€]	Other costs
		RoE	[%]	Return on Equity
		$equity$	[€]	Equity used for financing the ship

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Introduction

Ships play an unseen, but important role in our lives today, as it transports large volumes of food and materials all over the world. Furthermore, our energy supply is heavily dependent on the shipping industry, due to its role in the offshore oil and gas industry as well as the offshore wind industry. Ships, especially the ones in the offshore industry, are long-term assets that currently have an economic lifespan of around 25 years. From a sustainable and economic point of view, it is preferred to prolong this lifespan. However, it is difficult to prolong the service life, as ships face uncertainty. The uncertainty in the maritime industry is due to exogenous changes, such as continuous technological developments, constantly changing regulations and unclear changes in vessel operations. Especially nowadays, uncertainty is high due to the worldwide energy transition. Uncertainty is different from risk: "Risk is the situation under which the decision outcomes and their probabilities of occurrences are known to the decision-maker, and uncertainty is the situation under which such information is not available to the decision-maker" (Park and Shapira, 2017, p.1). Uncertainty in the maritime industry can be categorised into three different types of uncertainty, i.e. technological uncertainty, regulatory uncertainty, and operational uncertainty. An example of technological uncertainty in shipbuilding is the development of new technology to switch to a more sustainable fuel type, such as Liquefied Natural Gas (LNG) or methanol. Besides the development of technology, there may be significant changes in regulations, such as the maximum permissible quantity of greenhouse gas emissions, resulting in regulatory uncertainty (Mestemakers and Bosscha, 2022). An example of operational uncertainty involves emerging markets such as the offshore wind market, resulting in new requirements for offshore vessels. If more information becomes available over time, uncertainty is likely to decrease.

The main consequence of these uncertainties is that the actual capabilities of a vessel do not align with the required capabilities during a ship's life cycle. The gap between the actual capabilities of a vessel and the desired requirements of a ship owner may grow over time. Therefore, the perceived value a ship has to its owner could decrease over time. To regain value to the owner, a ship may be converted to change vessel capabilities that comply with the changed requirements due to uncertainty, as shown in Figure 1.1.

A ship may be prepared for a future conversion by taking changeability into account during the design process. Changeability is the extent to which system properties can easily be changed (Rehn et al., 2019). Life cycle properties mentioned by Rehn et al. are properties such as flexibility, agility, adaptability, and robustness (2019). More information about these properties can be found in chapter 2. Preparing a design for future change by adding additional features is commonly referred to as Design-for-Changeability (DFC). These additional features are called design preparations or options. Adding these options into a design results in a set of requirements that can be altered more easily, and therefore can be considered dynamic.

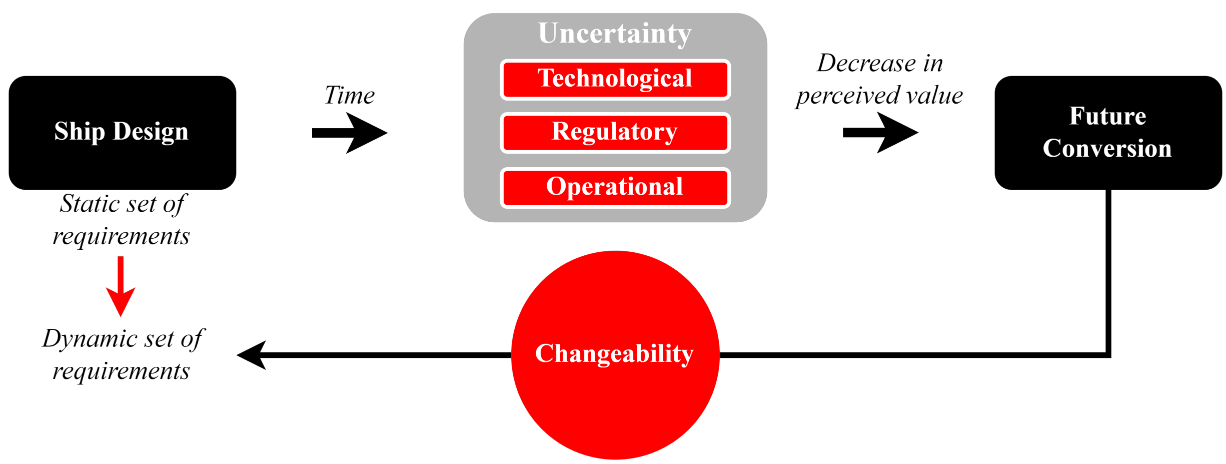


Figure 1.1: Problem breakdown

Design-for-Changeability comes with a couple of benefits. First, preparing a design for future changes by adding design preparations takes little time, because accessibility is still high while making the same changes during a conversion would take a lot of time. And second, the total amount of engineering hours may be reduced, because less time is needed to re-design the ship prior to a conversion. Both elements could result in lower costs when designing for conversion. Despite the benefits of taking changeability into account during early ship design, it initially takes extra time and comes with additional costs. However, a conversion without design preparation may take even more time and can result in higher costs.

This research is conducted in cooperation with Royal IHC, which is known for building complex offshore and dredging ships. These ship types require large amounts of energy because of their dynamic positioning capabilities and mission equipment. In the context of the global energy transition, the maritime industry is looking for less harmful fuel for their ships. An alternative fuel that has the potential to replace diesel fuels for these energy-demanding ships is methanol (CH_3OH). Using methanol also has some advantages compared to diesel and other alternative fuels. Methanol is biodegradable, therefore, it is allowed to be stored adjacent to the side shell as well as inside the double bottom. In addition, methanol is liquid at atmospheric pressure and temperature, thus there is no need to store it cooled and/or pressurised as with LNG or hydrogen H_2. Besides, methanol has different properties compared to diesel oils. The most important one is the fact that methanol has a lower volumetric energy density, resulting in more than twice the amount of fuel needed if one wants to operate a ship on methanol (DNV GL, 2022). Moreover, methanol is highly toxic for humans, causing classification bureaus to call for double walls between spaces available for personnel and tanks/ piping. In addition, methanol is highly flammable resulting in additional hazardous areas on board. However, as methanol is a relatively new fuel, uncertainty is still high. This uncertainty includes regulatory uncertainty, for example on storage conditions or required hazardous zones. Moreover, there is operational uncertainty, for example on the availability of green methanol around the world. Lastly, there is technological uncertainty due to the ongoing development of new technology for methanol application on ships. These uncertainties may impact how a ship needs to be converted to methanol, and consequently how to prepare for this.

The energy transition has increased uncertainty in ship design and operation, and methanol is mentioned as a potential alternative fuel for energy-demanding offshore ships. Most likely, a conversion will be needed in the future, once more information is available and uncertainty is decreased. A ship designer may design with a future conversion in mind, Design-for-Conversion (DFCo). However, information is incomplete on the potential of Design-for-Conversion. The aim of this research is to gain insights into the most important aspects of Design-for-Conversion, such as its benefits, cost, and uncertainty. As Design-for-Conversion to methanol has an impact on many stakeholders, the next section will discuss the relevance of this research area from different perspectives, such as relevance to science, industry, environment, policymaking, and economics.

1.1 Relevance

The energy transition is a topical issue, which greatly increased uncertainty in the maritime industry. Ships may be converted in the future to adapt to the consequences of uncertainty for which preparatory steps can be taken during the design phase. However, when a ship is prepared for future conversion, it will affect a wide range of stakeholders. Therefore, this section will discuss the relevance of this research for science, industry, environment, policymaking, and economy.

1.1.1 Scientific Relevance

Currently, most ships are designed for a static set of requirements. In addition, a lot of time elapses from an initial set of requirements for a concept design till the moment the ship is ready for operation. This can result in newly built ships that may not comply with the eventual requirements, which already may differ from the initial set of requirements used for concept design. This problem will grow during the lifetime of a ship because of changes in available technology, regulations, and operations. This research may initiate a fundamental change in the way researchers look at ship design. Due to uncertainty, ships should not be designed for a static set of requirements, but for value robustness during their lifetime.

Moreover, Reinhardt et al. defined for which types of systems it may be beneficial to add changeability (2001). This includes systems with: a stable core functionality but variable secondary function, long life cycles and fast technological developments, high complexity, and lastly, high development and maintenance costs. Once a method has been found which provides insights into the benefits of dealing with uncertainties in advance, it may be applied to a wide range of systems that meet the above requirements, and are also subject to uncertainty.

1.1.2 Relevance for Industry

Three categories of stakeholders from the industry are identified: ship owners, ship operators, and shipyards. The ship owners are important in the context of this research as they own the vessels. Furthermore, ship operators have an interest because, especially in the offshore market, ships need to be adjusted for different operations continuously. Lastly, shipyards may be impacted as they are involved in both shipbuilding and ship conversion.

The major interest of ship owners is to earn money with their fleet. Ships that are better able to cope with uncertainty can better serve the market, and therefore may have more earning potential during their lifetime. Most offshore vessels are owned by one owner for the major part of their lifespan. These ship owners can especially benefit from changeability if the additional investments pay themselves back during conversion. Additionally, "Changeability analysis for conceptual offshore ship design is particularly relevant, due to the uncertain and heterogeneous requirements in these markets, coupled with high investment costs" (Rehn et al., 2019, p.85).

ship operators will benefit as well from ships that can be changed more efficiently for a new operation. Preparing for change will result in conversions that take less time. If less time is needed between winning a tender and starting a project with a converted ship, a unique market position can be obtained.

Shipyards, such as Royal IHC, have an advantage over their competitors if they are able to design ships that are better prepared for uncertainties during their lifetime. If the research output is able to value certain design options, they will be able to convince ship owners to incorporate more changeability into ship design, which is quite difficult at the moment (Mestemakers and Bosscha, 2022). Not only this can be used as a unique selling point during tendering, but ship owners may also be more inclined to return to Royal IHC once they consider refitting their vessel.

1.1.3 Environmental Relevance

The emission of Greenhouse gases (GHG) is a global problem to which the maritime industry is a major contributor. In 2012 global shipping was responsible for the emission of 1016 million tons of CO_2 (3.1% of the global CO_2 emissions), and if no action is taken this will increase by 50-250% in 2050 (Perčić et al., 2020). A major part of the harmful emissions is emitted during a ship's operational phase, due to the usage of different types of diesel fuels. That is why switching to alternative fuels is a topical research field these days. Alternative fuels, like LNG, hydrogen, methanol, and ammonia are active fields of study. However, it is difficult to determine what the fuel of the future will be, because each of the fuels comes with its own drawbacks. Uncertainty about which fuel will be applied in the offshore maritime industry together with how it should be implemented on board ships underpins the relevance of this research.

1.1.4 Relevance for Policymaking

The transition to alternative fuels will require additional investments by ship owners in their ships. An external incentive is probably needed for ship owners to switch to alternative fuels. For example, a complete ban on certain harmful emissions is likely to result in many ships being converted to alternative fuels. On the other hand, if additional investments in Design-for-Conversion are subsidised, this is likely to result in more ships being prepared for alternative fuels, which results in a lower hurdle to switch to alternative fuels. This research may be used to test the impact of certain measures on the decision-making of ship owners, namely whether or not they will convert their ships towards alternative fuels in the case of a given measure.

1.1.5 Economic Relevance

Adding changeability to design inevitably comes with additional investment costs. This can be seen as the 'Cost of changeability' which varies with the amount of changeability added into a design, as shown in Figure 1.2. The more changeability is added, the higher the cost of changeability. However, the 'cost of changes' will reduce if more changeability is incorporated into a design (Fricke et al., 2000). Consequently, there is a trade-off between the increasing costs of adding changeability in a design and the decreasing costs of changes over a system's lifespan. There should be an optimal level of changeability resulting in the lowest life cycle costs, as shown by the red line in Figure 1.2.

A second trade-off that needs to be made is the execution timing of conversion versus the payback period of the new investment. To put it in other words, the 'costs of changes' must be recovered in the remaining lifetime, after the conversion, of the vessel. If the remaining lifespan is short, it is doubtful whether this new investment will repay itself.

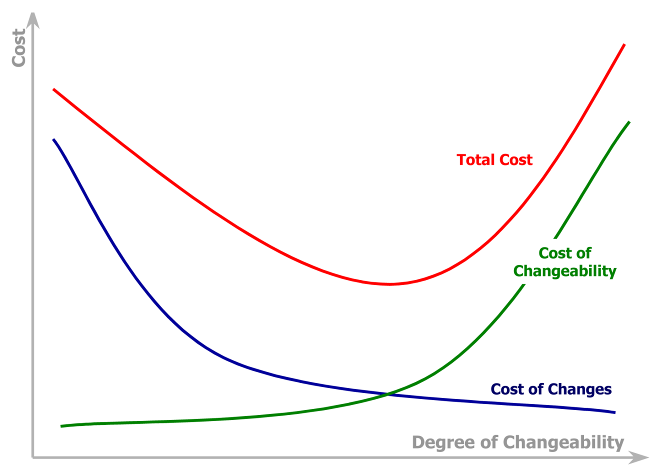


Figure 1.2: Degree of changeability and the expected evolution of cost over a system's life cycle when incorporating changeability into design (Fricke et al., 2000).

This section aimed to point out the relevance of this research topic, from multiple points of view. First, the relevance to science is discussed. It can be concluded that this research output may have broader applicability, especially for other complex and capital-intensive systems that are subjected to uncertainty. In addition, Design-for-Conversion affects shipowners and operators because ships can be changed more efficiently, better serving the changing market which results in higher profits. Shipyards are involved in both new builds as well as conversions and may use Design-for-Conversion as a unique selling point. Furthermore, the environmental impact of this research may be large as more ships will be prepared for alternative fuels, resulting in a drastic decrease in harmful emissions once these vessels are converted. Moreover, this research may support policymaking as the impact of certain measures may be tested. Lastly, the economic relevance of this research is pointed out, where the aim is to propose an optimal level of changeability, to minimise life cycle costs.

1.2 Problem Statement

The maritime energy transition has resulted in an increase in technological, regulatory and operational uncertainty. In addition, emission reduction measures are likely to have a large impact on ships, as most ships are still being designed with traditional fossil fuels in mind. Therefore, it is likely that ship conversion of existing vessels will be needed to maintain perceived value for a ship's owner over the complete lifespan of a ship. The current practice, to optimize a ship design for a static set of requirements, makes it difficult to accommodate changes in requirements (Knight and Singer, 2014).

To deal with this problem, changeability could be added to the ship design, in order to alter system properties more easily. As shown in Figure 1.2, the higher the 'Degree of Changeability', the lower the 'Cost of Changes'. However, the higher the 'Degree of Changeability' is, the higher the 'Cost of Changeability' will be. When looking at the total cost, it is evident that an optimum exists between reducing the cost of changes and increasing the cost of changeability. The importance of this trade-off when preparing for conversions has also been mentioned by Fricke and Schulz: "The trade-off between the right price to pay or the right amount of time to spend to the expected benefit is a critical consideration" (2005, p.355). However, one of the problems identified in cooperation with Royal IHC is the fact that the potential benefits of Design-for-Conversion are rather difficult to determine. In addition, the amount of work that needs to be done during the actual conversion can differ greatly from initial estimations, resulting in large budget overshoots. According to several employees of Royal IHC, these are the main reasons why it is difficult to convince decision-makers to make additional investments during ship design, even though it could be beneficial in the future (Mestemakers and Bosscha, 2022).

In the context of the energy transition, it is very likely that ships will need to switch to another fuel. Methanol is often mentioned as a suitable option for ships that require large amounts of power, such as pipelay vessels, even though it will take more space within the hull. Therefore, the general arrangement and tank layout will need to be revised once a ship is converted to methanol. A ship design may be prepared for a future conversion to methanol, which could result in lower life cycle costs, Figure 1.2. However, information is incomplete on the impact of Design-for-Conversion to methanol. The aim of this research is to fill this gap. To structure the research, some research questions have been drawn up, which will be discussed in the next section.

1.3 Research Questions

This research aims to investigate how the potential benefits of Design-for-Conversion can be quantified. Because of uncertainty, future changes in the ship design are needed and by preparing for this the lifecycle costs are to be minimized. However, it is difficult to determine the right amount of design preparation, because of uncertainty in the reduction of the costs of changes. The various aspects of Design-for-Conversion, are covered in the following research question:

"How to determine the value of Design-for-Changeability under uncertainty to find the optimal DFC level when preparing for conversion to methanol?"

The goal of the research is to propose and test a method that can be used to quantify the benefits of adding design preparations into ship design. These design preparations should make a conversion to methanol easier and less costly. The decision-making on whether or not to incorporate changeability into a ship design is to be explored by using a model-based method. Additionally, the effect of particular design preparation can be assessed. Once the model is verified for one type of ship, it may be applicable to other ship types as well.

To be able to answer the main research question, a research plan is set up to structure the research. Therefore, the problem is decomposed into the following sub-questions:

1. How is Design-for-Changeability used to deal with uncertainty during a ship's lifetime so far?
2. How can the value of options be expressed for designs over their lifetime?
3. How can the value of Design-for-Conversion be calculated under uncertainty?
4. Which factors drive the design, production and conversion costs when preparing for or converting to methanol?
5. What are the additional costs of Design-for-Changeability during new building, and how does the level of DFC impact the cost of changes?
6. What DFC level is most valuable when designing an offshore ship for conversion towards methanol while facing uncertainty?

The answers to the first three sub-questions are found in literature and will be discussed in section 2.1 - 2.3, respectively. Subsequently, a case study framework in which the theory can be applied will be discussed in chapter 3. The answer to the third research question can be found in this chapter as well. By combining information found in the literature, a methodology will be proposed to find an answer to the main research question. This methodology consists of two models, which will be discussed in chapter 4. In addition, more detailed information on both models will be given in chapter 5. Subsequently, the output of the models will be discussed in chapter 6, to support answers to sub-questions 5 and 6. Lastly, the research questions will be answered and the broader applicability of the models will be discussed in chapter 7, and a final conclusion will be drawn in chapter 8.

2

Theoretical background

The aim of this chapter is to review relevant information on ship design under uncertainty, and how measures that are taken to deal with uncertainty can be valued. As discussed in the previous chapter, uncertainty plays a major role in the maritime industry and has only increased because of the energy transition. Three types of uncertainty are identified, technological, regulatory, and operational uncertainty. Due to these uncertainties together with the long lifetime of ships, the perceived value of a ship to its owner may decrease over time. To maintain usability over time, a need for an expensive ship conversion arises, which is a type of active value robustness. Active value robustness is defined as insensitivity to changes in environment, preferences, or system offerings by using an external agent (Ross et al., 2008). A ship conversion can be seen as a way to change system properties, where 'the system' refers to a ship. In the context of the maritime energy transition, ship conversion to methanol is a topical issue. However, uncertainty makes it difficult for ship designers to design value-robust ships. That is why the first question that needs to be answered is: *"How is Design-for-Changeability used to deal with uncertainty during a ship's lifetime so far?"*

Subsequently, an answer will be found to the second research question: *"How can the value of options be expressed for designs over their lifetime?"* A design option is the right but not the obligation to use a design preparation and only has value if it is used during its lifetime (de Neufville, 2002). Moreover, when a ship is prepared to run on methanol in the future, additional investments are required. However, as discussed in the problem statement, the future value of these preparations is unknown, and difficult to determine because of uncertainty. Therefore, the third research question, *"How can the value of Design-for-Conversion be calculated under uncertainty?"*, needs to be answered as well.

First, the scientific background of system changes, including change agents, change effects, and change mechanisms will be discussed in section 2.1.1. Thereafter, the concept of Design-for-X will be introduced in section 2.1.2, which refers to designing for property X. Subsequently, research conducted on Design-for-Changeability will be discussed (section 2.1.3). To answer the second research question, methods for static valuation of design options over their lifetime will be discussed in section 2.2. In addition, the most appropriate valuation method will be selected according to established criteria based on the work of Keeney (1982). Consequently, methods that are able to determine the value of Design-for-Conversion under uncertainty will be discussed in section 2.3, and the most suitable method will be selected. Finally, the gap in literature will be discussed in section 2.4 to identify potential avenues for further research.

2.1 Design for Future Changes

A way to prepare a ship for future changes due to uncertainty, for instance a future change to methanol, is to add changeability to the design. Changeability is the extent to which system properties can easily be changed (Rehn et al., 2019). Next to changeability more so-called 'ilities' are discussed in the literature. An 'ility' refers to a property's ability to express that property. For example, changeability refers to the ability to change. Fricke and Schulz defined four key aspects of changeability, which are flexibility, agility, robustness, and adaptability, as shown in Figure 2.1 (2005). Flexibility says something about the ability of a system to be changed easily, whereas agility indicates whether a system can be changed rapidly (Fricke and Schulz, 2005). Robust systems deliver their intended functionality under varying operating conditions without being changed (Fricke and Schulz, 2005). Lastly, adaptability indicates a system's ability to adapt itself to changing environments, thus without being changed by means of an external agent. To identify which aspects should be incorporated in a design, two questions should be asked according to Fricke and Schulz: "Which degree of changeability is needed?" and "Is external actuation necessary/ possible?" (2005, p.347). Because a ship conversion is always done using an external agent, adaptability and robustness are outside the scope of this research. Making ships more adaptable or robust would probably lead to over-engineered ships with high investment and operational costs. That leaves only agility and flexibility within the scope. This is supported by the paper of Rehn et al., which states that time and cost are the two main drivers in Design-for-Changeability (2019). Time can be seen as a metric for agility, while cost can be seen as a metric for flexibility.

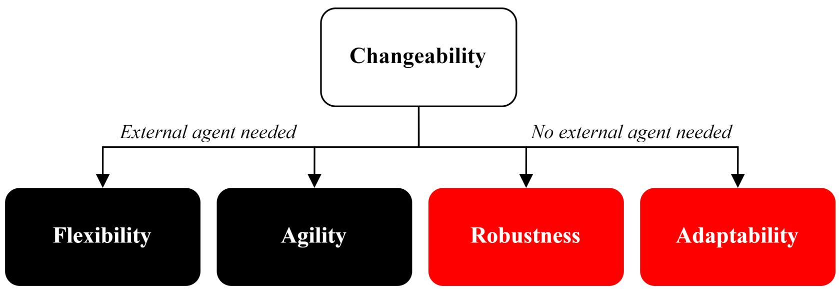


Figure 2.1: Aspects of changeability within a system, such as a ship, according to Fricke and Schulz (2005).

2.1.1 Change Agents, Change Effects and Change Mechanisms

A ship conversion can be seen as a change in form, function, or operation of a ship, or parts of it. More information is needed on the definition of change to understand the scientific background of conversions better. A conversion can be used as means to achieve change in ship characteristics. According to Ross et al. change can be defined as the transition over time, from an initial state to an altered state (2008). Three elements characterise a change event: the change agent, the change mechanism and the change effect (Ross et al., 2008). The change agent has the ability to set a change in motion, and in the context of this research, this can be done by a ship owner. More relevant are the change effects and change mechanisms.

The change effect is defined as the difference in states before and after a change. For example, if one wants to change from sailing on diesel fuel to sailing on methanol. Three types of effects are mentioned by Ross et al.: robustness, scalability and modifiability (2008). Robustness is defined in a similar manner as by Fricke and Schulz (2005). Scalability represents the ability to change the level of a parameter. "Modifiability is the ability to change the membership of the parameter set" (Ross et al., 2008, p.249).

Change mechanisms are used to describe the path that could be taken to transform from the previous state to the new state. "A change path details the necessary component to bring about the change, including conditions, resources, and constraints for the change" (Ross et al., 2008, p.250). One system's change may have more than one possibility, one so-called transition path, to bring about the same change effect. Each path comes with its own costs, which may include time as well as money. In general, "The more change paths are available for a system to follow, the more changeable the system is" (Ross et al., 2008, p.250). Despite the fact that these paths are constructed objectively, the decision on which path to follow is based on the circumstances, including available resources, as well as stakeholder preferences. Examples of change mechanisms to bring about the aforementioned change effect, from a small ship to a large ship, can be found in Figure 2.2 on the next page.

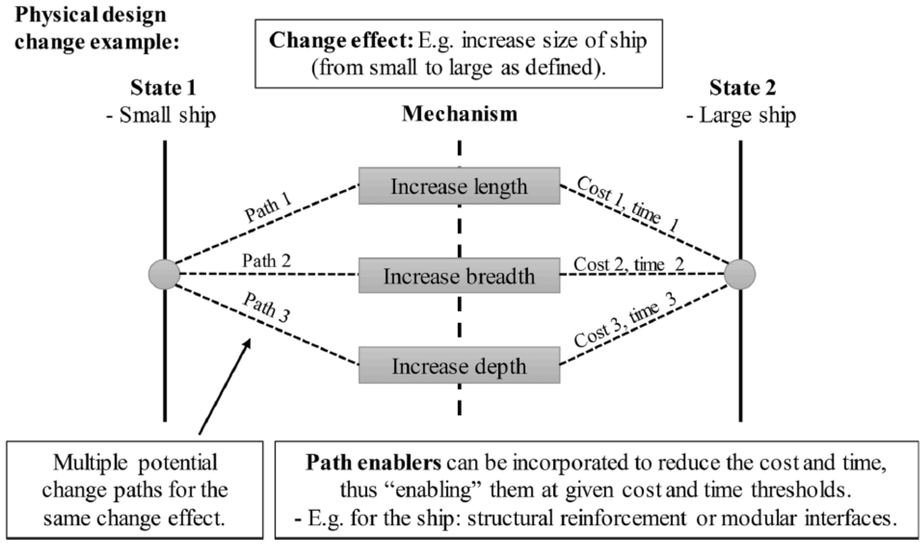


Figure 2.2: Example of a change effect, from state 1 (Small ship) to state 2 (Large ship). Multiple paths (change mechanisms) are shown, which show how this change effect can be achieved. If so-called path enablers (options) are incorporated into a ship design, changes can be done more easily, in other words, quicker and against lower costs (Rehn et al., 2019).

2.1.2 Design-for-X (DFX)

Change seems to be the most general solution to cope with uncertainty. The availability of transition paths, which can be used during a ship conversion, is essential to have the ability to change. Each transition path comes with its own 'costs' to bring about the same change effect.

If a certain property, such as change, is a very important system characteristic, a system designer could design for that property. In literature, this is called Design-for-X (DFX), which means design for property X. The generic family of methodologies DFX aims to improve both product design as well as design processes (Huang, 1996). Change is one of the properties a system designer could design for, covering the ability to improve change, which is Design-for-Changeability. "Design-for-changeability focuses on incorporating changeability into a system's architecture in order to enable for foreseen and unforeseen changes within the architecture throughout the systems lifecycle", (Fricke and Schulz, 2005, p.346). On the one hand, DFC could increase the number of available transition paths. And on the other hand, DFC could decrease the 'cost of changes' of a particular transition path, to better facilitate change, for example in less time or against lower conversion costs.

Fricke and Schulz mention multiple criteria to evaluate whether incorporating changeability will be beneficial within a system architecture (2005). The most relevant ones are:

- The system has a stable core functionality but variability in secondary functions and/or external styling;
- The system has a long life cycle with fast cycle times of implemented technologies driving major quality attributes (i.e., functionality, performance, reliability, etc.);
- The architecture and system are subject to a dynamic (that is, rapidly growing and strongly changing) marketplace with a varying customer base and strong competition;
- The architecture and system are highly interconnected with other systems sharing their operational context;
- The system requires high deployment and maintenance costs;
- It is a complex and highly unprecedented system, with an unknown market.

It can be concluded that ships, and especially offshore vessels, meet most of these criteria. As outlined in chapter 1 offshore ships are complex vessels which operate in changing markets with a lot of competition. In addition, technological developments go fast in the context of the maritime energy transition whilst ships have a long life cycle. Lastly, ships can be quantified as systems with high deployment and maintenance costs.

2.1.3 Design-for-Changeability (DFC)

The most essential DFX method in the context of this research, found in literature, is the Design-for-Changeability method of Rehn et al. (2019). The researchers present a generic method for quantification of the level of changeability. In the paper, two aspects of changeability are identified: quantification of the level of changeability, and valuation of changeability. Rehn et al. only assess the level of changeability without giving a valuation of changeability (2019). According to the paper quantification of the level of changeability has two main reasons. First, ”to be able to structure design alternatives with different levels of changeability, on which evaluation can be subsequently performed.” And second, ”for providing means for communicating system changeability between decision makers”, (Rehn et al., 2019, p.80).

Rehn et al. identified cost and time as the two most important factors in system engineering (2019). Increasing the level of changeability enables a design to change more quickly and against lower costs, resulting in increased agility and flexibility. Nevertheless, increasing the level of changeability usually requires an investment of time and money. Therefore, a trade-off must be made between the cost of changeability and the cost of changes, as shown in Figure 1.2 on page 5. The level of changeability can be controlled by the designer and must be specified in the conceptual design phase. Therefore, it is identified as a design variable which can control the cost resulting from uncertainty, which consists of the costs of changeability as well as the costs of changes.

Both Fricke and Schulz and Rehn et al. use the DFC variable as a design variable that structures sets of path enablers (2005; 2019). This design variable links the path enablers to other, more common, design variables. In Table 2.1, an example is shown of this DFC variable in combination with different path enablers.

Table 2.1: Example of DFC variable expressing multiple levels of changeability. The DFC variable defines and structures path enablers, which enhance changeability (Rehn et al., 2019).

DFC variable	Path enablers
0	Baseline (none).
1	Structural reinforcement.
2	Structural reinforcement and modular interfaces.
3	Structural reinforcement, modular interfaces, and ice-class capabilities.

2.1.4 Concluding Changeability

The aim of this section was to find an answer to the first research question: *”How is Design-for-Changeability used to deal with uncertainty during a ship’s lifetime so far?”* This uncertainty can be dealt with by facilitating change and taking changeability into account during ship design, so-called Design-for-Changeability. However, the application of this method in ship design results in additional investment costs, also known as the ’Cost of Changeability’. Moreover, the potential benefits of Design-for-Changeability are unknown because of uncertainty. It is expected that the ’Cost of Changes’ will be reduced when designing for changeability. A method is needed to assess the optimum amount of changeability that should be incorporated in ship design while minimizing total costs. To do so, additional research is needed to quantify the benefits of Design-for-Changeability for the IHC case. This is done by looking into methods that are capable of determining the value of options during their lifetime (section 2.2), and consequently, by looking into methods capable of determining the value of options under uncertainty (section 2.3).

2.2 Lifetime Value of Options

While there are many ways to deal with life cycle uncertainty, the most applicable method would be to facilitate change. This can be done by adding changeability into a design, for which multiple methods are found in the literature. However, adding changeability to a design comes with additional costs whilst future benefits are uncertain. Therefore, more research must be conducted into the valuation of an option, which is the possibility but not the obligation to use a design preparation, in the future. An answer must be found on the second research question: *"How can the value of options be expressed for designs over their lifetime?"*, to determine the value of changeability.

However, "Valuation of ilities as a single metric is an additional layer of analysis", (Ross et al., 2008, p.257). The reason why the valuation of options is quite difficult is the fact that most valuation techniques rely heavily upon assumptions regarding how to collapse utility, cost, time, and uncertainty into one metric (Ross et al., 2008). As the valuation of future benefits is rather difficult due to uncertainty, a method is needed to quantify these benefits. In this research, the choice has been made to first do a static valuation of an option without uncertainty by means of a valuation method, and subsequently model the value of that option under uncertainty by means of a modelling method (section 2.3). The difference here is that valuation methods can be used to value different options over each other, whilst modelling methods are capable of dealing with the dynamic characteristics of the problem. A valuation method can be considered static, only capable of a fixed determination of the value of options. On the other hand, a modelling method is able to capture key elements regarding the simulation of the future, such as uncertainty and decision-making, into a model. This section discusses multiple valuation methods and selects the most suitable one. To determine which method is most suitable, selection criteria must be set first.

2.2.1 Criteria for Valuation Methods

A valuation method should be able to express the potential value of an option. Criteria need to be set, to rank different valuation methods. Decision Analysis is used to set these criteria. The paper of Keeney points out the complexity of decisions. If a ship designer must determine which design preparations must be incorporated into the design, the following aspects should be taken into account (Keeney, 1982):

- Multiple objectives: the desire to optimize multiple objectives at once;
- Risk and uncertainty: it is not possible, in nearly every problem, to predict the consequences of each alternative;
- Long-time horizons: not all consequences of a decision are felt immediately, but often after a long period of time;
- Sequential nature of decisions: previous decisions will impact the choices a decision-maker has available today;
- Value trade-offs, a trade-off between things that are difficult to compare with each other, for example, economical costs versus environmental impact;
- Risk attitude, the willingness of decision-makers to take decisions that could have a large positive or negative impact.

Based on the aspects Keeney mentioned the following criteria are set, to rank different valuation methods. Its ability to:

1. value multiple design options in multiple scenarios (uncertainty);
2. value the consequences of a decision;
3. determine the time value of options;
4. weight multiple objectives.

2.2.2 Different Valuation Methods

In the literature, multiple methods are found that may be suitable for the valuation of options. This includes traditional financial methods, such as Net Present Value or Discounted Cash Flow, but also Filtered Outdegree, Pareto Theory, Multi-Criteria Valuation, and Black-Scholes theory. Below, these methods will be discussed successively.

Net Present Value (NPV)

The first valuation method found in the literature is a Net Present Value (NPV) calculation. The Net Present Value can be used in investment planning to asses the profitability of a project or a projected investment (Fernando et al., 2021). The result of NPV calculation is today's value of a future flow of payments, it is a metric that aims to show the time value of money. The most commonly used formula to calculate the Net Present Value is shown in Equation 2.1 (Fernando et al., 2021). R_t is the net cash flow during period t, and i is the discount rate, which is the return that can be earned from alternative investments.

$$NPV = \sum_{t=1}^{n} \frac{R_t}{(1+i)^t} \tag{2.1}$$

A NPV calculation can be performed for multiple options in different scenarios (Criterion 1). In addition, the consequences of decisions can be taken into account in future cash flows (Criterion 2). Moreover, the method is well suited to take the time value of options into account (Criterion 3). Lastly, NPV can deal with multiple objectives, although this is limited to time (t) and discount rate (i).

Filtered Outdegree (FOD)

The second method found in the literature is Filtered Outdegree (FOD). The Outdegree represents the number of alternative designs into which a design can be converted (Rehn et al., 2019). To construct the design tradespace, transition rules can be formulated which represent knowledge about physical constraints to delimit the tradespace of viable changes in later life cycle stages, Figure 2.3. The Filtered Outdegree can be found by filtering the Outdegree by a chosen threshold, this can be for example time and/or money. The more Outdegrees within the thresholds, the more changeable a system is.

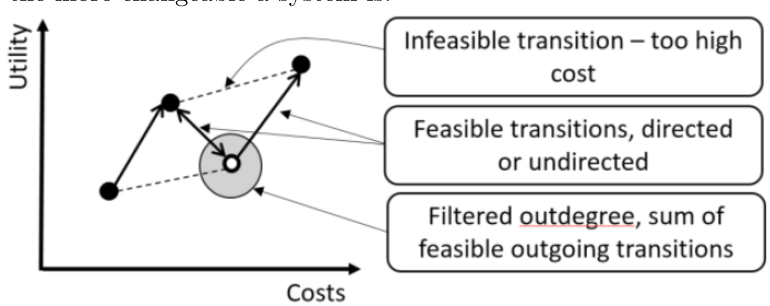


Figure 2.3: Transition paths and Filtered Outdegrees (Rehn et al., 2016).

Filtered Outdegree is capable of valuing multiple designs in multiple scenarios (Criterion 1). In addition, it is suited to take decision-makers' decisions into account (Criterion 2), as the impact of decisions will affect the tradespace. Moreover, there is a possibility to include time in the valuation, through the thresholds (Criterion 3). Finally, the method is well suited to weight multiple objectives (Criterion 4), through the aspects that are incorporated in the thresholds.

Normalized Fuzzy Pareto Trace (NFPT)

Pareto theory may be another suitable method for the valuation of options. The key characteristic of Pareto theory is the fact that one wants to optimize multiple objectives, but optimizing objective A results in a less preferable solution for objective B (Mehdi Khosrow-Pour, 2018). For the valuation of Design-for-Changeability, this may be the case if one wants to minimize both the 'costs of changes' as well as the 'costs of changeability'. Most likely 'Costs of Changeability' will increase if the 'Costs of Changes' are minimized. Furthermore, the most optimal solution for minimizing both objectives over multiple eras might not be on the Pareto Trace, but a fraction of the Pareto Trace, the so-called Fuzzy Pareto Trace (FPT). To account for bias in the selection of epochs, a Fuzzy Pareto Trace can be normalized by the number of considered epochs, the so-called Normalized Fuzzy Pareto Trace (Ross et al., 2009).

A Pareto Set can contain a lot of options (Criterion 1), which can be evaluated in multiple epochs, and multiple moments in time (Criterion 3). This method is also very suitable to weigh multiple objectives (Criterion 4). However, it is hardly possible to evaluate the consequences of decisions (Criterion 2).

Multi-Criteria Valuation (MCV)

Another method found in the literature for the valuation of changeability is the Multi-Criteria Valuation of Sushil (2017). In the paper, a Total Interpretive Structural Model (TISM) is combined with an Interpretive Ranking Process (IRP) to rank flexible initiatives according to a set of criteria, which cover both benefits and costs. The method is based on a multi-criteria ranking, which is the Interpretive Ranking Process, and uses expert opinions as well as big data analytics in the Total Interpretive Structural Model.

This method is able to value different design options (Criterion 1) and is very suitable to weigh multiple objectives (Criterion 4). However, the method needs expert opinions and consists of a lot of steps which results in complexity. Additionally, the method is less suitable for the valuation of the consequences of a decision (Criterion 2), and to determine the time value of an option (Criterion 3).

Black-Scholes Formula (B-S)

The last method found in literature is the Black-Scholes (B-S) formula, which is used for pricing European call options (Hayes et al., 2021). It takes into account risk factors as well as the impact of time. The Black-Scholes formula determines the Call price of an option (C_0), and it is as follows:

$$C_0 = S_0 \cdot N(d_1) - X \cdot e^{-rT} \cdot N(d_2) \tag{2.2}$$

with:

$$d_1 = \frac{ln(\frac{S_0}{X}) + (r + \frac{\sigma^2}{2}) \cdot T}{\sigma \cdot \sqrt{T}},\ d_2 = \frac{ln(\frac{S_0}{X}) + (r - \frac{\sigma^2}{2}) \cdot T}{\sigma \cdot \sqrt{T}} \tag{2.3}$$

Variables for the Black-Scholes and supporting formulae are:

- S_0: Price of the underlying asset
- $N(d_i)$: Normal distribution
- X: Strike price of an option
- r: Risk free interest rate
- T: Time until the expiration of the option
- σ: Volatility

The Black-Scholes formula scores quite well on its ability to determine the time value of options (Criterion 3). The main drawback is the fact that the method was developed for European call options, and it is doubtful whether it works for real options. Moreover, the method is less suitable if one wants to value multiple options (Criterion 1). The formula needs to be computed for every option, which may be time-consuming. Lastly, the formula is not suitable to determine the value of decisions (Criterion 2) and is not able to weigh multiple objectives (Criterion 4).

2.2.3 Comparison of Valuation Methods

Based on the above criteria and the considerations for each method as discussed above, Table 2.2 on the next page can be completed. This comparison is made to select the best suitable method for valuing options over their lifetime. It can be concluded that a Net Present Value calculation is the most appropriate method. It scores well on the first criterion, and excellently on the third criterion. Moreover, it can deal with the consequences of decisions and it can deal with multiple objectives, which are the second and fourth criteria. Now that a valuation method has been selected, the next section will select a modelling method, to model the dynamic part of the problem.

Table 2.2: Comparison of the valuation methods found in literature: Net Present Value (NPV), Filtered Outdegree (FOD), Normalized Fuzzy Pareto Trace (NFPT), Multi-Criteria Valuation (MCV), and the Black-Scholes formula (B-S).

		Methods				
	Weighting ↓	**NPV**	**FOD**	**NFPT**	**MCV**	**B-S**
Multiple options in multiple scenarios	4	4	4	5	4	2
Consequences of decisions	3	3	4	2	2	1
Time value of options	5	5	3	3	2	5
Multiple objectives	3	3	5	5	5	1
	Score:	59	58	56	47	39
	Normalised score:	0.79	0.77	0.75	0.63	0.52
	Rank:	**1**	**2**	**3**	**4**	**5**

2.3 Valuation of Options under Uncertainty

By building in (design) options, which is the right but not the obligation to perform an action, changeability can be increased (de Neufville, 2002). Subsequently, it is concluded that a static valuation of options over a design's lifetime can be done by means of Net Present Value. However, the value of these options in uncertain conditions is unclear. If one wants to determine what level of changeability should be incorporated in a design which is subjected to uncertainty, no answer is available. That is why an answer must be found on the third research question: *"How can the value of Design-for-Conversion be calculated under uncertainty?"* In this section, three modelling methods will be discussed: Epoch-Era Analysis, Real Options Analysis, and the Markov Decision Process. Before a method can be selected, criteria must be established first.

2.3.1 Criteria for Modelling Methods

To get an understanding of the effect of uncertainty on decisions, this needs to be modelled by means of a modelling method. Multiple methods may be used as modelling method, for modelling the dynamic aspects of the problem, such as uncertainties, decisions, and time. From the aspects mentioned by Keeney, as discussed in section 2.2, a modelling method must be assessed according to its ability to model (1982):

1. uncertainty;
2. decisions by decision-makers;
3. the sequential nature of uncertainty and decisions over a long horizon;
4. multiple options (at least 3).

2.3.2 Different Modelling Methods

Three methods are identified that may be used as a modelling method. This includes Epoch Era Analysis (EEA), Real Options Analysis (ROA), and Markov Decision Process (MDP), which will be discussed below.

Epoch Era Analysis (EEA)

"Epoch-Era Analysis is an approach for describing systems over time as existing in a series of static contexts, so-called epochs, that change stochastically" (Ross et al., 2011, p.1). The method gives a more detailed consideration of a system's future life cycle. For example by taking into account future contractual requirements or different market characteristics. EEA allows for the consideration of many future scenarios, called epochs, in which each design will have its own perceived value (Ross et al., 2011). Therefore, a design's ability to change by means of change mechanisms, changeability, will have a value of its own. However, as this value is difficult to quantify due to its dependency on time and context, Epoch-Era Analysis may be used for the valuation of changeability in a dynamic context. In the paper of Ross et al., a five-step method is introduced for application of EEA (2011):

1. Selection of Designs;
2. Calculation of Changeability Value;
3. Aggregation of Frequency Distribution;
4. Cross-Epoch Statistical Breakdown;
5. Stochastic Era Analysis.

The method provides insight into the potential of changeability in candidate designs across multiple epochs. However, the second step, 'calculation of Changeability Value', must still be done using a valuation method, as discussed in the previous section. The output of an Epoch-Era Analysis consists of statistical data.

Epoch-Era Analysis is well suited to model uncertainty (Criterion 1) and decisions by decision-makers can be modelled by means of epochs (Criterion 2). Moreover, the sequential nature of uncertainty and decision can be modelled through successive epochs (Criterion 3). Finally, EEA can be used to model different options (Criterion 4).

Real Options Analysis (ROA)

The second modelling method found in the literature is Real Options Analysis. It enables system designers and managers to decide whether a flexible design element is worth its costs (de Neufville, 2002). This is done by showing the value based on possible future outcomes when uncertainty is resolved (Gregor, 1994). The method provides a clear rationale to assess whether to include a specific type of flexibility in a systems design. "The result of a real options analysis is the determination of the value of flexibility" (de Neufville, 2002, p.1).

Real Options Analysis provides a Net Present Value or Discounted Cash Flow (DCF) like measurement of value (de Neufville, 2002). However, "Static budgetary techniques and NPV analysis underestimate the value of managerial and operational flexibility", (Knight and Singer, 2014, p.1). In addition, the time value of money is significant for major systems and must be a central ingredient in the measure of flexibility (Knight and Singer, 2014). In shipbuilding, this is the case, because it is a capital intense business and ships have a long lifespan. Moreover, ROA has one major advantage over just a Net Present Value or Discounted Cash Flow calculation. ROA shows the ability of designers to shape the evolution of a system over time, whereas DCF/NPV analyses assume the project and its cash flows are known beforehand (de Neufville, 2002).

Real Options is well suited for modelling uncertainty (Criterion 1) and decision-making (Criterion 2). A Real Options approach is also very suitable for modelling the sequential nature of these two aspects, Criterion 3. Finally, this method can also model multiple options (Criterion 4).

Markov Decision Process

Lastly, a Markov Decision Process may be used as a modelling method, as was done in the research of Niese et al. (2015). This was done under the assumption that changeability is a sequential, discrete-event problem. According to the researchers, decision-makers have multiple discrete opportunities, to invest in resources that affect the performance of their assets. Uncertainty, which is controlled by randomness is modelled by means of probabilistic distributions.

The framework of MDP consists of four aspects each covered in its own vector: States ($S\{s\}$), Actions ($A\{a\}$), Transitions ($T(s'|s,a)$) and Rewards ($R(s,a)$). $S\{s\}$ is a finite set of states a system can be in, and $A\{a\}$ is a finite set of actions a decision-maker can undertake. $T(s'|s,a)$ is the transition probability a system transforms from initial state s to a new state s' after execution of action a. $R(s,a)$ is the reward received from action a in state s. "The MDP identifies a policy defined as a mapping from states to actions, which maximizes the cumulative reward by following the agent's actions" (Niese et al., 2015, p.373).

The Markov Decisions Process is well suited for modelling of uncertainty (Criterion 1) and decisions by decision-makers (Criterion 2). Moreover, it can deal with the sequential nature of these two aspects (Criterion 3). However, the method is less suitable for modelling multiple options (Criterion 4).

2.3.3 Comparison of Modelling Methods

Based on the criteria set above, a comparison is made to select the most appropriate method. Based on the considerations for each method, as described above, Table 2.3 can be completed. It can be concluded that Real Options Analysis is the most suitable modelling method. It scores excellently on the first three criteria and is also capable of modelling multiple options.

Table 2.3: Comparison of multiple modelling methods: Epoch-Era Analysis (EEA), Real Options Analysis (ROA) and Markov Decision Process (MDP).

		Methods		
	Weighting ↓	**EEA**	**ROA**	**MDP**
Uncertainty	5	5	5	5
Decision-making	4	4	5	5
Sequential nature	4	4	5	3
Multiple options	5	4	4	2
	Score:	77	85	67
	Normalised score:	0.86	0.94	0.74
	Rank:	**2**	**1**	**3**

2.4 Concluding Theory

Uncertainty plays a big role in the maritime industry because ships are long-term assets while the conditions they need to operate in are constantly changing. It is expected that Design-for-Changeability can be used to minimize life cycle costs when ships need to be changed because of the reasons above. That is the reason why the first goal of this chapter was to find an answer to the question: *"How is Design-for-Changeability used to deal with uncertainty during a ship's lifetime so far?"*. Subsequently, answers to the second and third research questions had to be found: *"How can the value of options be expressed for designs over their lifetime?"* and *"How can the value of Design-for-Conversion be calculated under uncertainty?"*

Uncertainty in a ship's lifecycle can be dealt with by facilitating change and taking changeability into account during ship design, so-called Design-for-Changeability. However, the application of this method in ship design results in additional investment costs, also known as the 'Cost of Changeability' while the potential benefits of Design-for-Changeability are unknown because of uncertainty. Nevertheless, it is expected that the 'Cost of Changes' will be reduced when designing for changeability. Therefore, a method is needed to assess the optimum level of changeability that should be incorporated in ship design while minimizing total costs. The method can be subdivided into two theoretical perspectives. First, an option is evaluated without uncertainty by means of a valuation method. Subsequently, the value of the option is calculated under uncertainty, using a modelling method.

Net Present Value, Filtered Outdegree, Normalised Fuzzy Pareto Trace, Multi-Criteria Valuation, and the Black-Scholes formula were reviewed as potential valuation methods. Based on the criteria as discussed in section 2.2.1, a comparison was made to select the most appropriate method. Table 2.2 has shown that Net Present Value is the most suitable valuation method. Net Present Value is suited to take the consequences of decisions into account and it can weigh multiple objectives. Moreover, the valuation of multiple designs in multiple scenarios can be done by means of a Net Present Value calculation. In addition, it scores excellently on the criterion to include time in the valuation.

This valuation method will be used in conjunction with a modelling method, as shown in Figure 2.4, to model the dynamic part of the problem. Epoch-Era Analysis, Real Options Analysis and the Markov decision process have been studied as potential modelling methods. Based on the criteria as discussed in section 2.3.1, a comparison was made to select the most appropriate method. Table 2.3 has shown that Real Options Analysis is the most suitable modelling method. Real Options Analysis shows the value of flexibility based on possible future outcomes when uncertainty is resolved (Gregor, 1994). Real Options Analysis is well suited for modelling uncertainty and decision-making, including the sequential nature of these two aspects. Moreover, this method is capable of modelling multiple options.

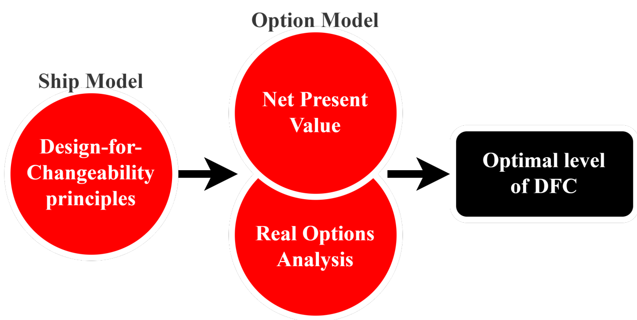


Figure 2.4: An overview of the methods selected from the literature, to be integrated into a methodology which is capable of valuation of Design-for-Changeability to determine the optimal level of DFC resulting in the lowest life cycle costs.

As shown in Figure 2.4, Net Present Value in conjunction with Real Options Analysis will be used in an option model to determine what level of changeability should be incorporated into a ship design to minimize life cycle costs. In order to do so, a cost breakdown is needed first, to be able to calculate the costs of changeability as well as the costs of changes. The DFC principles will be integrated into a ship model to assess the technical impact of Design-for-Conversion to methanol. To do so, more information on the background of methanol and the required changes for operating a ship on methanol is needed first. Moreover, a more in-depth analysis of the uncertainties should be done, which can be used in the option model. The next chapter will address these topics.

3

Case study

The previous chapter discussed the theoretical background of various topics concerning Design-for-Conversion. From theory is concluded that enabling change by means of adding change mechanisms into the ship design, can help to deal with uncertainty during a ship's lifetime. This is called Design-for-Changeability. Moreover, it was stated in the problem statement that the potential benefits of Design-for-Conversion are difficult to quantify, because of uncertainty in combination with the long lifetime of ships. In the previous chapter, it was concluded that the valuation of options over their lifetime may be done by means of a Net Present Value calculation, while the valuation under uncertainty can be done using Real Options Analysis. Adding design options into a ship design comes with additional costs, the so-called costs of changeability, but by adding these options it is expected that the costs of changes are reduced (Figure 1.2).

The discussed theory is more broadly applicable, however, to apply it to Design-for-Conversion to methanol, more information is needed on methanol and the specific design preparations for conversion to methanol. In addition, more information is needed to be able to determine the costs of changeability, made during the new-build phase, as well as the costs of changes, made during conversion. This is covered in the third research question: *"How can the value of Design-for-Conversion be calculated under uncertainty?"* Moreover, a case study will be conducted to have a framework for the application of the theory and practical implementation of the theory for the methanol case. For the case study, a representative ship needs to be selected. Subsequently, relevant uncertainties for Design-for-Conversion to methanol need to be defined for the case study.

This chapter will first introduce methanol as a maritime fuel, including its advantages and challenges, in section 3.1. Subsequently, the considered design preparations will be discussed more extensively in section 3.2, to clarify the chosen design preparations in the ship model. In addition, by means of a cost breakdown for both the costs of changeability and the cost of changes, an answer will be found to the third research question in section 3.3. Thereafter, the ship which will be used in the case study will be introduced in section 3.4. Moreover, the uncertainties regarding Design-for-Conversion to methanol, which are to be modelled, will be discussed in section 3.5. Lastly, all information will be briefly concluded in section 3.6.

3.1 Introduction to Methanol

This research is conducted in cooperation with Royal IHC, which is known for building complex offshore and dredging ships. These ship types require large amounts of energy because of their dynamic positioning capabilities and mission equipment. In the context of the global energy transition, the maritime sector is looking for a less harmful fuel for their fleets. An alternative fuel that has the potential to replace diesel fuels for these energy-demanding ships is methanol. The emission reduction potential of methanol is shown in Table 3.1. Using methanol has also some advantages compared to diesel and other alternative fuels. Methanol is biodegradable, and therefore it is allowed to store methanol adjacent to the side shell as well as inside the double bottom. Moreover, methanol is liquid at atmospheric pressure and temperature, thus there is no need to store it cooled and/or pressurised as with LNG or hydrogen.

Table 3.1: Greenhouse gas emission reduction compared to Light Fuel Oil (LFO) (Wärtsilä, 2022). ⋆For Green methanol only.

GHG	Reduction
CO_2	-92%⋆
NO_x	-60%
SO_x	-99%
PM	-95%

The chemical composition of methanol is CH_3OH, which can be formed by the synthesis of hydrogen (H_2) and carbon monoxide (CO). To obtain this structure multiple production processes can be used, as shown in Figure 3.1. There are three main types of methanol, which refer to the environmental impact of the type of methanol. These three types are green methanol, blue methanol and brown/grey methanol. Green methanol is low carbon-intense and renewable, whereas blue methanol is not renewable but at the same time has a lower carbon intensity compared to grey/brown methanol. Lastly, grey/brown methanol is available which is produced using fossil fuels and carbon capturing in the production process. However, this CO_2 will still be emitted when combusting methanol, and therefore, it has a high carbon footprint and is not renewable.

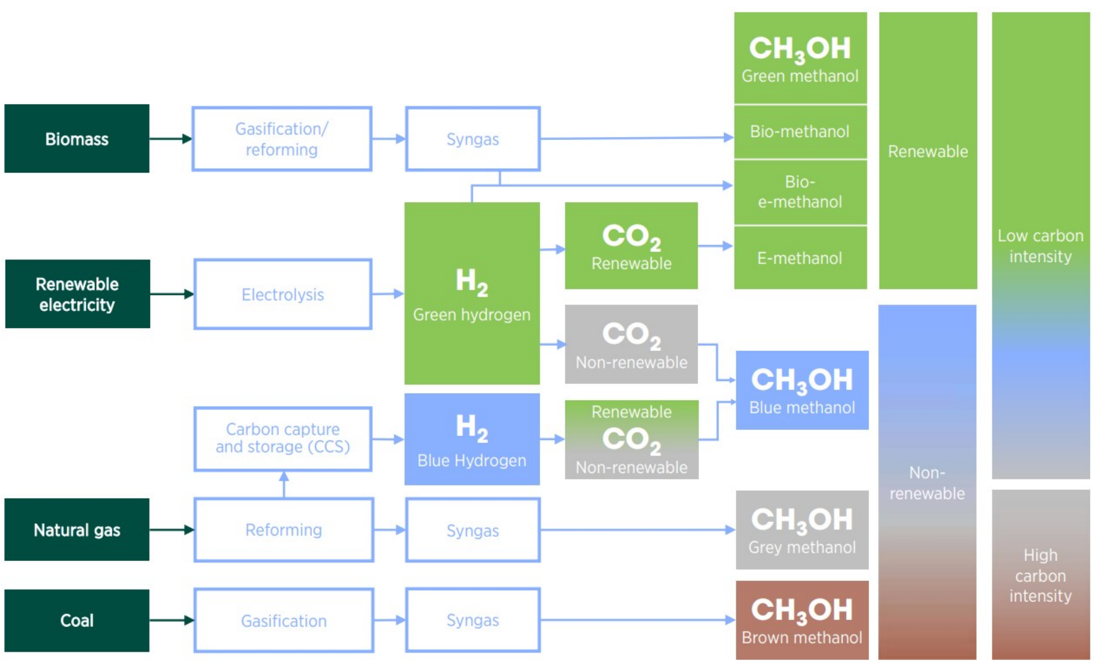


Figure 3.1: Current production routes for the production of methanol. Renewable CO_2 comes from bio-origin or through Direct Air Capture (DAC), whereas non-renewable CO_2 is from fossil origin or industry residual flows (IRENA and Methanol Institute, 2021).

Methanol has different properties compared to diesel oils, the differences are shown in Table 3.2. The most important one is the fact that methanol has a lower volumetric energy density, compared to Marine Diesel Oil (MDO). This results in more volume required for fuel if one wants to operate a ship on methanol (DNV GL, 2022). To maintain the same range, autonomy, and mission capabilities, a ship operated on methanol will require 2.19 times more volume for fuel storage.

Table 3.2: Information of uncontained fuel, required as model input (DNV GL, 2022).

	MDO	**CH_3OH**
Density $[kg/m^3]$	890	787
Lower Heating Value $[MJ/kg]$	44.0	22.7
Volumetric energy density $[MJ/m^3]$	39160	17865

Next to the differences in energy density, there is a second challenge that must be overcome when switching to methanol as fuel. Methanol is highly flammable, causing classification bureaus to call for double walls between spaces available for personnel and tanks or piping. Moreover, additional hazardous areas on board must comply with safety regulations. However, methanol has one advantage over MDO in terms of storage because it is allowed to store methanol adjacent to seawater. Table 3.3 shows which type of spaces may be adjacent to each other and which ones not, for both diesel fuel and methanol. If a ship designer wants to place a methanol tank adjacent to a space which has a minus sign in Table 3.3, a cofferdam must be placed.

Table 3.3: An overview of the storage conditions of methanol compared to Marine Diesel Oil (MDO). Methanol may be stored adjacent to seawater, or in other words, adjacent to the ship's skin. However, a cofferdam needs to be placed if one wants to locate a methanol tank adjacent to a space containing air.

	MDO	**Methanol**
Seawater	-	+
Air	+	-
Water ballast/ Anti-heeling Tank	+	+
The other fuel (in case of dual fuel)	+	+

Concluding, if a ship is converted to methanol several challenges have to be overcome. In the first place the difference in volumetric energy density, as shown in Table 3.2, results in more space occupied for fuel. And secondly, the different storage conditions for methanol fuel compared to diesel fuel, as shown in Table 3.3, result in additional cofferdams required by classification societies. However, more aspects of the ship design require change when converting to methanol. The next section will discuss these changes in more detail.

3.2 Design Preparations

Now more information about methanol is known, it is easier to understand what adaptations are required when switching to methanol fuel. To determine which design adaptations will benefit the most from early implementation, a list has been drawn up with the most important items that should be changed to a ship design when it is operated on methanol. This list includes modifications that must be made because of technological, operational, or regulatory reasons. For example, additional systems must be placed to pressurize the fuel before it is injected into the engine. Additionally, when a ship owner wants to maintain the same operational capabilities in terms of autonomy and mission, more volume is needed to store fuel as explained in the previous section. Furthermore, classification bureaus require double-walled piping as well as additional cofferdams when using methanol.

To identify which design preparations should be considered in the context of this research a list of required changes when converting to methanol is consulted. Due to confidentiality, this list is only visible to a limited number of readers in Appendix A. This research primarily focuses on the storage systems until the main pipeline, as these are the components that are impacted the most when switching to methanol. The removal and installation of additional equipment inside the engine room is removed from the scope, as Coenen et al. already researched the technical impact of Design-for-Retrofit of engine rooms (2015). Regarding design preparation measures, the placement of additional cofferdams and pre-installation of double-walled piping is considered, as these options are identified as having the most potential in cooperation with Royal IHC (Mestemakers and Bosscha, 2022). The main reason for this is the fact that accessibility during production is still high, while accessibility during conversion is very poor.

When designing for conversion to methanol, several employees at Royal IHC expect that the early installation of cofferdams and double-walled piping results in limited costs of changeability, and a significant decrease in the costs of changes. Therefore, these design preparations will be modelled in the ship model, to assess the technical impact of Design-for-Conversion to methanol. However, to make a proper estimation of the costs of changeability and the costs of changes when implementing these design preparations, a breakdown of these costs is needed first. The next section will give more insights into these cost breakdowns.

3.3 Design, Production & Conversion Costs

It is expected that the placement of cofferdams and pre-installing double-walled piping will benefit the most from early implementation when designing for conversion to methanol. Both the costs for adding changeability, the so-called 'costs of changeability', as well as the 'costs of changes' must be determined. The 'costs of changeability' are incurred during the new building phase whilst the 'costs of changes' are made when converting a ship to methanol. As discussed in the problem statement, there should be an optimal level of changeability, in which both the costs of changeability as well as the costs of changes are minimized, resulting in the lowest life cycle costs. To be able to find this optimum, a more detailed approach is needed for cost estimation. An answer must be found to the fourth research question: *"Which factors drive the design, production and conversion costs when preparing for or converting to methanol?"*

For the purpose of this research, both the new building and conversion costs need to be assessed. However, not all new building costs need to be known in detail, only the additional costs of taking changeability into account need to be assessed. The total costs for the preparation of a ship to methanol during new building or converting a ship to methanol are calculated in a slightly different way. However, the calculated values can be used to make a proper comparison between the costs for preparing a design for methanol and for converting a ship to methanol. Because of confidentiality, the values provided by Royal IHC are included in Appendix B, visible only to a limited group of readers. The sections below provide a high-level overview of the design and production costs during new building (section 3.3.1), as well as the conversion costs (section 3.3.2).

3.3.1 New Building Costs

The costs of changeability during the design and production phase, are subdivided into engineering, procurement, and production costs, as shown in Figure 3.2. The additional engineering costs are split into basic engineering and detailed engineering. The costs for basic engineering are fixed for different levels of changeability, whereas the costs for detail engineering vary with the amount of added steel weight. The amount of added steel, in this research, is the weight of added cofferdams.

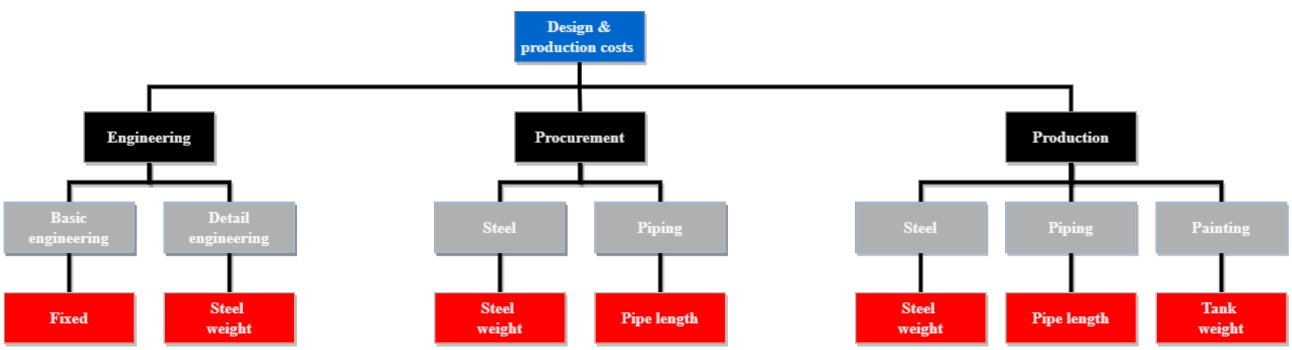


Figure 3.2: Overview of the most relevant costs when converting a ship to methanol. Only costs for installing cofferdams and double-walled piping are concerned.

The amount of steel and piping required to prepare a ship for methanol determines the procurement costs as well as a significant portion of the production costs. In addition, the weight of the methanol tanks is required, to be able to estimate the costs for the conservation of the tanks, the painting costs. Concluding, to be able to calculate the 'costs of changeability' when preparing a ship for methanol, the added steel weight, the length of piping, and the weight of the methanol tanks are required.

3.3.2 Conversion Costs

The 'costs of changes' consist of two parts, the costs for actually converting the ship to methanol and the lost income resulting from time the ship is not in operation. The conversion costs can be broken down in a similar way as the costs for preparing a ship for methanol during new building. Figure 3.3, on the next page, shows the cost breakdown for converting a ship to methanol. In contrast to the engineering costs during new building, a survey is done first to get actual information about the situation as built, resulting in additional costs. Just like the engineering costs from new building, these costs for conversion are fixed but do vary with the amount of changeability that is added. One can imagine that some of the costs for basic engineering do not have to be incurred twice when a ship is already (partly) prepared to operate on methanol. The same applies to the costs for detail engineering, whilst the difference is that these costs are not fixed, but variable with the amount of added steel weight. There is no difference in approach for estimating the procurement costs, just like during new building these costs depend on the amount of added steel weight and the length of the piping.

The main difference in the cost estimation can be found in the production costs. In contrast to new building, yard costs must be added for using a conversion yard including associated staff and equipment. These costs are paid per amount of time and therefore depend on the time schedule of the conversion. Subsequently, this planning is based on, among others, the amount of added steel weight and obviously varies for different levels of DFC. Moreover, it is very difficult to make this planning very accurate in advance because it is subjected to uncertainty, for example, due to setbacks when executing the conversion. The costs for steel work are subdivided into pre-work, which can be done in a workshop, and installation. The installation of these cofferdams is labour-intensive, and therefore planning is crucial again. It is concluded that both the costs for pre-work as well as the costs for installation heavily depend on the amount of steel that is added. There is no difference in approach to calculate costs for piping and painting compared to the cost estimation for new-building, other than using different ratios.

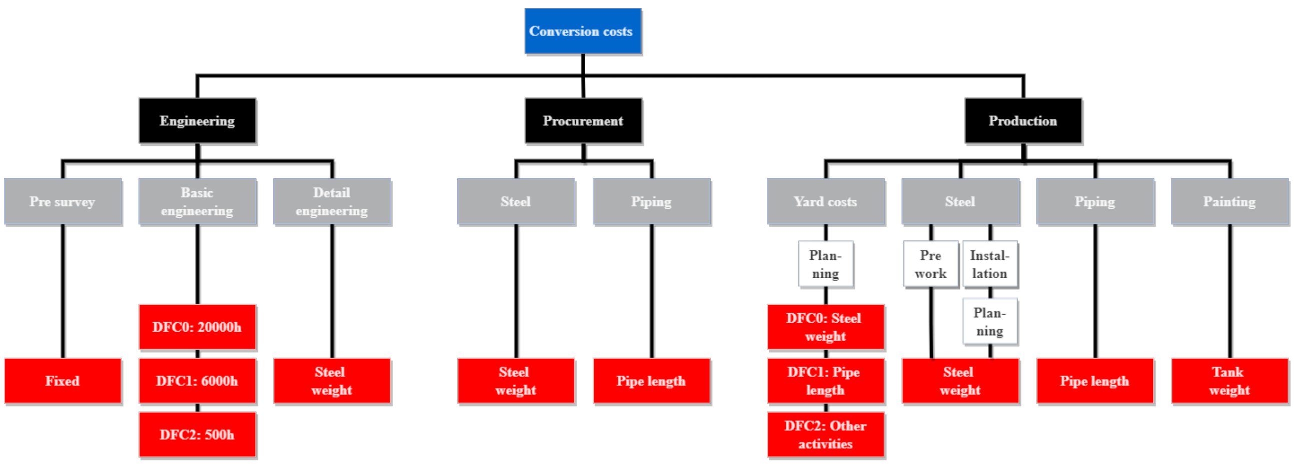


Figure 3.3: Overview of the most relevant costs when converting a ship to methanol. Only costs for installing cofferdams and double-walled piping are concerned. The used DFC levels can be found in Table 4.1.

Next to the costs for actually converting the ship there is another cost aspect that should be taken into account when assessing the costs of changes. Because a ship will not be in operation for the duration of the conversion, it is also not able to generate revenues for the ship owner. However, most running costs continue during the period of conversion resulting in additional costs of changes. This aspect is covered in the so-called loss of income, which will be added to the conversion costs because it affects the decision whether or not to prepare for conversion to methanol. This is done by multiplying the dayrate of a vessel by the amount of days that the ship is not in operation, the conversion planning. A more elaborate approach to establish the conversion planning is provided in Appendix B.

3.4 Pipe Layer Sapura Onix

The models will be used for running a case study, to show that the chosen methodology leads to valuable output for the different stakeholders as discussed in section 1.1. For this purpose, an example ship needs to be selected. In the first place, there is concluded that offshore vessels are typically interesting in the context of this research. First of all, offshore ships are highly complex and quite expensive. Moreover, they consume a lot of energy because of dynamic positioning (DP) and mission equipment. The last aspect makes it particularly interesting if a ship is converted to methanol because the amount of fuel needs to be more than doubled to maintain the same autonomy and mission capability. In addition, this type of ship is owned by one owner for a large part of its lifetime, which makes it particularly interesting to make additional investments in Design-for-Conversion to methanol which pays back its value at a later stage of the life cycle.

Within the group of offshore ships, a lot of variety exists, from offshore supply vessels to complex pipelay vessels. The choice has been made to select a pipelay vessel because its operational profile, general arrangement and power plant configuration are more complex than most other offshore ships. In addition, a lot of space is used for storage of pipes, thrusters, and other equipment which results in a lot of challenges when this type of offshore vessel needs to be converted to methanol. Royal IHC is known for building complex offshore vessels, including pipelay vessels. In 2015 they built the Sapura Onix (Figure 3.4), which is selected for the case study. The Sapura Onix was built in a series of six similar ships. Once the technical implications for one ship are determined, verified and possibly validated by means of an actual conversion project, the same approach can be used for the other ships in the series. Subsequently, it can be considered whether the method can also be used for other offshore vessels.

Figure 3.4: Sapura Onix, the pipelay vessel that will be used for a case study (Royal IHC, 2015)

Now that more information is known on methanol, the design preparation for methanol, the cost estimation, and the example ship, all the information needed for the ship model is available. Lastly, the uncertainties which may impact the value of Design-for-Conversion to methanol need to be studied more in-depth, which will be done in the next section.

3.5 Uncertainties

Due to the maritime energy transition, a lot of uncertainty is present in ship design. Relevant uncertainties for Design-for-Conversion to methanol need to be defined for the case study. Ship designers as well as ship owners know that a conversion to an alternative fuel will be needed in the nearby future, but it is uncertain when this conversion needs to take place and to which alternative fuel. In the previous chapter, it is concluded that Real Options Analysis may be used to deal with these uncertainties. This uncertainty includes regulatory uncertainty, for example on storage conditions of methanol inside the hull or a ban on CO_2-emitting ships. In addition, operational uncertainty is present, for example in the availability of green methanol around the world. Moreover, there is technological uncertainty due to the ongoing development of new technology for methanol application on ships. This section discusses the uncertainties that will be used in the case study.

3.5.1 Conversion Modelled as Uncertainty Instead of a Decision

The options that are added to a design will only have value if they are being used. However, whether they are used or not depends on whether a ship is converted to methanol or not, which is highly uncertain. The most straightforward way to look at the combination of uncertainties that determines whether a ship owner will decide to convert a ship to methanol, is to model this decision as uncertainty as a whole. It may be the case that a ship is converted to methanol, for which design preparations can be used resulting in lower costs of changes, or a ship is not converted or not converted to methanol, which makes the design preparations worthless.

3.5.2 Carbon Pricing (Regulatory Uncertainty)

Changes in regulations may have a significant impact on the choice of whether to convert or not and subsequently, whether to prepare for this conversion or not. An example of such is the measure taken by the European Committee to reduce CO_2 emissions for the industry by introducing an Emissions Trading System (ETS). This is a form of CO_2 pricing in which emitters need to have a permit for every tonne of CO_2 which is emitted. If such a measure would be introduced by the International Maritime Organisation (IMO) so that it takes effect worldwide, the Voyage Expenditures (VOYEX) will increase for ships sailing on diesel fuel. However, when converting to alternative fuels, such as methanol, these costs are not incurred, probably resulting in more ships being converted to methanol. Because the intention of policymakers to introduce such a type of measure is uncertain, it would be interesting to model it.

3.5.3 Carbon Ban (Regulatory Uncertainty)

In the same line of reasoning as for CO_2 pricing, another interesting measure would be a complete ban of CO_2-emitting ships. This is also a type of regulatory uncertainty, as it depends on future decisions by policymakers. If such a measure is introduced, there may be a point in time when ships should be converted, or scrapped. The impact of such a measure on the decision of whether to prepare for conversion to methanol or not is interesting to model.

3.5.4 Increase in Efficiency (Technological Uncertainty)

The second type of uncertainty is technological uncertainty. The development of engines on diesel fuels has been done for over a century and is still ongoing. However, the application of methanol as maritime fuel is new, and a lot of research is ongoing into the technical implementation of methanol. As a result, the tank-to-wake efficiency may increase over time, which will result in less required tank capacity. However, if a ship is prepared to store more fuel which will not be used in the future, capital has been lost. This may affect the decision of whether to prepare for conversion to methanol or not.

3.5.5 Decrease in Range & Autonomy (Operational Uncertainty)

The last type of uncertainty is operational uncertainty. This uncertainty includes the decision of a ship owner to decrease the range and/or autonomy of a ship in the future, which is unknown during the new building phase. However, this decision has an impact on the value of the design preparations in the same line of reasoning as above. Therefore, this will be modelled as an uncertainty, whether or not to decrease the ship's autonomy in the future.

3.6 Concluding the Case Study Framework

This chapter aimed to give more background to enable the application of the theory as discussed in chapter 2. More background on the properties and challenges of methanol was given. Two challenges have been identified, the first being the difference in volumetric energy density resulting in more volume required for fuel storage when converting to methanol. And second, the installation of cofferdams and double-walled piping required by classification societies will result in a significant amount of work and costs when converting to methanol. In cooperation with Royal IHC, it is concluded that these options will benefit the most from early implementation when designing for conversion to methanol. To be able to assess whether the life-cycle costs can be decreased when these design preparations are added into a design, both the costs for adding changeability as well as the costs of changes needed to be quantified. The answer to the fourth research question, "Which factors drive the design, production and conversion costs when preparing for or converting to methanol?", is found. These costs are driven by the cofferdam steel weight, the amount of pipe length and the tank weight. Moreover, a ship is selected which will be used in the case study and relevant uncertainties for the case study have been determined. Now that the theoretical background and application framework of Design-for-Conversion to methanol is known, the solution approach can be established.

4

Solution Approach

The aim of this chapter is to provide insight into the solution approach regarding the valuation of Design-for-Changeability under uncertainty. In chapter 2 is concluded that uncertainty during a ship's lifetime can be dealt with by making change easier, changeability, and taking that into account during the design phase, Design-for-Changeability. This can be done by adding change mechanisms or options, into the design. However, the potential benefits of adding these options are unclear because of uncertainty. That is why more research was conducted into determining the value of options over their lifetime. It was concluded that a Net Present Value calculation can be used for this purpose. Because uncertainty is not taken into account in this valuation method an additional method was needed for the valuation of options under uncertainty. In chapter 2 it is found that Real Options Analysis fits this purpose. Subsequently, the previous chapter aimed to give more background to enable the application of the theory. Conversion to methanol results in more volume required for fuel storage. Moreover, cofferdams and double-walled piping need to be installed.

Figure 4.1 shows an overview of the combination of models. Because the valuation of Design-for-Conversion may be more widely applicable, than just Design-for-Conversion to methanol it has been chosen to build two separate models. First, a ship model is built, to quantify the technical impact of Design-for-Conversion for methanol, which can be adapted and extended to include other alternative fuels. Second, an option model is used to determine the value of Design-for-Conversion under uncertainty, which can also be used for the valuation of options in other systems, that have similar properties as offshore ships. For instance, for the valuation of options in complex systems that also operate in uncertain conditions, require a lot of capital and have a long lifespan.

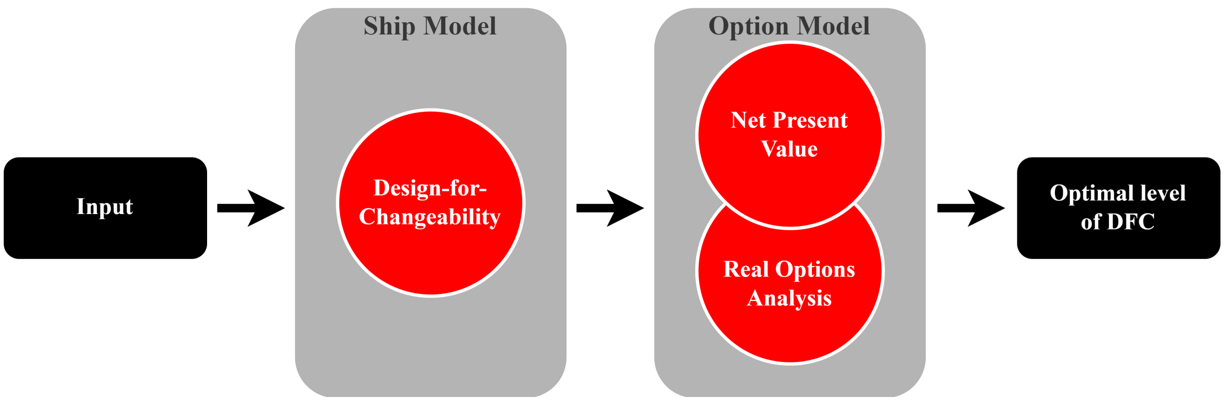


Figure 4.1: An overview of the solution approach used to determine the value of Design-for-Conversion under uncertainty. The theory as discussed in chapter 2 is used in the models, to find the optimal level of Design-for-Changeability that should be added into a design.

The output of the model is the valuation of different levels of DFC to support decision-making by ship owners and ship designers to prepare ships for methanol or not. Furthermore, it should be able to identify whether to convert or not, if different levels of DFC are implemented. Moreover, the model should provide insights into when a ship should be converted to methanol. In addition to the insights for ship owners and designers, it would be valuable if the model's output could support decision-making by policymakers as well. Therefore, various measures, such as CO_2 pricing or a complete ban on CO_2-emitting ships as discussed in section 3.5 will be modelled. Subsequently, their effectiveness in terms of instigating ships to convert will be evaluated.

In the remainder of this chapter, insight into the choices made for this solution approach will be provided. This will be done by first zooming in on the ship model in section 4.1. Subsequently, the choices for the option model will be outlined in section 4.2.

4.1 Overview of the Ship Model

The aim of the ship model is to simulate the technical aspects of Design-for-Conversion to methanol. In other words, it investigates which change mechanisms can be used to enhance a future conversion to methanol. As discussed in the previous chapter, quite some adjustments must be done when converting a ship to methanol. Due to the properties of methanol, classification societies require additional cofferdams and double-walled piping, which are expected to benefit the most from implementation during the design and production phase. Therefore, it is necessary to model a detailed ship layout such that these design preparations can be added. An overview of the ship model's black box is shown in Figure 4.2.

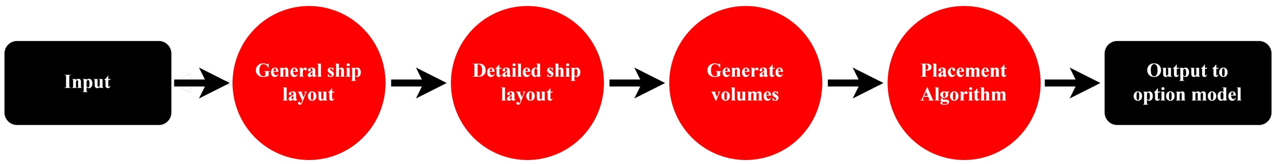


Figure 4.2: An overview of the ship model which aims to determine the technical impact of Design-for-Conversion for methanol. General ship characteristics are required as input, together with some fuel properties. The output of the ship model will be used in the option model.

The ship model will take general ship parameters to generate a high-level layout. Subsequently, a more detailed ship layout will be generated using more detailed ship information. After the detailed ship layout is generated, the available volumes for methanol will be calculated. Lastly, the model will assign certain volumes as methanol tanks using a placement algorithm. The ship model's output for different levels of DFC will be used in the option model, which will be discussed in further detail in the next section.

As in the research of Rehn et al., which is discussed in section 2.1.3, the DFC variable will be used to quantify different levels of changeability. The levels of design preparation are defined as shown in Table 4.1.

Table 4.1: The DFC variable expressing multiple levels of changeability in Design-for-Conversion to methanol.

DFC variable	**Path enablers**
0	Baseline (none)
1	Cofferdams
2	Cofferdams and piping

$DFC0$ is the baseline scenario, in which no design preparations are implemented. The $DFC1$ level is the lowest level with design preparation, in which only cofferdams are placed. The highest level of design preparation, $DFC2$, consists of both adding cofferdams during production and installing double-walled piping.

As explained in section 3.3, part of the conversion costs are subjected to uncertainty, especially costs that depend on the conversion planning. Therefore, the ship model aims to model the cost drivers, which are steel weight, piping length, and tank weight. Subsequently, the impact of uncertainty on the costs may be modelled in the option model. On the one hand, the costs of changeability for adding design preparations need to be identified for $DFC1$ and $DFC2$. On the other hand, the costs of changes to achieve the same change effect during a conversion need to be quantified for all levels of DFC. Both the cost of changeability as well as the cost of changes for all levels of DFC will be used as input for the option model. More detailed information on how the ship model is built can be found in chapter 5.

4.2 Overview of the Option Model

In the ship model, both the costs of changeability during new building, as well as the costs of changes during conversion will be calculated, for all DFC levels. The option model will be used to find the level of DFC that results in the lowest life cycle cost. From theory, a Net Present Value calculation has been selected to value options over the ship's lifetime, while Real Options Analysis is selected for determining the impact of uncertainty. This section will discuss how these methods are applied in the option model.

To implement Real Options Analysis, a combination with decision tree mapping is used as described by Yao and Jaafari (2003). This is because projects like ship conversions involve unique uncertainties, such as the ones mentioned in section 3.5, and: "Decision Tree analysis permits mapping of project options coupled with associated (market) uncertainties" (Yao and Jaafari, 2003, p.55). Figure 4.3 shows an example of a real options decision tree for the development of a gold mine, to better explain decision tree analysis.

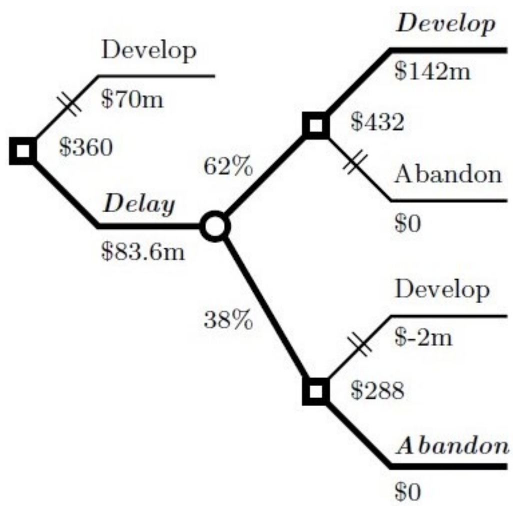


Figure 4.3: A goldmine example of Decision Tree Analysis (DTA) involving decisions (squares) as well as uncertainties (circles) (Sick and Gamba, 2005). First, a decision must be made to develop the mine, yielding $70m, or to wait. If it is chosen to delay for 1 year, the gold price changes to either $432 or $288, after which a new decision can be made. The mine can either still be developed or abandoned. However, because of the price change revenues differ from the previous decision, $142m and $-2m for a price increase or price decrease, respectively.

The round nodes represent moments in time uncertainty is present, and the probability of occurrence is shown at its path. The squared nodes are moments in time where a decision-maker has the ability to make a decision, either 'Develop' or 'Delay'. The initial gold price equals $360 and after year 1, it has a 62% probability to increase by 20% to a value of $432, and a 32% probability of decreasing by 20% to a value of $288. After the price change, the decision-maker has a new decision moment, either 'develop' or 'abandon' the mine. Mostly, decision trees are solved backwards, starting from the tips of the tree, which correspond with the last considered moment in time. A decision-maker shall always make the decision with the highest value, and the associated value of that option is taken to the preceding node (Sick and Gamba, 2005). Nodes corresponding to uncertainty, are valued by taking the expected value of the options (Sick and Gamba, 2005). The expected value can be calculated by means of Equation 4.1.

$$exp_{value} = \text{payoff}_{value,\ 1} \cdot \text{prob}_1 + \text{payoff}_{value,\ 2} \cdot \text{prob}_2 + ... + \text{payoff}_{value,\ N} \cdot \text{prob}_N \tag{4.1}$$

To calculate the expected value, the value of each option needs to be multiplied by the probability of that option. The payoff value is the sum of all costs and revenues for the combination of decisions and uncertainties of an option. In the option model, the time value of options is accounted for by means of a net present value calculation, as shown in Equation 2.1. The value of each node is taken to the previous node and is discounted for the time value of money In the example tree, a 6% discount rate is used and the decision moments are one year apart.

One of the main advantages of Decision Tree Analysis is its ability to structure all feasible actions within a changing market or environment. In contrast to just a Discounted Cash Flow or Net Present Value method, where all future cash flows have to be determined in advance, more information can be gathered over time and options with the highest value can be chosen. In this way, a decision-maker can retain upside potential while reducing downside risk (Sick and Gamba, 2005). However, if a decision tree is further expanded with more decision moments and/or more options per node, building and analysing the decision tree can become very time-consuming and complex.

The option model is setup to model a Real Options Decision Tree, as discussed above. A global overview of the steps within the option model is shown in Figure 4.4.

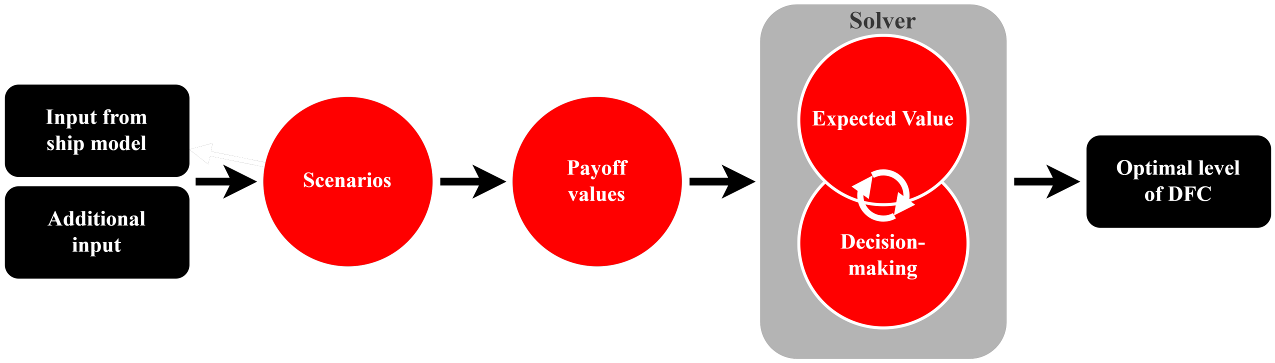


Figure 4.4: An overview of the option model, to model uncertainty and decision-making by means of a Real Options Decision Tree. A Net Present Value calculation is integrated to account for the time value of money. This approach is set up to find the optimal level of Design-for-Changeability that should be added to a design.

The first step is to generate all scenarios, by combining consecutive decision and uncertainty moments. Each scenario has its own payoff value, which is determined by the costs and revenues of that particular combination of options. Consequently, a module is needed that can solve the tree, the so-called solver. As the decision tree is solved backwards, the solver will first check whether a payoff value is present, as is the case at the tip. While solving the nodes, it will either use the expected value if it is an uncertainty node or take the decision with the highest (expected) value. As the probability of occurrence of an uncertainty option is unknown, the model should be able to vary the probability at these nodes. In this way, insights can be obtained into the influence of uncertainties on decisions, for the whole range of probabilities. More detailed information on how the option model is built can be found in section 5.3.

In addition to input from the ship model, the option model needs decision moments and uncertainty as input. Moreover, valuation parameters are needed to determine the payoff value for different design options. The model's output should identify for which situations a DFC level would be preferred and at what moment in time a ship should be converted. A case study will be conducted to obtain this output. Detailed information about the case study is discussed in the previous chapter.

5

Methodology: Ship Model & Option Model

The aim of this chapter is to provide detailed information about both models. The previous chapter discussed the solution approach, and how the methods selected from the literature will be applied to the Design-for-Conversion to methanol problem. In the ship model, the technical impact of Design-for-Conversion will be modelled by means of the Design-for-Changeability principles. Subsequently, uncertainty and decision-making will be modelled in the option model by means of a Real Options decision tree, to determine the value options under uncertainty. The Net Present Value of options will be calculated to account for the time value of money. This chapter provides a detailed description of both models.

First, an in-depth insight is given into the ship model in section 5.1. Moreover, verification of the ship model will be done using the example ship, which will be discussed in section 5.2. Second, a detailed description of the option model will be discussed in section 5.3. In addition, verification of the option model is done, which will be discussed in section 5.4.

5.1 Detailed Ship Model

A more detailed layout of the ship is needed to model the technical impact of the selected design preparations, which have been discussed in section 3.2. The model should identify available spaces and select which ones to use for methanol storage, resulting in the lowest costs according to the cost breakdown as defined in section 3.3. To assess whether uncertainties in the costs have an impact on the decision to prepare for methanol or not, it will be modelled in the option model. For that reason, the underlying cost drivers, the added steel weight, the pipe length and the tank weight, need to be the output of the ship model.

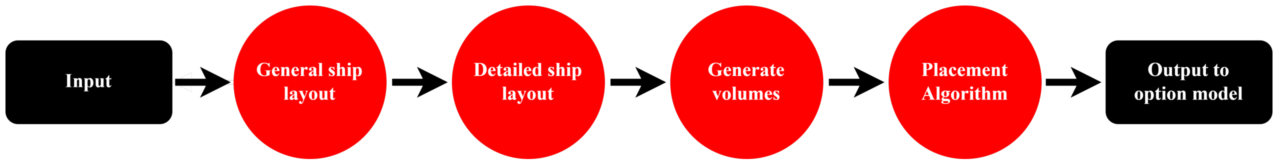


Figure 5.1: An overview of the ship model which aims to determine the technical impact of Design-for-Conversion for methanol. General ship characteristics are required as input, together with some fuel properties. The output of the ship model will be used in the option model.

The first module of the ship model, generation of the general ship layout, will be discussed in section 5.1.1. Subsequently, the generation of the detailed ship layout will be discussed in further detail in section 5.1.2. Once the detailed ship layout is known, volumes need to be generated which can be used for methanol, which is discussed in section 5.1.3. Lastly, the placement algorithm, which will select the spaces used for methanol storage, will be discussed in section 5.1.4.

5.1.1 Generation of General Ship Layout

The general layout is defined as a rectangular-shaped box, containing watertight bulkheads, double shells, and decks. To enable the ship model to generate the ship's layout, the model needs some very basic input parameters. Table 5.1 shows the parameters for the case study ship Sapura Onix.

Table 5.1: Required general vessel information for generation of the ship's layout. Values shown in the table are from the example ship Sapura Onix built by Royal IHC, which was delivered in 2015.

Name	Symbol	Value	
Length overall	L_{oa}	145.95	[m]
Beam	B	29.94	[m]
Draught	T	7.6	[m]
Depth	D	13.0	[m]
Block coefficient	C_B	0.782	[-]

In addition to these parameters, the model also needs to know the locations of (watertight) bulkheads to generate the basic ship layout. For the Sapura Onix, these bulkheads are located at frames 15, 33, 57, 90, 107, 125, 151, and 169. The model also needs the frame spacing to be able to convert the frame numbers to x-coordinates. Moreover, the model has been built to deal with varying frame spacing over the ship's length. This is because, for the Sapura Onix, a value of 780[mm] applies between frames 15 and 169, while a frame spacing of 600[mm] is used outside this range. In addition to the locations of the bulkheads, the model also needs to know where the decks are located. The locations of the decks of the example vessel are shown in Table 5.2 on the next page. The decks are located at a vertical distance z_{loc}, measured from the baseline at the keel plating. Furthermore, the decks run from the starting frame until the ending frame in the x-direction and from y_{start} until y_{stop} in the y-direction, which is measured from the starboard shell plate.

Table 5.2: Required deck information for generation of general vessel layout. Values shown in the table are of example ship Sapura Onix.

Name	Starting frame [-]	Ending frame [-]	y_{start} [m]	y_{stop} [m]	z_{loc} [m]
Deck 1 (Tanktop)	0	57	0.0	29.94	2.0
Deck 1 (Tanktop)	57	183	0.0	29.94	1.5
Deck 2	0	33	10.47	19.47	6.0
Deck 3	90	125	0.0	29.94	9.5
Deck 4 (Main deck)	0	183	0.0	29.94	13.0

To generate the double shell the width of the longitudinal bulkheads must also be given as input to the model. The width of the shell (W_{shell}) may vary along the length of the ship. Moreover, it may be the case that no double shell is present in the fore and aft ship. Therefore, the start and end frame of a certain double shell width must be given as input to the model as well, as shown in Table 5.3.

Table 5.3: Required model input for the generation of the double shell in the general vessel layout. Values shown in the table are from the example ship Sapura Onix.

Starting frame [-]	Ending frame [-]	W_{shell} [m]
0	57	2.97
57	125	2.22

Based on the ship's length overall (L_{oa}), beam (B) and information about locations of the decks, watertight bulkheads and the double shell, a general ship layout is generated which is shown in Figure 5.2. As most input information is given in frames, the frame spacing also needs to be known allowing the model to calculate distances in metres which will be necessary for the calculation of volumes. Because the frame spacing varies over the hull's length, a function is built that converts frames to x-coordinates in a proper way.

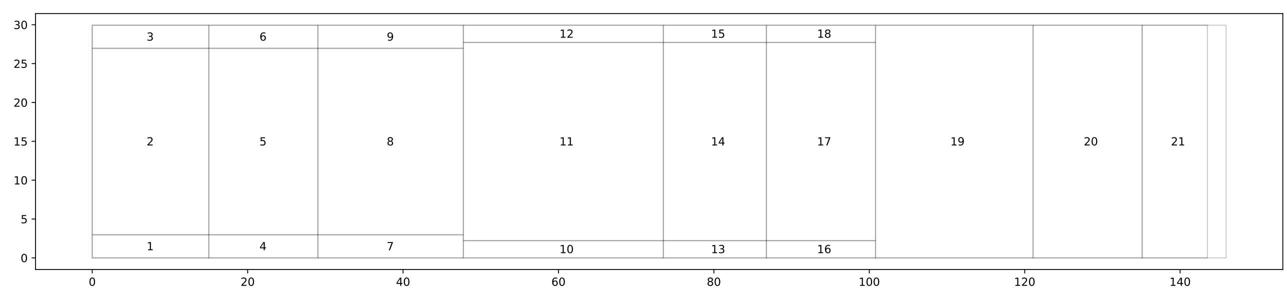


Figure 5.2: Overview of general ship layout at z=0

In Figure 5.2 the generated layout of the double bottom of Sapura Onix is shown. The fore ship is located on the right-hand side, where no double shell is present. In the aft ship, a double shell is present, which in turn is wider than at the midship. Layouts are generated for all deck heights given as input, Table 5.2. To be able to determine where to place methanol tanks, a higher level of detail is needed, which will be discussed in the next section.

5.1.2 Generation of Detailed Ship Layout

The general ship layout is not detailed enough to locate methanol tanks and determine where cofferdams should be placed. Therefore, a more detailed ship layout must be generated by the model. First, the large volumes as shown in Figure 5.2 are split into spaces that match the actual situation. This is done in the first place by adding additional transverse and longitudinal bulkheads as well as additional decks. Moreover, the ship's outer shape is constructed and volumes which are completely outside of these lines will be dropped.

Place Bulkheads

Information needed by the model includes an extended list of longitudinal and transverse bulkheads, as well as a list of additional decks. For the example vessel, Sapura Onix, these lists can be found in Appendix C. Subsequently, longitudinal and transverse bulkheads are placed according to the actual vessel layout. In addition, multiple (smaller) decks are added. The resulting detailed ship layout for the double bottom is shown in the figure below.

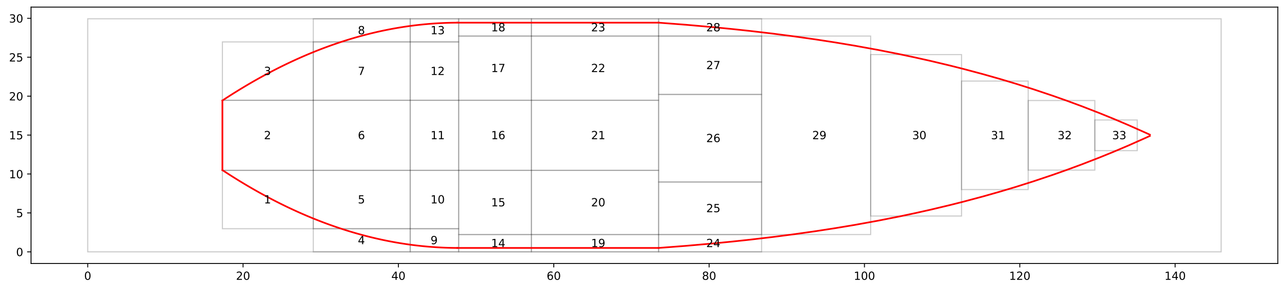


Figure 5.3: The generated detailed ship layout at z=0[m], including additional bulkheads and the hull's shape.

Hull Shape

The model needs information to model the hull's shape at different ranges of z-locations, from z_l to z_u. Polynomials are used to correct the generated volumes for the hull's shape at the fore and aft ship, which apply from x_l to x_u. For these polynomials to be generated the information as shown in Table 5.4 is needed. At lower z-locations, the order of the polynomials is lower, and once the ship's shape gets more curvy higher orders are required. At the aft ship, the hull's curved shape can be cut off at a certain y-location, y_l and y_u, between which the transom runs straight.

Table 5.4: Required model input for generation of polynomials to correct volumes for the hull's shape. Values shown in the table are used for example ship Sapura Onix.

Bound	x_l [-]	x_u [-]	y_l [m]	y_u [m]	z_l [m]	z_u [m]	order
B1	18	57	10.47	19.47	0.0	2.0	2
B2	-10	27	10.47	19.47	2.0	6.0	2
B3	-10	27	10.47	19.47	6.0	9.5	8
B4	-10	3	1.00	28.94	9.5	13.0	8
B5	90	172			0.0	1.5	4
B6	99	178			1.5	6.0	6
B7	118	179			6.0	9.5	8
B8	125	179			9.5	13.0	10

B1-B4 correspond to polynomials used to correct the aft ship, whilst B5-B8 are used to correct the fore ship. In the case of the fore ship, the hull lines are plotted at the given x-locations and from $\pm B/2$ until the centre line. Equation 5.1 is used to construct the polynomial lines which are used as hull lines. $i = 1...4$ correspond to the starboard fore boundary, port side fore boundary, starboard aft boundary, and port side aft boundary, respectively.

$$y_i = a_i \cdot x^{order} + b_i \tag{5.1}$$

Supporting equations, Equation 5.2 - 5.5, are needed to construct all hull lines at different locations. At the height of the double bottom, the bounds are plotted at $B/2 - 1/3 \cdot Bilge$, at all other heights the bilge is set to zero. For different vertical locations, z_l, the hull shape is plotted. The hull shape at the location of the double bottom is plotted in red, as shown in Figure 5.3.

For the hull shape in the fore ship:

$$a_1 = \frac{B/2 - bilge}{{x_u}^{order} - {x_l}^{order}},\ a_2 = -\frac{B/2 - bilge}{{x_u}^{order} - {x_l}^{order}} \tag{5.2}$$

$$b_1 = \frac{-(B/2 - bilge) \cdot {x_l}^{order})}{{x_u}^{order} - {x_l}^{order}} + bilge,\ b_2 = \frac{(B/2 - bilge) \cdot {x_l}^{order})}{{x_u}^{order} - {x_l}^{order}} - bilge + B \tag{5.3}$$

For the hull shape in the aft ship:

$$a_3 = \frac{y_l - bilge}{{x_l}^{order} - {x_u}^{order}},\ a_4 = -\frac{y_l - bilge}{{x_l}^{order} - {x_u}^{order}} \tag{5.4}$$

$$b_3 = bilge,\ b_4 = -bilge + B \tag{5.5}$$

Drop Volumes

Spaces that are located completely outside the ship's hull shape are dropped. As shown in Figure 5.3 a lot of spaces in the aft ship of the double bottom are dropped in the case of Sapura Onix. When the transom is straight, as is the case for the example ship, the spaces at the aft ship are cut off and their x_l value is adjusted. Correction of volumes which intersect with the hull shape will be discussed in the next section.

5.1.3 Generate Volumes

Now that the detailed ship layout is known, together with the ship's hull shape, the volumes of all spaces can be calculated. First, the box volumes of all volumes will be calculated, as most spaces are rectangular-shaped. Consequently, the spaces that intersect with the hull will need a correction on their box volume. Additionally, the centres of gravity of all spaces as well as their adjacent area to other spaces need to be calculated. Lastly, the calculation of the steel weight of the cofferdams and the length of the piping need to be calculated, as these factors drive the planning and costs as discussed in section 3.3.

Box Volumes & Corrected Volumes

All spaces have a box dimension which is defined by $[x_l, x_u, y_l, y_u, z_l, z_u]$ in x, y, and z-direction, respectively. As most volumes are rectangular shaped, their volumes can be easily calculated by means of Equation 5.6.

$$V_{box} = dx \cdot dy \cdot dz = (x_u - x_l) \cdot (y_u - y_l) \cdot (z_u - z_l) \tag{5.6}$$

If a volume intersects with one of the hull lines, the polynomial at the bottom side of the space (z_l) is used. This results in an expected underestimation of the corrected volumes. This polynomial is integrated by means of the trapezoidal rule, over the x domain of the volume. This results in an area which is outside the boundary. By multiplying this area by the height of the concerned volume, the corrected volume is determined. By subtracting this volume from the boxed volume, the corrected volume is obtained. Subsequently, a filling grade of 0.98 is used for all spaces to compensate for volume which is taken by stiffeners and so on. Consequently, spaces are dropped whose volume is less than $10[m^3]$ because using such small spaces for methanol storage will not contribute to the targeted amount of fuel storage significantly.

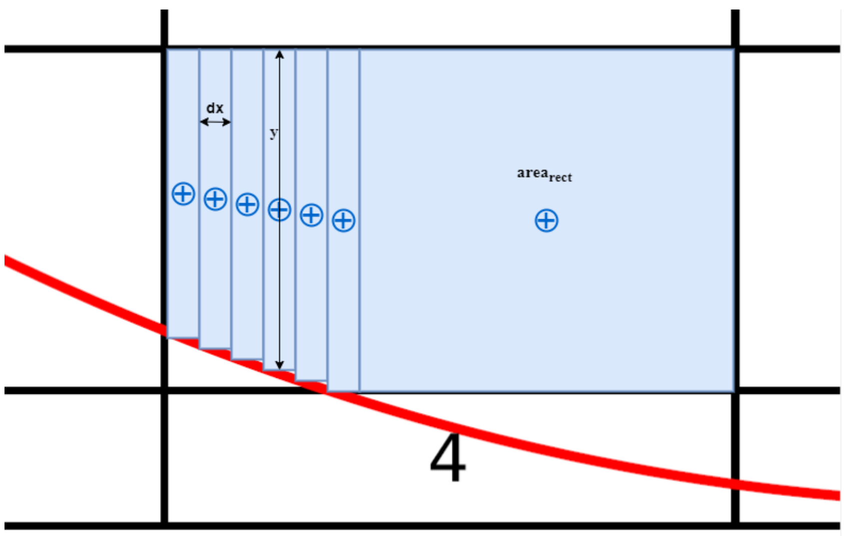


Figure 5.4: Calculation method of corrected volume

Centres of Gravity

For the spaces which are not corrected by the ship's hull, and thus rectangular shaped, the COGs are equal to the COGs of the box volumes, which can be calculated using Equation 5.7. For the other volumes, which are corrected for the ship's shape, another approach is needed.

$$LCG_{box} = x_l + \frac{x_u - x_l}{2},\ TCG_{box} = y_l + \frac{y_u - y_l}{2},\ VCG_{box} = z_l + \frac{z_u - z_l}{2} \tag{5.7}$$

The Longitudinal Centres of Gravity (LCG) are not corrected for the hull shape. The main reason for this is the fact that the change in LCG is expected to be limited, and secondly, it is expected that enough ballast possibilities are available to trim the ship correctly. In contrast, the Transverse Centres of Gravity (TCG) do need to be corrected, because the placement algorithm may select more spaces on one side of the centre line resulting in a transverse imbalance. The TCGs are calculated by means of the trapezoidal rule, which is shown in Equation 5.8.

$$TCG_{trapz} = \frac{y/2 \cdot y \cdot dx}{area_{trapz}} = \frac{0.5 \cdot y^2 \cdot dx}{area_{trapz}} \tag{5.8}$$

For volumes which intersect with the hull shape in such a way as shown in Figure 5.4 the TCG_{trapz} should be combined with TCG_{rect} of the rectangular shaped part of the volume, Equation 5.9.

$$TCG = \frac{TCG_{trapz} \cdot area_{trapz} + TCG_{rect} \cdot area_{rect}}{area_{tot}} = \frac{TCG_{trapz} \cdot area_{trapz} + \frac{dy}{2} \cdot area_{rect}}{area_{trapz} + area_{rect}} \tag{5.9}$$

Lastly, the Vertical Centres of Gravity (VCG) are corrected because an underestimation of these values will significantly impact stability calculations. Therefore, a VCG of a space which is slightly larger than the actual VCG is preferred, rather than the other way around. Because the corrections for the ship's hull shape will mostly correct for volume which is reduced at the bottom of a space, the VCG of the box volume will be lower than the actual VCG of the volume. Therefore, the choice has been made to correct the VCG of all corrected volumes by 20% as shown in Equation 5.10.

$$VCG_{actual} = 1.2 \cdot VCG_{box} \tag{5.10}$$

Calculation of Cofferdam Steel Weight

Now the model generated all possible spaces including their volume and centres of gravity, the model needs to determine whether a cofferdam is needed or not if a space is filled with methanol. As discussed in section 3.3, the planning as well as the costs of adding cofferdams into a design strongly depends on the amount of steel weight that is added. Equation 5.11 can be used to calculate the steel weight that needs to be added if the model selects a particular space as a methanol tank. To do so the plate area needs to be multiplied by the plate thickness. As a rule of thumb, a factor of 1.5 is applied to account for the weight of stiffeners and so forth. The plate area ($A_{\text{plate},i}$) is calculated by means of the adjacent area between spaces.

$$m_{\text{cofferdam},i} = A_{\text{plate},i} \cdot t_{\text{plate},i} \cdot \rho_{\text{steel}} \cdot 1.5 \tag{5.11}$$

Adjacent Area

As the model will choose in which spaces methanol is to be stored for the lowest additional costs, the placement algorithm, which will be discussed in section 5.1.4, needs to know whether spaces are adjacent or not, and if so, how large the adjacent area is. Therefore, the choice has been made to use a matrix that can be used by the algorithm to calculate the cofferdam weight by multiplying this matrix by a filling vector of the algorithm. An example of such a matrix is shown in Equation 5.12. The model determines whether volumes are adjacent to each other, by comparing each space to all other spaces and checking whether the dimensions match or not. For example, the x_u (ending x-location) of space XX is checked with the x_l (starting x-location) of volume XY. By doing the same for the y and z directions it is checked whether the volumes are adjacent or not. If they are adjacent, the adjacent area of the two is calculated and stored in the matrix. The matrix is symmetrical over its diagonal because the adjacent area of space XX to space XY is equal to the adjacent area of space XY to space XX. The diagonal of this matrix consists of zeros only, as spaces cannot be adjacent to themselves.

$$[adj_{area}] = \begin{bmatrix} 0 & adj_{area,1,2} & \dots & adj_{area,1,m} \\ adj_{area,2,1} & 0 & \dots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ adj_{area,n,1} & \dots & \dots & 0 \end{bmatrix} \tag{5.12}$$

However, based on the storage conditions as discussed in section 3.1 there is no need for a cofferdam if a methanol tank is adjacent to a water ballast or anti-heeling tank. Therefore, a user of the model can specify that certain spaces do not need a cofferdam. For example, the double bottom of the Sapura Onix only consists of water ballast and anti-heeling tanks. Thus there is no need to place a cofferdam between two spaces in the double bottom, and the corresponding areas in the matrix are set to zero.

In addition to spaces being adjacent to each other, the decision whether to place a cofferdam or not also depends on what substance is located outside the ship's hull. For spaces adjacent to the outside of the ship's structure, an additional vector (Equation 5.13) is needed, that can be used by the placement algorithm. This is a vector because no dependency exists between storing methanol in adjacent spaces and the need for a cofferdam in the concerned space. The need for a cofferdam only depends on whether there is seawater or air adjacent to the concerned space. For spaces below the minimum waterline (T_{min}), no cofferdam is required by classification societies. However, for all spaces adjacent to the air a cofferdam needs to be placed. Air can be either next to a space, such as in the side shell, or on top of a space, as is the case on the main deck, for example. Therefore, each space is checked whether it is located at the ship's skin above the waterline, or whether the space is located just beneath the main deck. If so, the adjacent area is stored in the vector.

$$\overline{adj}_{air} = \begin{bmatrix} adj_{air,1} \\ adj_{air,2} \\ \vdots \\ adj_{air,n} \end{bmatrix} \tag{5.13}$$

Complexity Factor

Some spaces require more work when a cofferdam is installed than other spaces. For example, spaces inside the double bottom are more difficult to access compared to spaces just beneath the main deck. In addition, it is more difficult to hoist a cofferdam of several tonnes of steel into place. To account for this, a complexity factor is added to increase the amount of work required to install a cofferdam in spaces inside the double bottom or double shell, as shown in Equation 5.14. A factor of 1.5 and 1.2 is taken, respectively. For all other spaces, a factor of 1 is taken.

$$\overline{cpl}_{factor} = \begin{bmatrix} cpl_{factor,1} \\ cpl_{factor,2} \\ \vdots \\ cpl_{factor,n} \end{bmatrix} \tag{5.14}$$

Calculation of Piping Length

In addition to the amount of added steel weight, the design, production and conversion costs also depend on the amount of pipe length used for double-walled piping. Calculation of the amount of piping that needs to be used is composed of several aspects because loop pipelines are used on both sides of the vessel, starboard and port side. That is why four times the distance between the engine room and aft-most tank is used, and this is multiplied by a factor of 1.1 to account for detours because of obstacles. Additionally, the height at which the pipes run through the ship changes, which is the reason why the pipe length of all four pipes is extended by half times the depth. Additionally, four times the beam is added to account for crossover lines which are used for bunkering and redundancy. Lastly, each tank is connected to the ring pipeline with a 5-metre length of pipe. The complete formula is shown in Equation 5.15.

$$L_{\text{piping}} = 4 \cdot (x_{\text{ER}} - x_{\text{aft tank}}) \cdot 1.1 + 4 \cdot 0.5 \cdot D + 4 \cdot B + \# \text{ of tanks} \cdot 5[m] \tag{5.15}$$

5.1.4 Placement Algorithm

The model cannot use all spaces which will be generated in the detailed ship layout for methanol storage because of the current situation as built. For example, cargo holds, engine rooms, and other machinery rooms cannot be used. These occupied spaces for Sapura Onix are shown in Table 5.5. If a ship has a moonpool, spaces located in the moonpool should be excluded as well. Also, other spaces, such as the double bottom of a dredging vessel containing hopper doors, can be excluded by means of this input if necessary. For plotting reasons the radius (r), as well as the positions of the centres of the baskets, are also required as input. Basket 1: r=23.40[m] at frame 75. Basket 2: r=17.16[m] at frame 43.

Table 5.5: Input needed for the model to know which volumes cannot be used for methanol storage. The input for example ship Sapura Onix is shown: ER1= Engine room 1, ER2= Engine room 2, TR1= Thruster room 1, SR1= Storage room 1, WR_{PS}= Winch room port side, and WR_{SB}= Winch room starboard.

	Space	$\mathbf{x_l}$ **[-]**	$\mathbf{x_u}$ **[-]**	$\mathbf{y_l}$ **[m]**	$\mathbf{y_u}$ **[m]**	$\mathbf{z_l}$ **[m]**	$\mathbf{z_u}$ **[m]**
Cargo holds	Basket1	57	90	2.22	27.72	1.5	13.00
	Basket2	30	57	2.92	26.97	1.5	13.00
Engine room and machinery rooms	ER1	107	125	2.22	27.72	1.5	13.00
	ER2	125	186	0.00	29.94	1.5	13.00
	TR1	-10	15	0.00	29.94	0	13.00
	SR1	15	30	10.47	19.47	6	13.00
	WR_{PS}	90	107	19.47	27.72	1.5	13.00
	WR_{SB}	90	107	2.22	8.97	9.5	13.00
	Cable duct	15	125	26.96	29.94	9.5	13.00
Moonpool	MP	90	107	8.97	20.97	0	13.00

Because of the storage conditions as mentioned in section 3.1 the locations of the current water ballast and anti-heeling tanks as well as the voids of Sapura Onix must be known as well. Most of the spaces inside the double bottom of Sapura Onix are either voids or water ballast/ anti-heeling tanks. A complete list is shown in Table 5.6. Also most spaces in the side shells up and till deck 2 are of this category.

Table 5.6: Spaces in the Sapura Onix marked as void, water ballast tank or anti-heeling tank

		$\mathbf{x_l}$ **[-]**	$\mathbf{x_u}$ **[-]**	$\mathbf{y_l}$ **[m]**	$\mathbf{y_u}$ **[m]**	$\mathbf{z_l}$ **[m]**	$\mathbf{z_u}$ **[m]**
Double bottom	Aft	-10	57	0.00	29.94	0.00	2.00
	Fore	57	107	0.00	29.94	0.00	1.50
Side shell PS	Aft	-10	57	26.97	29.94	2.00	9.50
	Fore	57	125	27.72	29.94	1.50	9.50
Side shell SB	Aft	-10	57	0.00	2.97	2.00	9.50
	Fore	57	125	0.00	2.22	1.50	9.50

Moreover, the model needs to know how much fuel needs to be stored. Therefore, the amount of diesel which can be stored in Sapura Onix needs to be known to the model. Subsequently, to be able to calculate the steel weight of the cofferdams the model needs to know the density of steel (ρ_{steel}), for which a value of 7800[kg/m^3] is taken. Additionally, the plate thickness must be defined, 15[mm] is set as default. Lastly, the model needs to know how much space should be left between the original panel and the cofferdams to be installed. A cofferdam width of 760[mm] is taken according to the MARPOL convention (International Maritime Organisation, 2005). It should be added that this distance applies to MDO adjacent to the ship's skin. In addition, from BV Pt. B, Ch. 2, Sec. 2, 1.2.1: "As a rule, a cofferdam is to be properly ventilated and of sufficient size to allow for inspection" (Bureau Veritas, 2022, p.66). For inspection purposes, a distance of 760[mm] is expected to be sufficient as well.

Next, the model should propose spaces that will be used for methanol storage in the future. For this purpose, a Gurobi optimizer is used, which is a mathematical algorithm capable of solving linear and quadratic optimizing problems. However, the model needs to know which variables it can adjust, it needs to know which spaces cannot be used, it needs an objective to optimize and it requires constraints to be met. Lastly, a stability check must be performed.

Filling Variable

The algorithm can assign the function methanol tank to the generated volumes. Therefore, a vector is used which has a length that corresponds with the number of volumes m. This is a discrete variable, which can only have a value of 1 or 0. A value of 1 will indicates if a space is a methanol tank, and 0 if not. Additionally, the algorithm needs to know the volume of that space if it is utilized as a methanol tank. This information is stored in the vector $\overline{V}_1$. For programming reasons, a second vector is used, $\overline{X}_2$, which had the same length as $\overline{X}_1$ and consists of ones. By computing $\overline{X}_2 - \overline{X}_1$, the unfilled spaces are known to the model as well.

$$\overline{X}_1 = \begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_m \end{bmatrix}, \ \overline{V}_1 = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_m \end{bmatrix} \tag{5.16}$$

Exclusion Matrix

Because vectors X_1 and V_1 contain all spaces of the ship, the algorithm can fill all these spaces. However, spaces occupied by cargo, machinery and such, as defined in Table 5.5, cannot be filled with methanol. Therefore, the volumes of these spaces must be set to zero, to prevent the algorithm from choosing these spaces to fill. This is done by multiplying V_1 by an exclusion matrix $[EXC]$ (Equation 5.17), as shown in Equation 5.18. This matrix is filled with zeros, except for the diagonal which consists of ones. However, if a space needs to be excluded the 1 on the diagonal of the corresponding space is set to zero, resulting in a volume of zero after multiplication ($\overline{V}_2$).

$$[EXC] = \begin{bmatrix} exc_1 & 0 & \dots & 0 \\ 0 & exc_2 & \dots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \dots & \dots & exc_m \end{bmatrix} \tag{5.17}$$

$$\overline{V}_2 = \overline{V}_1 \cdot [EXC] = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_m \end{bmatrix} \tag{5.18}$$

Objective Function

The objective function used by the algorithm is shown in Equation 5.19. It consists of four parts, the first part consists of the costs involved with the cofferdams, and the second part consists of the costs involved with piping. Subsequently, the costs of conserving the methanol tanks should be added. The last part is added to prevent the model from choosing occupied spaces. Despite the fact that the volumes of these spaces were set to zero, the model selected these spaces for methanol because this resulted in lower costs for storing methanol adjacent to these rooms. Therefore, it is chosen to add a large amount of costs if the model selects occupied spaces, in order to prevent them from being selected.

$$MIN(C_{cofferdams} + C_{piping} + C_{painting} + C_{occupied\ spaces}) \tag{5.19}$$

Constraint

Only one constraint is set, and that is the target amount of volume of methanol that needs to be placed by the model, Equation 5.20. This is based on the amount of fuel required for operating on MGO, multiplied by 2.19 to account for the difference in volumetric energy density. The volumes of the spaces where cofferdams are placed must be reduced by the plate area of the cofferdam times the width of the cofferdam ($W_{\text{cofferdam}}$).

$$\text{Volume Constraint:} \sum(\overline{V}_2 - W_{\text{cofferdam}} \cdot \big((\overline{X}_2 - \overline{X}_1) \cdot [adj_{area}] + \overline{adj}_{air}\big) \cdot \overline{X}_1) \geq target\ volume \tag{5.20}$$

Stability Check

Finally, a stability check is needed to guarantee the vessel's safety. Because of the storage conditions as mentioned in section 3.1, it is expected that the model will use spaces in the double bottom and side shell first. When only placing cofferdams under the original VCG of the lightship no stability issues can be expected. Therefore, it has been chosen to only perform a stability check after the algorithm has finished optimizing. If in future cases stability becomes a problem, a stability constraint can be added to the constraints used by the algorithm. The following stability check is performed, by means of Equation 5.21.

$$GM_T = KB + BM_T - KG > 0 \tag{5.21}$$

Now the amount of added steel weight is known, the new draught can be calculated. This can be done by determining the rising of displacement per cm immersion (TPI). This value can be calculated by means of Equation 5.22, in which the waterline area is multiplied by 1[cm] and the density of seawater. Consequently, the new draught can be calculated by means of Equation 5.23.

$$TPI = A_{WL} \cdot 0.01 \cdot \rho_{sw} \tag{5.22}$$

The waterline area is calculated by dividing the ship into three parts: aft ship, midship and foreship. The areas at the aft and foreship are calculated by integrating the boundary at $z = T$ over the corresponding x-domain. The waterline area of the parallel midship is calculated by multiplying the remaining x-domain with the beam.

$$T_{\text{new}} = T + \frac{\sum_{i=1}^{N} m_{\text{cofferdam},i}}{TPI} \tag{5.23}$$

Consequently, the parameters that required to compute Equation 5.21 need to be calculated. The distance between the keel and the centre of buoyancy is calculated by means of Equation 5.24. It is assumed that changes in draught are small, and therefore, C_B can be assumed to be equal to the previous draught.

$$KB = \frac{0.5 \cdot T_{\text{new}}}{{C_B}^{1/3}} \tag{5.24}$$

Equation 5.25 is used to calculate the distance between the centre of buoyancy and the metacentric height. To do so, the moment of inertia of the waterplane area is divided by the volumetric displacement. A similar approach is chosen to the one used in Equation 5.22, the ship is divided into three parts, the aft ship, a parallel midship, and the fore ship. The moment of inertia of the moonpool is subtracted from the total moment of inertia.

$$BM_T = \frac{I_{xx}}{\nabla} = \frac{I_{xx,\text{ aft ship}} + I_{xx,\text{ midship}} + I_{xx,\text{ foreship}} - I_{xx,\text{ moonpool}}}{L_{wl} \cdot B \cdot T_{\text{new}} \cdot C_B} \tag{5.25}$$

Lastly, the new vertical centre of gravity needs to be calculated. This is done by means of Equation 5.26. In this equation, $VCG_{\text{lightship}}$ is the vertical centre of gravity of the lightship and $m_{\text{lightship}}$ is the weight of the lightship. Furthermore, the weight of each cofferdam is multiplied by the VCG of that cofferdam, for all cofferdams $i = 1...N$.

$$KG = \frac{VCG_{\text{lightship}} \cdot m_{\text{lightship}} + \sum_{i=1}^{N} VCG_{\text{cofferdam},i} \cdot m_{\text{cofferdam},i}}{m_{\text{lightship}} + m_{\text{cofferdams}}} \tag{5.26}$$

5.2 Ship Model Verification

To check whether the model works the way it is intended to work, verification needs to be performed. This is done by using the input parameters of Sapura Onix, construction number 730, in the model and checking whether the obtained output corresponds to the data available from Sapura Onix as built. Verification is done based on two aspects, first, the verification of the generated spaces including their centres of gravity (section 5.2.1). And second, the stability values obtained from the model will be compared to the ones available from Sapura Onix (section 5.2.2).

5.2.1 Volumes & Centres of Gravity

Verification of the generated volumes by the model is done by means of comparing the generated spaces with the spaces from Sapura Onix. Most relevant are spaces inside the double bottom because it is expected that these spaces will be selected by the model for methanol storage. Moreover, these spaces are in the most curved part of the ship, thus correction of the box volumes may differ the most from the actual values for these spaces.

Figure 5.5 and Figure 5.6 show the layout of the double bottom of Sapura Onix and the model, respectively. An enlarged version of both figures can be found in Appendix D. The volumes in both figures are numbered, Table D.1 in Appendix D shows which volumes of the model correspond to the numbers of the spaces of Sapura Onix. It must be noted that differences are present between the modelled volumes and the spaces of Sapura Onix. For the shown figures there are three differences. In the first place shapes that intersect with the hull shape look rectangular-shaped, while the volumes are corrected for vessel shape, for example, volumes 4 and 8 in Figure 5.6. Secondly, due to the difference in height of the double bottom as well as the change in width of the double shell, volumes 11 and 16 in Figure 5.6 seem to be two separate spaces, while this corresponds to one volume, volume 22, in Figure 5.5. The same applies to all other volumes around the same frame in the double bottom, for a complete overview, see Table D.1 in Appendix D. Lastly, the moonpool is modelled as one space, whilst for the Sapura Onix some voids, ducts and tanks are located around the moonpool.

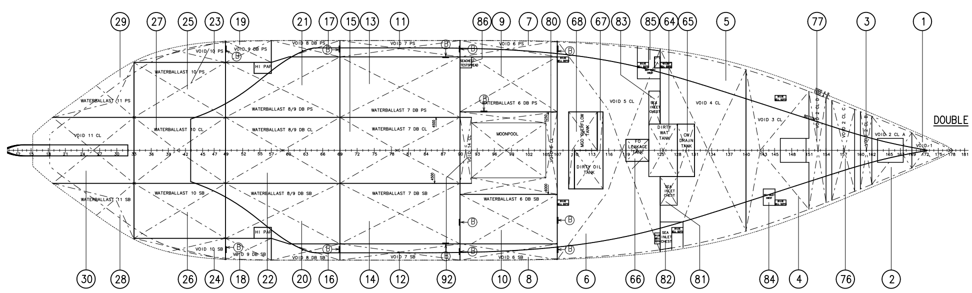


Figure 5.5: Overview of the double bottom of Sapura Onix at z=0.0[m]

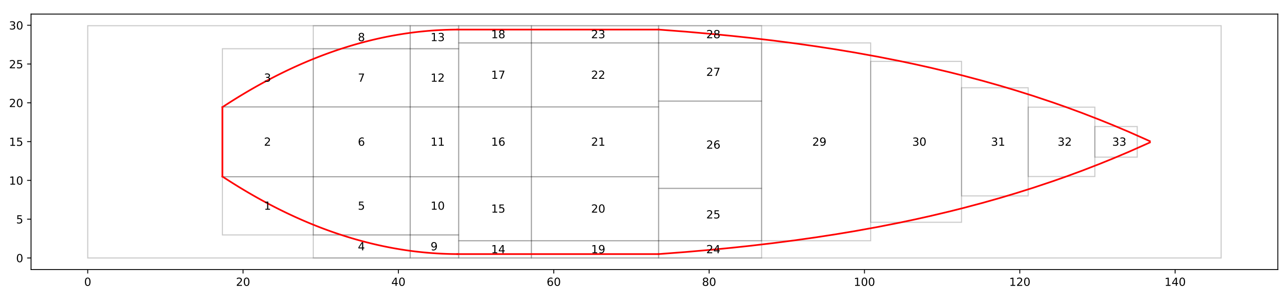


Figure 5.6: Overview of the double bottom of ship model output at z=0.0[m]

Table 5.7, on the next page, shows the verification of the volumes including their COGs of the spaces modelled inside the double bottom. It can be concluded that spaces around the parallel mid-ship, frame 49-107, are correctly modelled, as only small deviations are present. In the fore ship volumes are slightly underestimated, which may be due to the polynomial chosen as a boundary. Between frames 162 and 179, a huge underestimation is present because these spaces run to an upper deck. However, because this volume is relatively small, and located forward of the crash bulkhead this space cannot be used as a methanol tank. At the aft ship volumes are corrected significantly, because of the curved hull shape at that location. However, the deviation in volume between the model's volumes and the volumes of the spaces of Sapura Onix is acceptable.

Subsequently, verification of the centres of gravity is performed. It can be concluded that the Longitudinal Centres of Gravity (LCGs) of the model reasonably match the LCGs of Sapura Onix for most x-locations. Only between frames 15-33, a larger deviation occurred because the LCGs are not corrected for the hull shape boundary. Regarding the Transverse Centres of Gravity (TCGs) no error is present. Lastly, the Vertical Centres of Gravity (VCGs) are verified. The correction of the VCG is done rather crudely, which can be seen by the deviation here. Although the relative errors are significant, the absolute errors are limited. Therefore, it has been chosen not to look for another method for VCG correction, which could possibly result in smaller errors.

Table 5.7: Verification of the volumes and COGs of the spaces generated by the model which are located in the double bottom. Verification is done for the sum of spaces between certain frames, as shown in the leftmost column. Volumes in the

	Volumes $[m^3]$			**LCG** $[m]$			**TCG** $[m]$			**VCG** $[m]$		
Frame	730	Model	Err.	730	Model	Err.	730	Model	Err.	730	Model	Err.
15-33	1007.8	1072.8	6%	15.36	14.49	-6%	0.00	0.00	0%	3.53	3.33	-6%
33-49	598.9	583.8	-3%	29.46	29.28	-1%	0.00	0.00	0%	1.22	1.02	-16%
49-69	750.5	767.4	2%	42.93	42.83	0%	0.00	0.00	0%	0.92	0.88	-4%
69-90	713.5	720.8	1%	59.31	59.31	0%	0.00	0.00	0%	0.76	0.75	-1%
90-107	556.1	554.4	0%	74.87	74.13	-1%	0.00	0.00	0%	0.77	0.77	0%
107-125	564.2	525.7	-7%	87.94	87.78	0%	0.00	0.00	0%	0.76	0.90	18%
125-140	389.1	360.2	-7%	100.74	100.65	0%	0.00	0.00	0%	0.78	0.90	15%
140-151	236.5	217.1	-8%	111.03	110.79	0%	0.00	0.00	0%	1.06	0.90	-15%
151-162	120.5	118.9	-1%	118.51	119.37	1%	0.00	0.00	0%	1.19	0.90	-24%
162-179	220.2	188.1	-15%	128.43	130.02	1%	0.00	0.00	0%	4.18	3.94	-6%

5.2.2 Stability

Verification of the stability is done based on several aspects. First, the displacements at a range of draughts are compared to the value from Sapura Onix (730). Secondly, the amount of tonne per centimetre immersion (TPI) is verified. Subsequently, stability values BM and KM of the model are verified using the values of Sapura Onix provided by Royal IHC.

The first thing to notice in Table 5.8 is the deviation of the displacement. The cause for this is the C_B value used for calculating the displaced volume, which is not changed over the draught. The C_B value used for this calculation applies for $T = 8.3[m]$ but should get smaller for smaller draughts.

The model's values for TPI, tonne per centimetre immersion, do not change over the draught because the hull shape is defined at $z = 6.0[m]$ and $z = 9.5[m]$. As the model takes the lowest boundary, in this case at $z = 6.0[m]$, values will deviate more for larger draughts. This will result in a greater increase in draught when loading the vessel in the model than is actually the case as would be for Sapura Onix.

From the table can be concluded that Vertical Centres of Buoyancy (VCB), also known as KB values, are very accurate. However, the KM values deviate quite a bit. The only cause for this can be a deviation in BM values. However, BM values for the example ship are not available. The BM values are calculated according to Equation 5.25, in which the displaced volume is used as well as the moment of inertia of the waterplane area (I_{xx}). In the same line of reasoning as for TPI, it is expected that I_{xx} is underestimated for draughts larger than $T = 6.0[m]$. As the moment of inertia is calculated by the width at the waterline level to the power of 3, this error can get significant. In this case, the I_{xx} is divided by the displacement, resulting in a deviation that is acceptable. Moreover, KM are underestimated resulting in an early warning for a user of a model when stability becomes critical, as some reserve stability is available.

Table 5.8: Verification of the model's displacement, tonne per centimetre immersion, Vertical Centre of Buoyancy (VCB), and KM.

Draught from base	**Displacement** $[t]$ $\rho = 1.025$ $[t/m3]$			**TPI** $[t/cm]$			**VCB** $[m]$			**KM** $[m]$ transv.		
	730	Model	Err.	730	Model	Err.	730	Model	Err.	730	Model	Err.
6.50	20201	21045	4%	37.01	37.00	0%	3.50	3.53	1%	16.06	15.85	-1%
6.60	20572	21369	4%	37.12	37.00	0%	3.56	3.58	1%	15.95	15.71	-1%
6.70	20944	21693	4%	37.24	37.00	-1%	3.61	3.64	1%	15.84	15.59	-2%
6.80	21316	22016	3%	37.33	37.00	-1%	3.67	3.69	1%	15.74	15.46	-2%
6.90	21690	22340	3%	37.41	37.00	-1%	3.72	3.74	0%	15.64	15.34	-2%
7.00	22065	22664	3%	37.51	37.00	-1%	3.78	3.80	1%	15.55	15.24	-2%
7.10	22440	22988	2%	37.61	37.00	-2%	3.83	3.85	0%	15.46	15.13	-2%
7.20	22817	23312	2%	37.69	37.00	-2%	3.89	3.91	1%	15.37	15.03	-2%
7.30	23194	23635	2%	37.77	37.00	-2%	3.94	3.96	0%	15.28	14.93	-2%
7.40	23572	23959	2%	37.85	37.00	-2%	4.00	4.02	1%	15.20	14.84	-2%
7.50	23951	24283	1%	37.93	37.00	-2%	4.05	4.07	0%	15.12	14.74	-3%
7.60	24330	24607	1%	38.00	37.00	-3%	4.11	4.12	0%	15.05	14.65	-3%
7.70	24711	24930	1%	38.06	37.00	-3%	4.16	4.18	1%	14.97	14.58	-3%
7.80	25092	25254	1%	38.13	37.00	-3%	4.21	4.23	0%	14.90	14.49	-3%
7.90	25473	25578	0%	38.19	37.00	-3%	4.27	4.29	1%	14.83	14.42	-3%
8.00	25855	25902	0%	38.25	37.00	-3%	4.32	4.34	0%	14.76	14.35	-3%
8.10	26238	26226	0%	38.31	37.00	-3%	4.38	4.40	1%	14.70	14.28	-3%
8.20	26621	26549	0%	38.37	37.00	-4%	4.43	4.45	0%	14.63	14.21	-3%
8.30	27005	26873	0%	38.42	37.00	-4%	4.49	4.50	0%	14.57	14.15	-3%
8.40	27390	27197	-1%	38.47	37.00	-4%	4.54	4.56	0%	14.51	14.09	-3%
8.50	27775	27521	-1%	38.53	37.00	-4%	4.59	4.61	0%	14.45	14.03	-3%

Now verification of the ship model is done, it can be used to generate the required output for the option model. This output will be discussed in chapter 6. However, to be able to use this output, more detailed information about the option model is required first. That is why the next couple of sections will discuss the option model in more detail.

5.3 Detailed Option Model

Chapter 4 discussed the methodology and how the methods selected from the literature will be applied to the Design-for-Conversion to methanol problem. Section 5.1 discussed how the Design-for-Changeability principles are used in the ship model, after which verification of the ship model is performed. Subsequently, according to the set methodology, uncertainty and decision-making must be modelled by means of a Real Options decision tree. This is done in an option model.

The aim of this section is to provide more information about the option model's input and its black box. From the ship model, the amount of added steel, the pipe lengths and, the tank weights are outputted, which are identified as the main cost drivers. To assess whether uncertainty impacts the decision to prepare for methanol or not various uncertainties, as discussed in section 3.5, need to be modelled in the option model. An overview of the option model is shown in Figure 5.7. The option model should generate scenarios consisting of the decision to incorporate a certain level of DFC as well as uncertainties. Subsequently, the expected value of options must be calculated to determine their value under uncertainty. Lastly, decision-making must be done, in order to select the DFC level which is expected to result in the lowest life cycle costs.

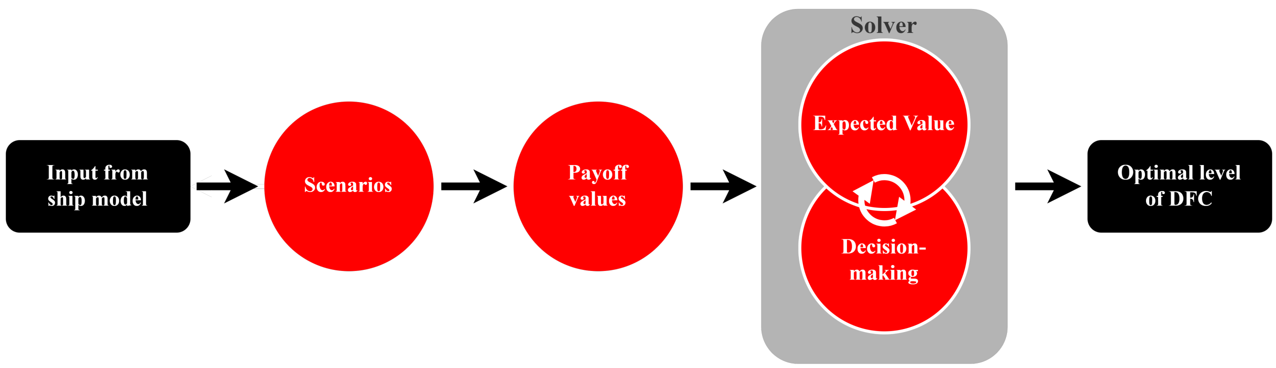


Figure 5.7: An overview of the methodology which will be used to determine the financial impact of Design-for-Conversion to methanol under uncertainty. In the option model a Real Options decision Tree is used together with a NPV calculation. This methodology is set up to find the optimal level of Design-for-Changeability that should be added to a design.

Firstly, the generation of the scenarios will be discussed in more detail in section 5.3.1 Subsequently, the calculation of the payoff values will be discussed in section 5.3.2. Moreover, the decision tree needs to be solved, which will be discussed in further detail in section 5.3.3. Lastly, verification of the option model will be discussed in section 5.4 using an example decision tree from the literature.

5.3.1 Generate Scenarios

The first step when modelling a Real Options Decision Tree is to construct the Tree by means of all possible scenarios. The scenarios generated by the option model should at least include the initial decision on which DFC level should be chosen and a second decision on whether the ship will be converted to methanol or not. In addition, the model should know which decision moments and uncertainties need to be modelled in the rest of the decision tree. For this purpose, information like the information as shown in Table 5.9 on the next page, must be provided to the model. In this case, three moments in time are modelled, moments $1 - 3$, of which the first two are decisions (1) and the last one is an uncertainty (0). For each moment, either two or three options can be provided: $[Opt1, Opt2, Opt3]$. Moreover, for uncertainty moments, a probability per option must be given to the model, $[Prob1, Prob2, Prob3]$. Additionally, information to skip a certain option can be given. In this case, if a ship is converted to methanol during decision moment 2, it does not matter if a CO_2 ban is introduced in the next moment, allowing that option to be skipped in the scenarios that contain the option CH_3OH.

Table 5.9: Example of model input. First, a decision must be made on the level of changeability to incorporate in design, $DFC0$, $DFC1$ or $DFC2$. Consequently, time passes and after a certain period of time, it must be decided whether to convert or not: CH_3OH or MDO. Lastly, uncertainty is present, whether or not a CO_2 ban is introduced, 0.75 probability that a CO_2 ban will be introduced, and a 0.25 probability that no ban will be introduced. However, because the probability of occurrence is unknown, the probability will be varied between 0 and 1.

Moment	Dec/ Unc	Name	Nr Opt	Opt1	Opt2	Opt3	Prob1	Prob2	Prob3
1	1	DFC Level	3	DFC0	DFC1	DFC2			
2	1	Convert	2	CH_3OH	MDO				
3	0	CO_2 Ban	2	Ban	No Ban		0.75	0.25	

Skip1	Skip2	Skip3
3		

Now that the required input is known, the model can generate the scenarios, as shown in Table 5.10. The model runs through the list of moments and puts the options of the first decision moment into a data frame. Subsequently, the next moment, which can be either a decision or uncertainty, is evaluated. The scenarios generated till now are duplicated or triplicated depending on the number of options that must be added in the new decision moment. The existing scenarios are duplicated if two options need to be added, and the scenarios are triplicated if three options need to be added.

Table 5.10: Example of how the scenarios are generated by the model. The first set of options is added to a data frame. Subsequently, the 2 options of 'decision moment' 2 need to be added. This is done by first duplicating the original data frame and subsequently adding the options, CH_3OH and MDO, to the scenarios.

Scenario	Options	Scenario	Options	Scenario	Options
1	[DFC0]	1	[DFC0]	1	[DFC0, CH_3OH]
2	[DFC1]	2	[DFC1]	2	[DFC1, CH_3OH]
3	[DFC2]	3	[DFC2]	3	[DFC2, CH_3OH]
		4	[DFC0]	4	[DFC0, MDO]
		5	[DFC1]	5	[DFC1, MDO]
		6	[DFC2]	6	[DFC2, MDO]

End Option and Skip Option

An end option is defined as an option after which no other options must be appended. An example of such an option is "sell", after which it does not make sense to choose whether to convert your ship to methanol or not, because it is already sold. If the last option of a scenario is in the list of end options, no new option will be added, and the scenario will remain unchanged. A list of ”End Options” must be provided as input to the model.

In addition to an end option, some options should only be skipped if a particular option precedes the option to be skipped. In the example input of Table 5.9, a CO_2 ban does not affect the scenarios in which a ship is already converted to methanol. In this situation, the option model is able to skip this option for particular scenarios containing the option CH_3OH.

Remove Duplicate Scenarios

Because of the ’skip option’ and ’end option’ functionalities in combination with the method used to generate the scenarios a lot of twin scenarios are generated. To drop these scenarios, the options in all scenarios are compared, and if these are the same, one of the scenarios is removed from the data frame.

5.3.2 Payoff Values

Combining all options results in scenarios, as discussed in the previous section. Each scenario comes with a payoff value, as shown in Figure 4.3. The payoff value is defined as the sum of all costs and earnings of a scenario. If no uncertainty was involved, a decision-maker would choose the scenario with the highest payoff value. In this section, the different aspects that can be incorporated into the payoff value are discussed.

Cost of changeability and cost of changes

First of all, the costs of changeability should be added if a certain DFC level is chosen in a scenario. Moreover, the cost of changes should be added if there is chosen to execute a conversion in a certain scenario. For the example in Table 5.11, a ship is prepared with $DFC1$, which costs an additional 1.4 million euros during new building. When a ship is converted an additional investment needs to be done of for example 6.1 million euros, resulting in a payoff value of -7.5M euros. For calculation of the actual costs related to the cost of changeability as well as the cost of changes the following parameters from the ship model are required: added steel weight, added pipe length, and tank weight.

Table 5.11: Example of a payoff value for two scenarios, one with $DFC0$ and one with $DFC1$. The costs for no design preparations ($DFC0$) are 0.0M, and the cost of changeability for $DFC1$ is 1.4M. If a ship without design preparations is converted it will cost 10.7M, if a ship is prepared it will cost only 6.1M. The payoff value is the sum of all costs and revenues in a scenario, -10.7M if a ship is converted without design preparations and -7.5M if a ship is prepared with the $DFC1$ level. For this example, fictitious values are used.

Level of DFC	**Costs of change-ability [€]**	**Cost of changes [€]**	**Payoff value [€]**
0	0.0M	-10.7M	-10.7M
1	-1.4M	-6.1M	-7.5M

Profit

To be able to determine whether a conversion should be executed or not, the future profits of a vessel should be calculated. Moreover, a conversion to methanol may impact the ship's annual profits. Therefore, the ship's profit must be known, which can be calculated by Equation 5.27. Subsequently, the differences in profit between a ship operated on MDO and methanol need to be identified.

$$profit = revenues - costs \tag{5.27}$$

The annual revenues can be calculated by multiplying the number of operational days times the day rate of such a vessel, Equation 5.28. Based on knowledge within Royal IHC the day rate of Sapura Onix is set at approximately 205000 USD per day.

$$revenues = day\ rate[€/day] \cdot up\ time[days] \tag{5.28}$$

The number of operational days per year depends on whether a ship needs to be docked in that year. In a normal year, it is expected that a ship can operate 360 days per year (Aalbers, 2000). If docking needs to be done, which is required in years $[3, 5, 8, 10, 13, 15, 18, 20, 23, 25]$ according to Aalbers, the amount of operational days is only 355 days. Moreover, if a conversion to methanol is executed, the number of operational days is further reduced. In that case, the number of operational days should be further decreased with the amount of time needed for the conversion.

In addition to the revenues, the costs need to be calculated if one wants to know the total profit. These costs, as shown in Equation 5.29, consist of capital expenditures (CAPEX), operational expenditures (OPEX), and voyage expenditures (VOYEX). The assumption had been made, that only VOYEX change when a ship is converted to methanol.

$$costs = CAPEX + OPEX + VOYEX \tag{5.29}$$

VOYEX

The voyage expenditure (VOYEX), which are the costs involved with each trip, must be calculated first. In the context of this research, it is expected that only differences in fuel costs (C_{fuel}) can be expected when switching to methanol. However, as explained in section 3.5 a carbon pricing measure may be introduced, which will increase the VOYEX. Therefore, the VOYEX can be calculated by means of Equation 5.30 in which the carbon costs (C_{carbon}) are zero if no carbon pricing measure is introduced.

$$VOYEX = C_{fuel} + C_{carbon} \tag{5.30}$$

The fuel cost depends on the number of operational days, the consumption per day and the fuel price, as shown in Equation 5.31. It is assumed that the consumption of a ship on methanol is 2.19 times the volume consumed by a ship on MDO, due to the difference in densities this results in 1.94 times more tonnes of fuel consumption per day. Additionally, the assumption is made that the fuel price of methanol is equal to that of MDO (Wärtsilä, 2022). The fuel price is set on 1050[€/t] (Marine Methanol, 2022).

$$C_{fuel} = up\ time[days] \cdot daily\ consumption[t/day] \cdot fuel\ price[€/t] \tag{5.31}$$

The costs for a carbon pricing measure can be calculated by means of Equation 5.32. The formula does not differ much from the equation above, except for the fact that for every tonne of MDO 3.114 tonne of CO_2 is emitted (Krantz, 2016). In addition, one should take the carbon price of 85[€/t] instead of the fuel price (Trading Economics, 2022).

$$C_{carbon} = up\ time[days] \cdot daily\ consumption[t/day] \cdot 3.114[t/t] \cdot carbon\ price[€/t] \tag{5.32}$$

CAPEX

Based on the paper of Aalbers the capital expenditures (CAPEX) of a ship can be determined. These expenditures consist of expenses incurred for a loan, and the yearly depreciation of the vessel Equation 5.33. According to Aalbers a typical division between debt and equity is 60%/40%. The depreciation can be calculated by dividing the new build value minus residual value by the economical lifetime of 25 years of the ship. Furthermore, the amount of interest that needs to be paid can be calculated by multiplying the outstanding debt by the interest rate.

$$CAPEX = depreciation + debt_{interest} \tag{5.33}$$

OPEX

In addition to capital expenditures, operational expenditures are also incurred. As shown in Equation 5.34, these expenditures consist of costs for the crew, insurance, maintenance, docking, management, and some additional costs such as paint, lubrication oil and so on. Except for the crew expenditures, all costs are a function of the new build value. Not every year docking needs to be done, that is why these costs only need to be made in years $[3, 5, 8, 10, 13, 15, 18, 20, 23, 25]$. The crew costs can be calculated by multiplying the amount of crew by a factor of 1.5, and multiplying that amount of crew times the yearly costs of one crew member (Aalbers, 2000).

$$OPEX = C_{crew} + C_{insurance} + C_{maintenance} + C_{docking} + C_{management} + C_{other} \tag{5.34}$$

Return on Equity

To be able to compare the profitability of a ship on MDO with a ship operated on methanol a Return on Equity (RoE) calculation can be used. The RoE can be calculated by dividing the profit, which can be calculated by means of Equation 5.27, by the equity as shown in Equation 5.35. As explained above 40% of the ship's new build value is financed by equity (Aalbers, 2000).

$$RoE = \frac{profit}{equity} \cdot 100\% \tag{5.35}$$

Valuation parameters

To enable the model to calculate the payoff values in different scenarios, multiple input parameters must be provided to the model. First of all the financial parameters used for costs estimation as discussed in section 3.3 must be provided to the model. These will be used to calculate the costs of changeability as well as the costs of changes. Moreover, additional financial information about the ship is needed to be able to calculate the costs for operating a vessel like the Sapura Onix. The required (financial) information of the ship is listed below:

- For depreciation: New build value [€];
- For crew costs: number of crew [-], costs of one crew year [€/year];
- For VOYEX: daily fuel consumption MDO [m^3/day], fuel price [€/t], densities MDO and CH_3OH[t/m^3];
- For calculation of the revenues: day rate [€/day];
- For NPV calculation: discount rate [%].

5.3.3 Solver

Now all scenarios including their payoff value are known, the model should solve the tree, which is done backwards. As shown in Figure 5.8 this is done by running through all scenarios and taking the one with the largest number of options, as this is a scenario in which the last option is located at the end of the branch. The last option is removed from the scenario, and by comparing this item to all other scenarios from which the last item is removed, the other options at the same node are found. Subsequently, the model has to look up in the input whether it is an uncertainty node or a decision node. For the first type, the expected value needs to be calculated, and for the latter decision-making needs to be done. Both possibilities are explained below.

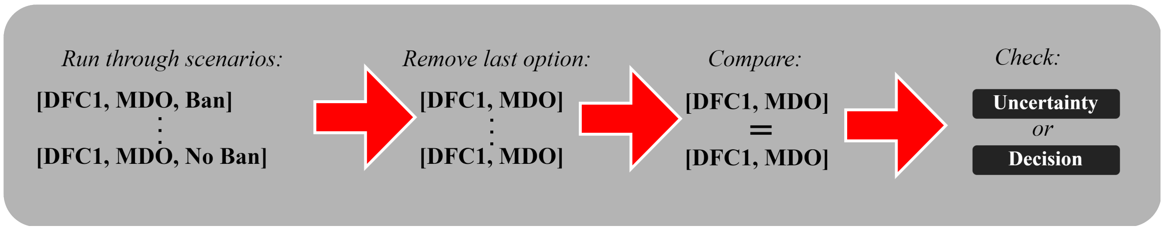


Figure 5.8: The way a decision tree is solved iteratively by the model.

Expected value

Now the scenarios are generated, and the payoff values can be calculated, the model needs to solve the decision tree. In the case of an uncertainty node, the model needs to calculate the value of options under uncertainty. As discussed in chapter 4, this will be done by means of an expected value calculation, Equation 5.36. The expected value can be calculated by multiplying the payoff value of each option by the probability of that option. The model is able to process the expected value of either two or three options. Because of the definition of uncertainty, these probabilities are unknown and will be varied by the option model.

$$exp_{value} = \text{payoff}_{value,\ 1} \cdot \text{prob}_1 + \text{payoff}_{value,\ 2} \cdot \text{prob}_2 \ (+\text{payoff}_{value,\ 3} \cdot \text{prob}_3) \quad (5.36)$$

Figure 5.9 shows how the uncertainty node from the example of Figure 5.8 is solved. The node [DFC1, MDO] has two options: [Ban, No Ban]. Subsequently, the model looks up in the model's input (Table 5.9) whether this is an uncertainty node (0) or a decision node (1). In this case, it is an uncertainty node which can be solved by taking the expected value: $-1.4M \cdot 0.75 + 8.6M \cdot 0.25 = 1.1M$. The probabilities have been looked up in the input table (Table 5.9) but will be varied during the experiments.

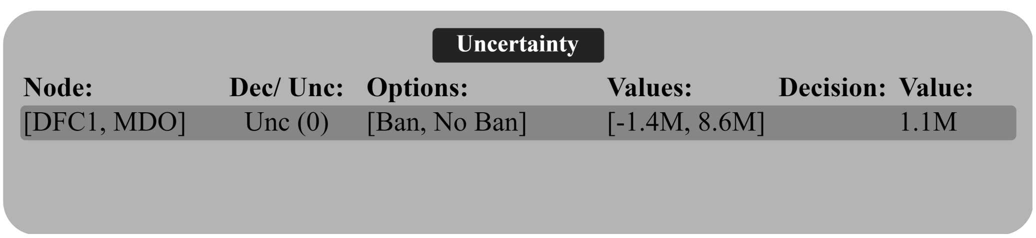


Figure 5.9: The way the model solves an uncertainty node in the decision tree.

Decision-making

The value at uncertainty nodes is calculated by means of the expected value, as discussed above. Once arrived at a decision moment, the subsequent options are evaluated. If the decision needs to be made at the end of the tree, the payoff values of the options are compared, and the option with the highest payoff value is chosen. If the decision in question is more to the root of the tree, and uncertainty is present after the decision, the values from the data frame are evaluated, and the option with the highest value is chosen again. Figure 5.10 shows an example decision of whether to convert to methanol or not [CH_3OH, MDO] if a ship is prepared with the $DFC1$ level. The (expected) values of the uncertainty nodes are calculated beforehand, as shown in Figure 5.9, after which the model makes the decision with the highest value. In the $DFC1$ case, the model decides to convert to methanol (CH_3OH) because the value of this option (2.5M) is higher than the MDO option (1.1M). The time value of money is accounted for by calculating the Net Present Value of future options, Equation 2.1. To make this example more clear, a discount rate of zero is used in this case which does not change the value of the option.

Decision

Node:	Dec/ Unc:	Options:	Values:	Decision:	Value:
[DFC1, MDO]	Unc (0)	[Ban, No Ban]	[-1.4M, 8.6M]		1.1M
[DFC1, CH_3OH]	Unc (0)	[Ban, No Ban]	[2.5.M, 2.5M]		2.5M
[DFC1]	Dec (1)	[CH_3OH, MDO]	[2.5M, 1.1M]	CH_3OH	2.5M

Figure 5.10: The way the model solves a decision node in the decision tree.

Once the length of all scenarios is zero, the initial decision needs to be made. This is done in the same way as discussed above, after which the loop is terminated. In all experiments, this initial decision is the decision to use a certain level of design preparation. Now the option model is set up, the next step is to perform verification to check whether the model does what it is intended to do.

5.4 Option Model Verification

The previous section discussed how the option model works, three modules were built: Generation of scenarios, Expected value, and Decision-making. Verification is required to determine whether the option model works the way it is intended. For this purpose, an example tree is selected, which is shown in Figure 5.11. A more detailed description of the decision tree is given in section 4.2. This is a suitable example tree because it has decisions as well as uncertainties which have an impact on the payoff value of an option. Moreover, it has the 'end option' called "Develop", after which no further decisions need to be taken. First, verification of the generated scenarios will be discussed in section 5.4.1. Subsequently, verification of the decision-making will be discussed in section 5.4.2.

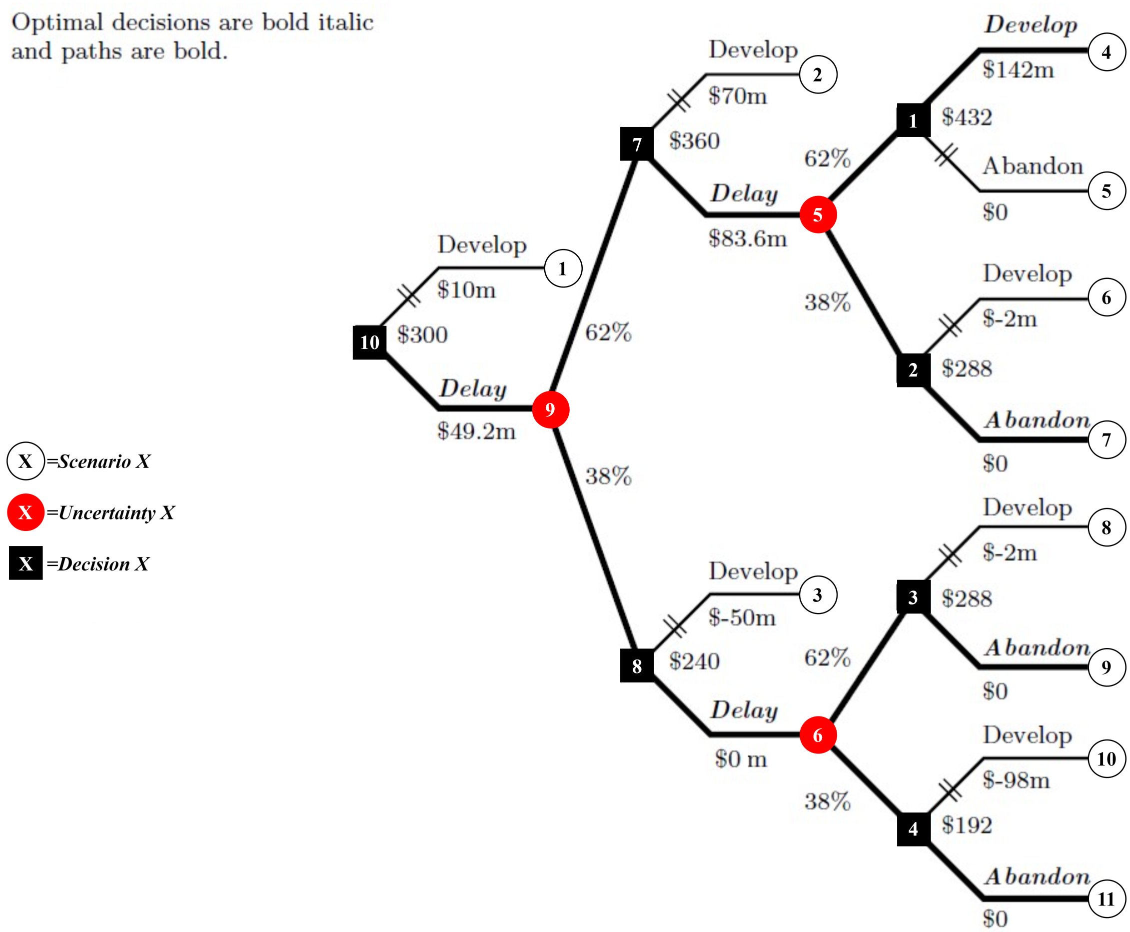


Figure 5.11: The example Decision Tree used for verification of the option model (Sick and Gamba, 2005). The scenarios are marked in white. The decision and uncertainty nodes are marked in black and red, respectively. The example uses a discount rate of 6%.

5.4.1 Scenarios

The first module of the option model is the generation of scenarios. In this module, all consecutive decision moments and uncertainties are combined resulting in all possible scenarios. Table 5.12 on the next page shows the scenarios which are generated by the model, including their payoff value. Eleven scenarios were generated, which is equivalent to the example tree. Moreover, the payoff values calculated per scenarios match the ones from the example tree. For example, the decision is to develop the mine immediately, resulting in a profit of $10M (Scenario 1), or to delay this decision for one year. For clarity the scenarios generated by the model are numbered in the same way as the scenarios from the example tree as shown in red in Figure 5.11.

Table 5.12: The scenarios generated by the option model which correspond to the decision tree of Figure 5.11

Scenario nr.	Options	Payoff
1	['Develop1']	$ 10M
2	['Delay1', 'High1', 'Develop2']	$ 70M
3	['Delay1', 'Low1', 'Develop2']	$ -50M
4	['Delay1', 'High1', 'Delay2', 'High2', 'Develop3']	$ 142M
5	['Delay1', 'High1', 'Delay2', 'High2', 'Abandon']	$ 0M
6	['Delay1', 'High1', 'Delay2', 'Low2', 'Develop3']	$ -2M
7	['Delay1', 'High1', 'Delay2', 'Low2', 'Abandon']	$ 0M
8	['Delay1', 'Low1', 'Delay2', 'High2', 'Develop3']	$ -2M
9	['Delay1', 'Low1', 'Delay2', 'High2', 'Abandon']	$ 0M
10	['Delay1', 'Low1', 'Delay2', 'Low2', 'Develop3']	$ -98M
11	['Delay1', 'Low1', 'Delay2', 'Low2', 'Abandon']	$ 0M

5.4.2 Solver

The tree is solved backwards, starting with the scenarios with the most consecutive option, as shown in Table 5.13. At the first four nodes, decisions needed to be taken between "Develop" or "Abandon". The table shows that the decisions were taken with the highest payoff value. Subsequently, two uncertainty nodes, node 5 and node 6, are evaluated at which the expected value should be calculated. At node 5 the model shows a value of $83.0M whilst the example tree shows a value of $83.6M. This is probably due to a rounding error. This works its way through the expected value at the first uncertainty node, node 9. The correct value is shown in Equation 5.37. In this Net Present Value calculation, a discount rate of 6% is used and the time between the decision nodes is one year as shown in the denominator.

$$\frac{0.62 \cdot \$83.0M + 0.38 \cdot \$0.0M}{1.06^1} = \$48.5M \tag{5.37}$$

Table 5.13: Example decision tree, as shown in Figure 5.11, solved by the model. The table shows expected values if an uncertainty node (0) is evaluated, or the highest value if a decision node (1) is evaluated.

	Node	Unc_Dec	Options	Values
1	['Delay1', 'High1', 'Delay2', 'High2']	1	['Develop3', 'Abandon']	[142M, 0.0M]
2	['Delay1', 'Low1', 'Delay2', 'High2']	1	['Develop3', 'Abandon']	[-2.0M, 0.0M]
3	['Delay1', 'High1', 'Delay2', 'Low2']	1	['Develop3', 'Abandon']	[-2.0M, 0.0M]
4	['Delay1', 'Low1', 'Delay2', 'Low2']	1	['Develop3', 'Abandon']	[-98.0M, 0.0M]
5	['Delay1', 'High1', 'Delay2']	0	['High2', 'Low2']	[142M, 0.0M]
6	['Delay1', 'Low1', 'Delay2']	0	['High2', 'Low2']	[0.0M, 0.0M]
7	['Delay1', 'High1']	1	['Develop2', 'Delay2']	[70.0M, 83.0M]
8	['Delay1', 'Low1']	1	['Develop2', 'Delay2']	[-50.0M, 0.0M]
9	['Delay1']	0	['High1', 'Low1']	[83.0M, 0.0M]
10	[]	1	['Develop1', 'Delay1']	[10.0M, 48.5M]

	Decision	Value
1	Develop3	$ 142M
2	Abandon	$ 0.0M
3	Abandon	$ 0.0M
4	Abandon	$ 0.0M
5		$ 83.0M
6		$ 0.0M
7	Delay2	$ 83.0M
8	Delay2	$ 0.0M
9		$ 48.5M
10	Delay1	$ 48.5M

6

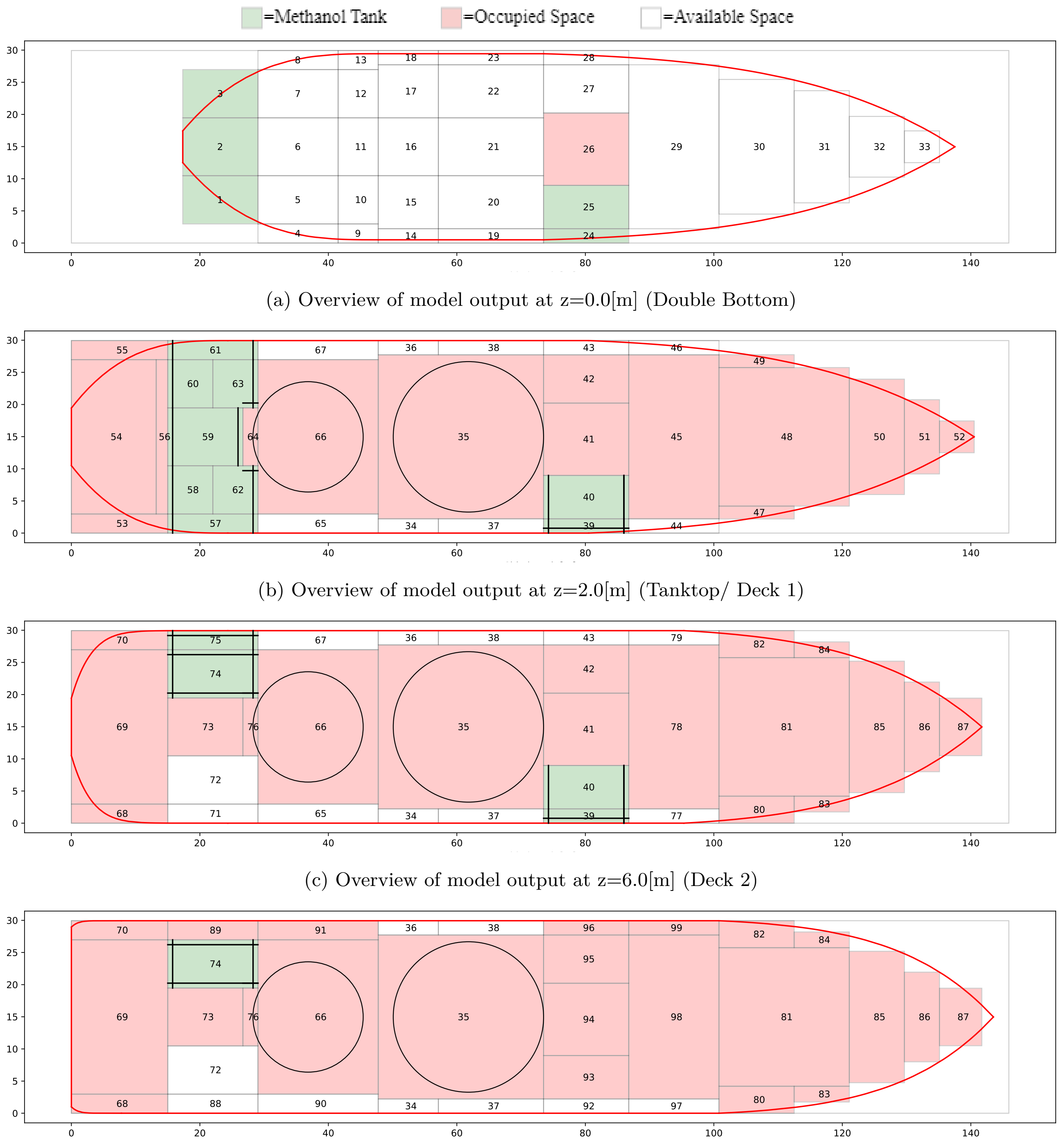
Case Study Results

The previous chapters discussed the theoretical background of various topics concerning Design-for-Conversion for methanol. Design-for-Changeability principles are incorporated in the ship model to assess the technical impact of Design-for-Conversion to methanol, whilst a Real Options decision tree is used in the option model to determine the value of design preparations under uncertainty. In the case study, this methodology is used to investigate if preparation for future conversion to methanol indeed results in lower life cycle costs, due to a reduction in change costs through small investments during new building. In this chapter, the fifth research question will be answered: *What are the additional costs of Design-for-Changeability during new building, and how does the level of DFC impact the cost of changes?* Moreover, the last research question, *What DFC level is most valuable when designing an offshore ship for conversion towards methanol while facing uncertainty?*, needs to be answered. In the case study a complex offshore ship, the Sapura Onix, is used as it is expected that if the methodology is proven for a complex vessel, it is also applicable to simpler vessels.

This chapter will first discuss the technical implications of the Design-for-Changeability principles for Sapura Onix in section 6.1. The locations of methanol tanks will be shown, together with the cost drivers, steel weight, pipe length, and tank weight, which can be used to calculate the costs of changeability as well as the costs of changes. Moreover, both the costs of changeability as well as the cost of changes will be calculated without uncertainty. Subsequently, the case study results of modelling different uncertainties will be discussed in section 6.2. The different uncertainties used in the experiments, can be found in section 3.5. Lastly, the results will be discussed and put into perspective in section 6.3.

6.1 Technical Impact of Design-for-Conversion to Methanol

When a ship is operated on methanol, 2.19 times more volume is needed for fuel to maintain the same autonomy compared to MDO. Moreover, cofferdams need to be placed according to the criteria as shown in Table 3.3, and classification societies require double-walled piping for methanol transport. In cooperation with Royal IHC, these two aspects are identified as having the most impact on the costs when converting a ship to methanol. The pipelay vessel Sapura Onix currently has a bunker capacity of approximately 1220 $[m^3]$, resulting in an autonomy of thirty days. However, when this ship is converted to methanol a fuel capacity of approximately 2670 $[m^3]$ is needed for the same autonomy. The spaces inside Sapura Onix utilised as methanol tanks are shown in green in Figure 6.1. The algorithm has optimized for the lowest conversion costs without design preparations.



(a) Overview of model output at z=0.0[m] (Double Bottom)

(b) Overview of model output at z=2.0[m] (Tanktop/ Deck 1)

(c) Overview of model output at z=6.0[m] (Deck 2)

(d) Overview of model output at z=9.5[m] (Deck 3)

Figure 6.1: Ship Model's output for optimizing the costs for $V_{fuel} = 2670[m^3]$, which 100% autonomy of Sapura Onix on MDO

The red spaces are indicated as spaces that cannot be used for methanol storage because they are already occupied. The green spaces have been designated by the model as methanol tanks, a complete list can be found in section E.1 of Appendix E. The model places most methanol tanks adjacent to at least one other tank, which makes sense because no cofferdam is needed in that case. Different than expected beforehand, the model selects only a few spaces in the double-bottom. This can be explained because the costs of a horizontal cofferdam are large because the amount of adjacent area results in a lot of added steel weight, which is one of the major cost drivers. The used spaces in the double bottom are adjacent to the methanol tanks above, eliminating the need for a cofferdam. Moreover, no cofferdam is placed between the methanol tanks in the double bottom and the other spaces inside the double bottom. This is correct because only voids and water ballast tanks are located inside the double bottom, which do not require a cofferdam. In addition, no cofferdams are placed between the moonpool, spaces 26, 41, and 94, and the adjacent methanol tanks because that is not required by classification bureaus. A cofferdam which attracts attention is the one between spaces 74 and 75 at deck 2, although both spaces contain methanol, a cofferdam is located in between. However, because space 74 is also adjacent to space 89 at deck 3, a cofferdam is required between space 74 and 89. The model only calculated the cofferdam area between spaces 74 and 89, and not between 74 and 75, which is correct, resulting in the right amount of steel weight added, although a cofferdam is plotted. Stability data can be found in Table E.1 on page 98.

Table 6.1: The values for the cost drivers coming from the ship model.

		Autonomy			
		100%	**90%**	**80%**	**70%**
Steel weight	$[t]$	240.3	218.3	198.7	172.4
Pipe length	$[m]$	573.3	563.3	548.3	553.3
Tank weight	$[t]$	765.8	666.9	568.6	568.1

The leftmost column of Table 6.1 shows the costs drivers which were identified in section 3.3. The second column shows the corresponding values of these cost drivers for the layout as shown in Figure 6.1 which is generated for 100% autonomy. To be able to find out the impact of reducing the ship's autonomy to lower values, the ship model has also been run for $[90\%, 80\%, 70\%]$ autonomy. The values for all cost drivers for these runs are also shown in Table 6.1. From the table can be concluded that the amount of added steel weight is reduced significantly when reducing the autonomy. Moreover, a significant decrease in tank weight can be obtained when reducing the autonomy to 90% and 80%. However, for a reduction to 70% autonomy, no additional reduction is obtained. Moreover, only a limited decrease in pipe length is achieved when reducing the ship's autonomy.

Table 6.2 shows the planning for converting the Sapura Onix to methanol, for the different levels of design preparation. The values shown in the table are for the conversion to the layout as shown in Figure 6.1 which corresponds to the autonomy of 100% compared to MDO. For $DFC0$ the amount of days needed for piping can be done simultaneously with the steelwork, resulting in no additional days planned for installation of piping. For the items which are left outside the scope of this research, additional time is added to the planning when needed. Although a ship is prepared for methanol using either $DFC1$ or $DFC2$, additional work needs to be done for instance for installation of pumps and also time for commissioning is needed. It is expected that at least 7 days are needed for installation of other components, which might overlap with other activities such as steelwork or installation of piping. If the amount of days needed for steelwork or piping is less than 7, the additional time is added to the item "*Other*". Additionally, at least one week of commissioning is needed, after all other works has been completed.

Table 6.2: Planning in days which corresponds to the values which drive the planning as shown in Table 6.1 for 100% autonomy. DFC0: No preparations, DFC1: Cofferdams, and DFC2: Cofferdams & Piping.

	DFC0	**DFC1**	**DFC2**
Preparation [days]	4.8	0.6	0.0
Steelwork [days]	47.9	0.0	0.0
Piping [days]	0.0	6.5	0.0
Painting [days]	3.0	3.0	0.0
Other [days]	0.0	0.5	7.0
Commissioning [days]	7.2	7.0	7.0
Total [days]	**62.9**	**17.6**	**14.0**

Now that the values for the cost drivers are known and a conversion planning has been drawn up, the costs can be calculated according to the costs breakdown as shown in section 3.3 and the values provided in Appendix B. Table 6.3 shows an overview of the costs of changeability (NB. costs) and the costs of changes, which consist of the conversion costs (Conv. costs) and the loss of income. These values vary for the different levels of design preparation and are shown for all levels of autonomy. What is noteworthy is that the planning only gets shorter for $DFC0$, resulting in no changes in the loss of income when converting for lower autonomy. Moreover, only the conversion costs of $DFC0$ drop significantly when choosing a lower autonomy, while the other costs do decrease, but not as much as the conversion costs for $DFC0$.

Table 6.3: Based on the results as shown in Table 6.1 and Table 6.2 costs for adding changeability, as well as the costs of changes, can be calculated for all levels of changeability.

			Cost of Changeability	*Cost of Changes*	
Autonomy	**DFC level**	**Planning**	**NB. costs**	**Conv. costs**	**Loss of income**
100%	DFC0	62.9 days	€ -	€ 10,131,684.00	€ 9,956,823.00
	DFC1	17.6 days	€ 1,744,507.00	€ 4,709,495.00	€ 2,166,770.00
	DFC2	14.0 days	€ 2,203,179.00	€ 2,500,000.00	€ 1,547,693.00
90%	DFC0	58.7 days	€ -	€ 9,624,260.00	€ 9,234,566.00
	DFC1	17.6 days	€ 1,583,564.00	€ 4,608,819.00	€ 2,166,770.00
	DFC2	14.0 days	€ 2,034,236.00	€ 2,500,000.00	€ 1,547,693.00
80%	DFC0	51.6 days	€ -	€ 8,905,324.00	€ 8,013,609.00
	DFC1	17.6 days	€ 1,432,668.00	€ 4,501,732.00	€ 2,166,770.00
	DFC2	14.0 days	€ 1,871,340.00	€ 2,500,000.00	€ 1,547,693.00
70%	DFC0	44.9 days	€ -	€ 8,289,764.00	€ 6,861,437.00
	DFC1	17.6 days	€ 1,328,942.00	€ 4,496,920.00	€ 2,166,770.00
	DFC2	14.0 days	€ 1,771,614.00	€ 2,500,000.00	€ 1,547,693.00

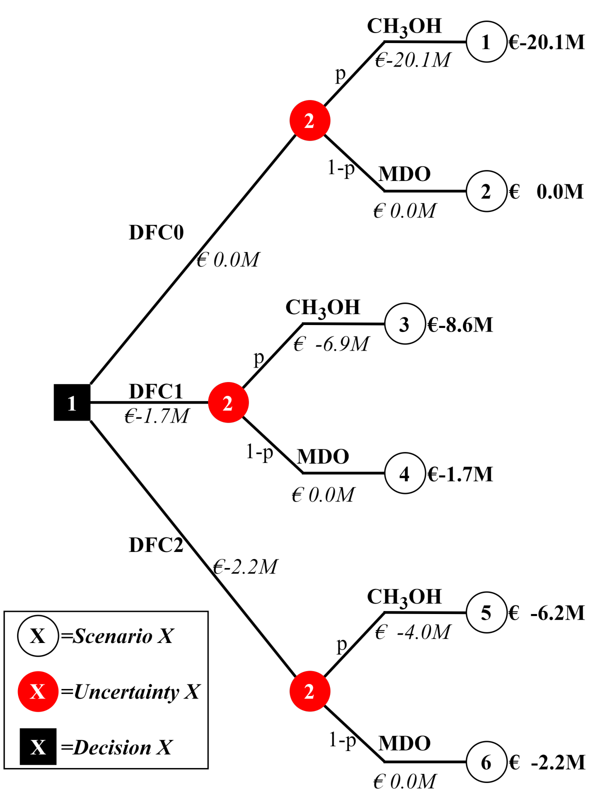
This section aimed to provide insights into the technical impact of Design-for-Conversion to methanol. Spaces inside Sapura Onix are designated as methanol tanks, in such a way that the conversion costs are minimized. The way the cofferdams are placed resulted in values for the three cost drivers: added steel weight, piping length, and tank weight. By means of these values, the conversion planning could be established and the various costs aspects could be calculated for the three levels of design preparation. Now the costs of adding changeability are known, as well as the costs of changes, the next step is to model uncertainties that have impact on the value of these options.

6.2 Modelling Uncertainty

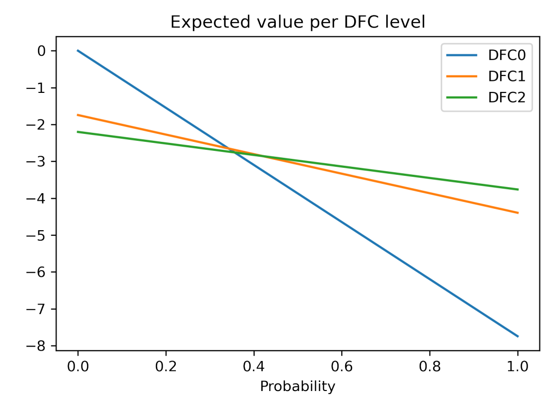
Now the technical impact of Design-for-Conversion to methanol is known, the next step is to model uncertainties that may have an impact on the value of the design preparations. Four different simulations have been run. In the first experiment, section 6.2.1, the decision to convert to methanol in the future or not is modelled as one uncertainty, covering all uncertainties underlying the decision whether to convert or not. Subsequently, the impact of a potential carbon pricing measure is modelled in section 6.2.3 together with a complete ban on CO_2 emitting ships, of which the results will be discussed in section 6.2.4. Furthermore, the impact of reducing the autonomy on the chosen DFC level will be discussed in section 6.2.5. The cash flows per experiment used in the Net Present Value calculation, can be found in Table E.2 on page 100. In addition, the cost of changeability from Table 6.3 are used in all experiments, of which no Net Present Value calculation has been done because these costs are made in year 0.

6.2.1 The choice whether to convert or not as uncertainty

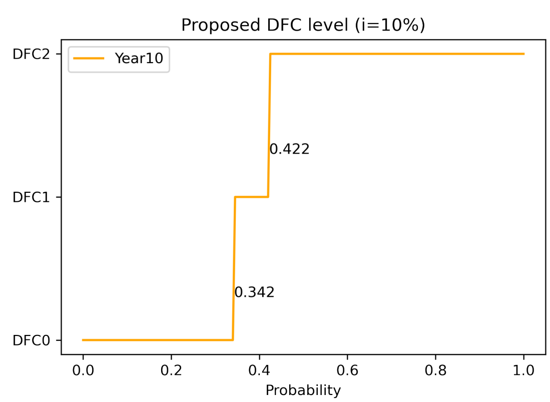
The options that are added to a design will only have value if they are being used. However, whether or not they are used depends on whether a ship is converted to methanol, which is highly uncertain. The most straightforward way to look at the combination of uncertainties that determines whether a ship owner will decide to convert a ship to methanol (CH_3OH) or not (MDO), is to model this decision as uncertainty as a whole, as shown in Figure 6.2. Prior to that, the decision must be taken on which level of Design-for-Changeability, DFC0, DFC1, or DFC2, needs to be incorporated into the design. The probability of occurrence (p) of the option CH_3OH is varied between 0 and 1, the probability of occurrence for the other option, which is keep running on MDO, equals $1 - p$. Figure 6.2 also shows the expected values for the different levels of DFC for the whole range of probabilities and which DFC level should be chosen according to the model, given a certain probability of conversion.



(a) Example decision tree



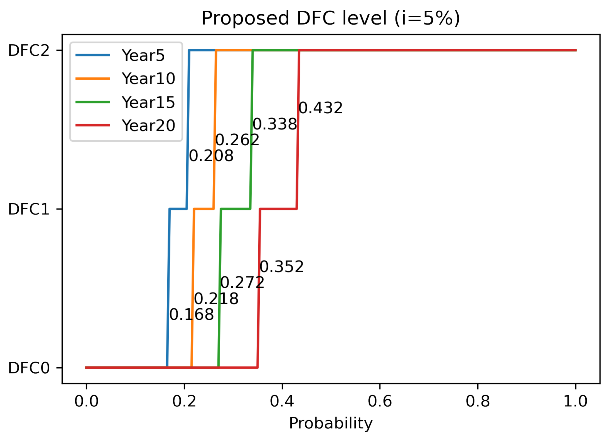
(b) Expected values



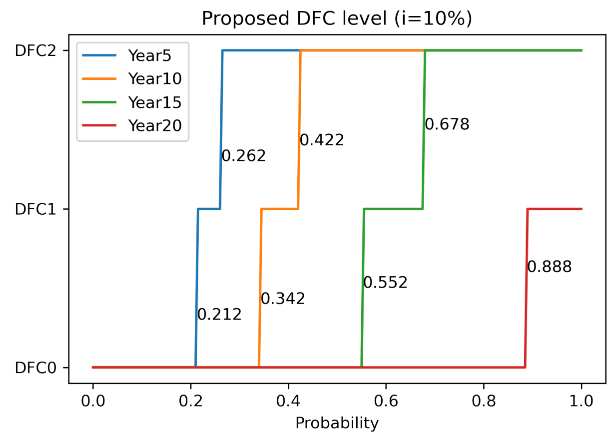
(c) Proposed DFC level for varying p values

Figure 6.2: Real Options Decision Tree as used in the first experiment. First, a decision node is modelled, after which the decision to convert or not is modelled as uncertainty. The used cash flows can be found in Table E.2. For this experiment, a conversion in year 10 is evaluated and a discount rate $i = 10\%$ is used.

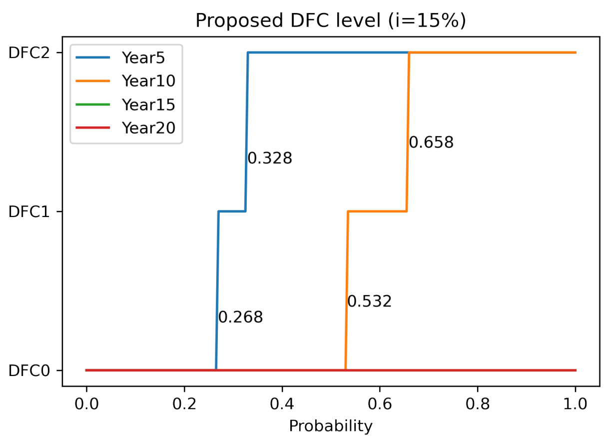
The new building and conversion costs, as well as the loss of income as shown in Table 6.3, are used to generate the results shown in Figure 6.2. The probability of a conversion in the future is varied, the probability for which another DFC level is proposed is annotated in the bottom right graph of Figure 6.2. In the option model, the Net Present Value of future costs is calculated. For this, two parameters have to be provided as input, the execution year of the conversion and the discount rate. To determine the impact of those two parameters, a new set of experiments is done, of which the results are shown in Figure 6.3. For these experiments a conversion at years [5, 10, 15, 20] is modelled, using various discount rates: $i = [5\%, 10\%, 15\%, 20\%]$.



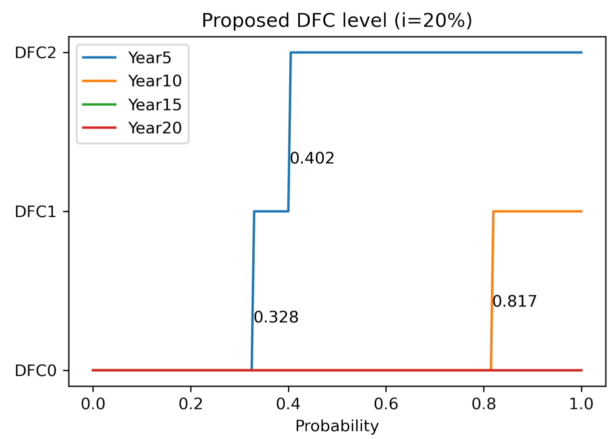
(a) Discount rate $i = 5\%$



(b) Discount rate $i = 10\%$



(c) Discount rate $i = 15\%$



(d) Discount rate $i = 20\%$

Figure 6.3: The impact of the Discount Rate and moment of conversion execution on the proposed DFC level when modelling the decision whether to convert or not as an uncertainty. The used cash flows are the same as in Figure 6.2 and can be found in Table E.2.

Impact of Conversion Execution Moment

From the figures as shown in Figure 6.3 on the previous page, one thing immediately stands out. When the moment of conversion is later in the ship's life cycle, a higher probability of conversion is needed before a design preparation level is proposed. This can be explained by looking at the Net Present Value calculation. In the NPV calculation, as shown in Equation 2.1, the future cash flows are divided by the discount rate to the power t. Thus the impact of costs made later on in the ship's life cycle, such as the costs of conversion, is low because they are divided by a value which exponentially becomes larger with the number of years.

Impact of Discount Rate

In Figure 6.3 the decision for a certain level of design preparation is shown for four different discount rates, $i = [5\%, 10\%, 15\%, 20\%]$. Because this discount rate is taken to the power t and is part of the denominator of the NPV calculation, a higher discount rate results in a significant decrease of the impact of the costs made during the later stages of the ship's life cycle. For investments in fast-developing or uncertain markets, it is often chosen to use a higher discount rate. It can be concluded that design preparation becomes worthless if a ship is converted at year 15 or 20 when using a discount rate of 15% or 20%.

DFC1 Level

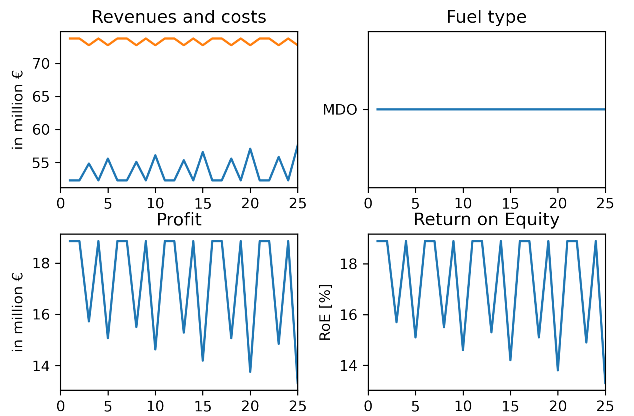
Figure 6.3 shows that only for a small range of probabilities the $DFC1$ level is chosen. Therefore, the additional value of the $DFC1$ level is limited, especially when it is considered that it takes quite some effort to define the $DFC1$ level. However, it can be concluded that the $DFC1$ is chosen more often when the conversion is executed later in the ship's life cycle or when choosing higher discount rates.

A common discount rate used in businesses is somewhere between 5 and 10 per cent. However, for businesses operating in uncertain markets with fast developments a higher discount rate is more appropriate. To be able to compare the following results with a baseline experiment, and to eliminate one variable in the following experiments it was chosen to apply a discount rate of 10 per cent in the remainder of the experiments.

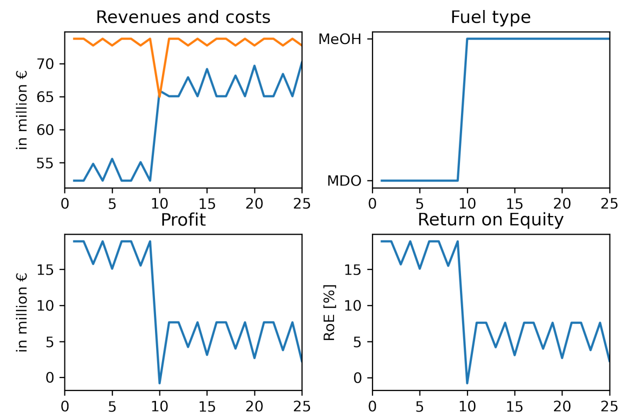
6.2.2 Instigator

As concluded above, the decision whether to prepare a ship for conversion to methanol heavily depends on the probability a ship will be converted to methanol in the future, the used discount rate, and the conversion execution year. However, the probability that a ship is actually converted must be further examined. To get a better understanding of which factors may drive ship owners to convert their ships in the future, more information is needed on the ship's revenue model.

First, the finances for the Sapura Onix without conversion to methanol (Figure 6.4a) are calculated, and subsequently, the ship finances when converting to methanol in year 10 are shown (Figure 6.4b). This was done using the equations from section 5.3.1. The expenditures are shown by the blue line in the top left figure of Figure 6.4a, whilst the yearly revenues of Sapura Onix are indicated by the orange line. In addition, the profit and the Return on Equity (RoE) are calculated, without conversion to methanol.



(a) Financial data for a ship that runs on MDO for the complete lifetime.



(b) Financial data for a ship that is switched to methanol in year 10.

Figure 6.4: Estimated impact of conversion to methanol on the earning potential of the Sapura Onix. It can be concluded that an instigator is needed before ship owners decide to convert their ships. The used cash flows can be found in Table E.2.

Figure 6.4b shows the ship finances for a ship which is converted to methanol in year 10. Until the conversion, there is no difference in revenues and costs, resulting in no difference in profit and RoE. However, when a ship is converted to methanol it costs an additional amount of money and takes quite some time, resulting in a loss in year 10. Moreover, annual costs increase because more fuel is used resulting in a decrease in profit and return on equity after a ship is converted to methanol. From this, it can be concluded that an instigator is needed to give ship owners an incentive to convert their ships to methanol. Potential instigators could be a carbon pricing or a carbon ban as part of regulatory uncertainty. The following two sections discuss these instigators and uncertainty around potential introduction of these measures.

6.2.3 Carbon Pricing

As discussed before, design preparation will only have value if a ship is converted to methanol in the future. The previous section discussed that an instigator is needed, to give ship owners an incentive to convert their vessels to methanol sooner, an example of such an instigator is carbon pricing. To examine the impact of a carbon pricing measure, as part of regulatory uncertainty, on the value of Design-for-Conversion, first, it needs to be examined if a ship is converted if such a measure is introduced by policy-makers. Therefore, additional costs for CO_2need to be taken into account, next to the costs as defined in Table 6.3 and the fuel costs. The list of all used cash flows per experiment can be found in Table E.2. The current price of CO_2permits for emissions of industry inside the European Union is 85 [€/t] (Trading Economics, 2022). According to Krantz 3.114 tonnes of CO_2 are emitted for every tonne of MDO, which can be used to calculate the additional costs of a CO_2-Pricing measure (2016). Moreover, additional costs for fuel are made, because more fuel is used when operating on methanol. According to Wärtsilä it can be assumed that the price of methanol is equal to that of MDO, fuel costs increase by a factor of 2.19 when converting to methanol.

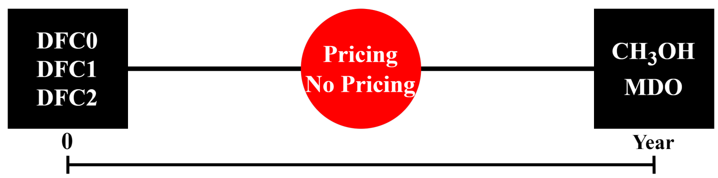
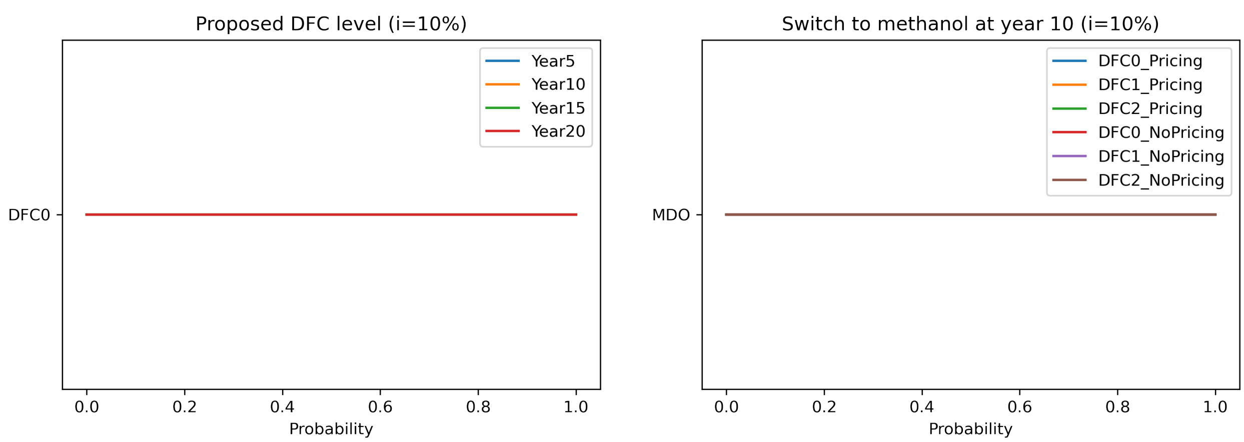


Figure 6.5: Overview of the consecutive decision and uncertainty moments, which are modelled. First, the decision must be made to incorporate $[DFC0.DFC1, DFC2]$ after which the potential introduction of a CO_2-Pricing measure is modelled as uncertainty (circle). Lastly, the decision whether to convert to methanol or not is modelled as a decision (square). Because the amount of time between the initial decision and the moment of conversion must be known for NPV calculation, the time span must be given as input.

To assess the effectiveness of such a CO_2-Pricing measure, the following has been modelled as shown in Figure 6.5. First, the initial decision is which level of design preparation must be chosen. Consequently, an uncertainty node is modelled, whether or not a CO_2-Pricing measure will be introduced. Lastly, a new decision is available where it can be decided whether to convert to methanol or not. The results when varying the probability of introducing such a measure, are shown in Figure 6.6.



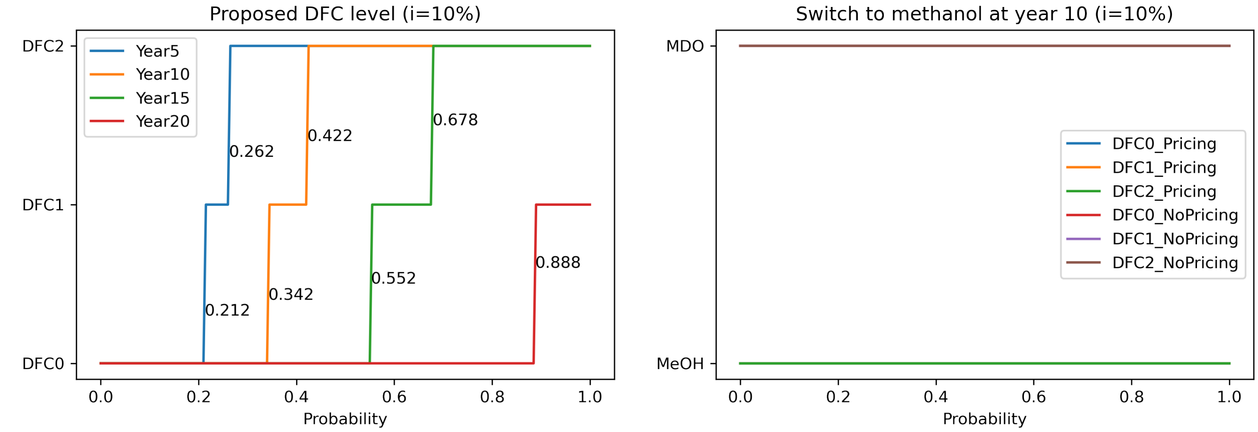
(a) Proposed DFC level by the model.

(b) Decision whether to convert or not.

Figure 6.6: The impact of a CO_2-Pricing measure as instigator, CO_2 price of 85 [euro/t]. It was found that this instigator does not result in ships being converted to methanol, and therefore, the model proposes not to do any design preparations.

It was found that by introducing such a measure no ships will be prepared for methanol, and the $DFC0$ level is proposed for all probabilities, Figure 6.6a. After examining the output of this experiment in more detail, it was found that ships were not being converted to methanol at all, despite the pricing measure Figure 6.6b. When further examining the costs and revenues it was found that the additional costs of a CO_2-Pricing measure are cancelled out by the increase in fuel costs when converting to methanol. Therefore, an increase of the CO_2

price is proposed, which at least compensates for the increase in fuel costs when operating a ship on methanol. The price for CO_2 is set at 420 [euro/t] and a new experiment is performed, of which the results are shown in Figure 6.7.



(a) Proposed DFC level by the model. (b) Decision whether to convert or not.

Figure 6.7: The impact of a CO_2-Pricing measure as instigator, CO_2 price of 420 [euro/t].

It was found that the model proposes to use the DFC levels in a wide range of probabilities, as shown in Figure 6.7a. This is done because if a pricing measure with a CO_2 price of 420 [euro/t] is introduced, ships will be converted to methanol, as shown in Figure 6.7b. However, this decision is not subjected to uncertainty, so the decision does not vary for the different probabilities. For that reason, an additional experiment is performed, as shown in Figure 6.8. In this experiment, the uncertainty and decision to convert or not are reversed.

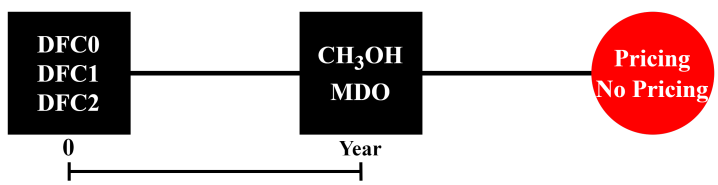
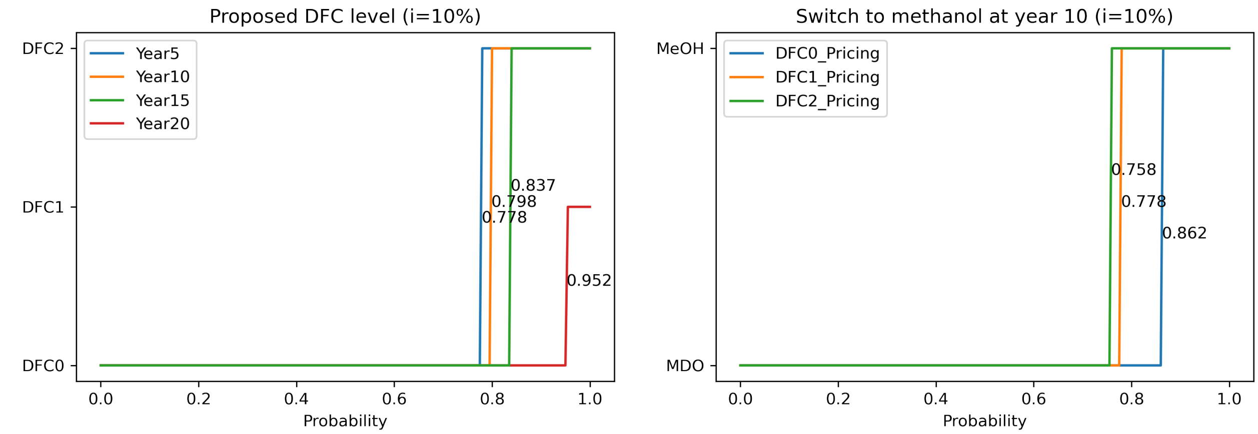


Figure 6.8: Overview of the consecutive decision and uncertainty moments, which are modelled. Compared to the previous experiment the decision whether to convert to methanol or not is taken first, after which an uncertainty node is modelled, whether a CO_2-pricing measure is introduced or not.

The results of this experiment are shown in Figure 6.9 on the next page. In Figure 6.9a it is noticeable that the $DFC1$ level is skipped for nearly every conversion execution year, except for conversion in year 20. This shows once again that the $DFC1$ level has very limited added value. The second aspect that stands out is the fact that the decision whether to convert or not, Figure 6.9b, varies with the probability that a pricing measure is introduced contrary to the previous experiment.



(a) The proposed DFC level. (b) The decision whether to switch to methanol or not.

Figure 6.9: The impact of the probability of a potential CO_2-Pricing measure by policy-makers as part of regulatory uncertainty. The $DFC1$ level is not chosen in this case. Ships with a higher level of design preparation are converted earlier compared to the base level case $DFC0$. The used cash flows can be found in Table E.2.

Fuel and Carbon Pricing

From previous experiments can be concluded that the price that needs to be paid for each tonne of carbon emitted, greatly influences the results. In addition, the fuel price influences the decision to convert or not, and subsequently whether to prepare or not. Therefore, the next experiment is set up in which the same sequence of decision and uncertainty nodes is modelled as shown in Figure 6.8. However, the tree is now successively solved for a number of combinations of carbon and fuel prices. The carbon price is varied between 50 and 500[€/t] and the fuel price is varied between 50 and 1200[€/t]. A step size of 10[€/t] is used.

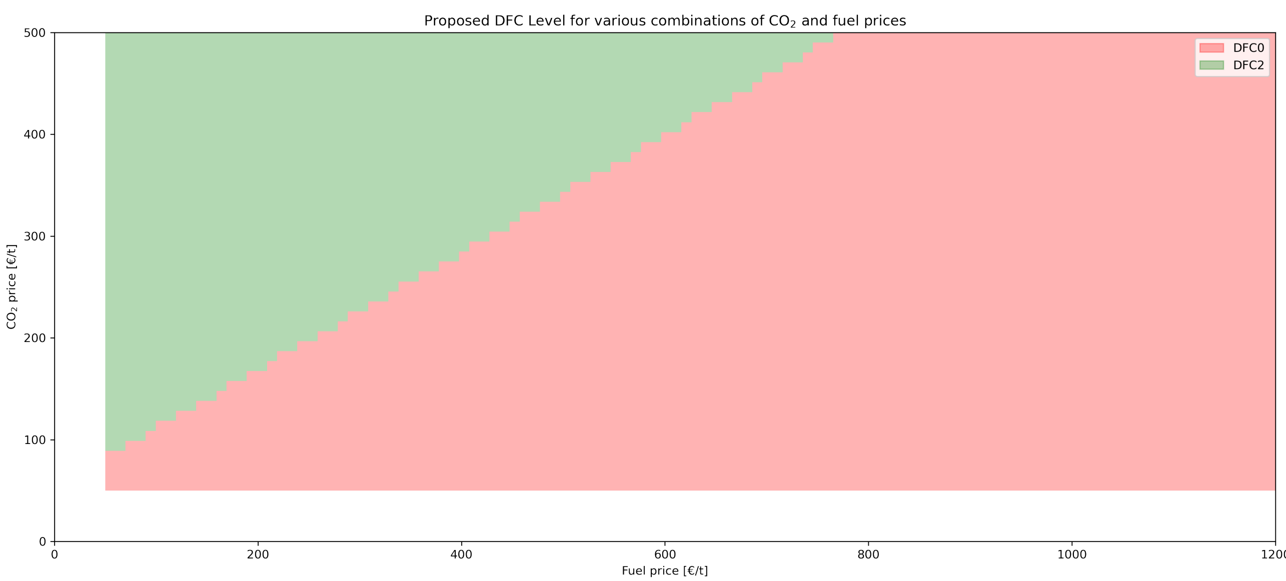


Figure 6.10: Impact of fuel price and CO_2 price on the decision of a ship owner to prepare a ship for future conversion. For this experiment, the probability of whether a carbon pricing measure will be introduced is fixed and set at 0.5. This experiment is also performed with P=0.1 and P=0.9, of which the results can be found in Figure E.1 on page 101.

Figure 6.10 shows the proposed DFC level for the most realistic combinations of fuel and carbon prices. The carbon and fuel price as used in the experiment of Figure 6.9, 420 and 1050[€/t] respectively, results in a ship that is not prepared for methanol, for a probability of 0.5. From this, it can be concluded that those experiments do not deviate from each other. However, Figure 6.10 illustrates the impact of the full range of potential of fuel and carbon prices on the decision of whether to prepare or not. The experiment is repeated for a probability of occurrence for a carbon pricing measure of 0.1 and 0.9, to provide a complete insight into the impact of uncertainty and pricing. Results of these experiments are shown in Figure E.1 on page 101.

Two main conclusions can be drawn from this set of experiments. The first is that the price for CO_2 in a carbon pricing measure has a significant impact on the decision of whether ship owners convert their vessel to methanol or not. And subsequently, whether they decide to prepare for this future conversion to methanol or not. Moreover, the period over which the uncertainty is present has an impact on the decision of whether to prepare for future conversion. From Figure 6.7 can be concluded that if the decision whether to convert or not precedes the uncertainty of whether a pricing measure is introduced or not, ships will be prepared for methanol sooner compared to the experiment as shown in Figure 6.9. This could be explained by the fact that the time span over which the measure is active, is much longer for the first experiment, compared to the second experiment.

6.2.4 Carbon Ban

The previous section discussed a carbon pricing measure as part of regulatory uncertainty. Another measure that may be taken is a ban on carbon emitting ships, which is also part of regulatory uncertainty. To evaluate the impact of such a measure on the preparation of ships for methanol, a new experiment is set up in the way as shown in Figure 6.11. To be able to make a comparison with a carbon pricing measure, the set-up is the same as the experiment as shown in Figure 6.9.

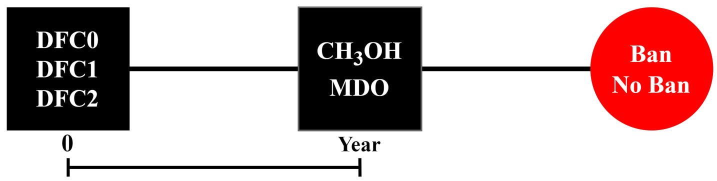
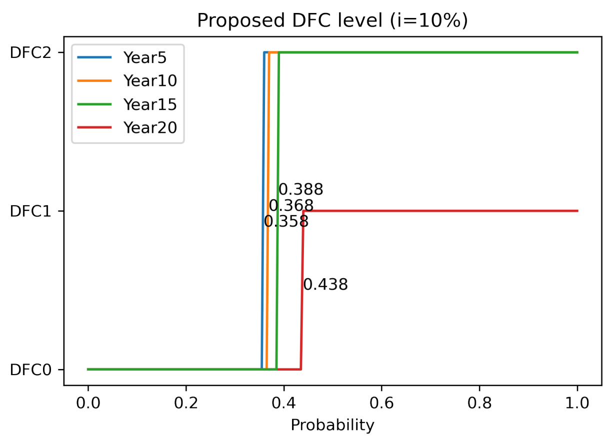
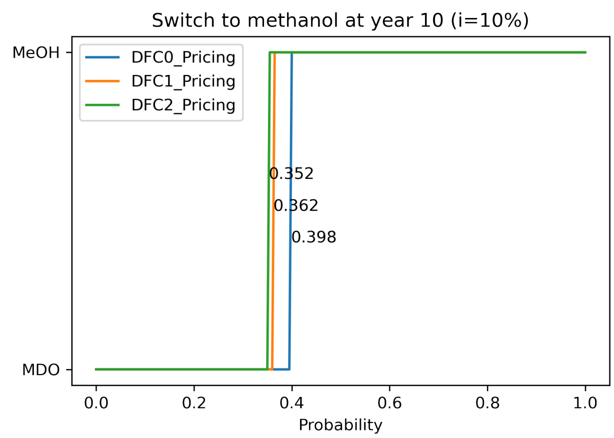


Figure 6.11: Overview of the consecutive decision and uncertainty moments, which are modelled. First, the decision must be made to incorporate $[DFC0, DFC1, DFC2]$ after which the decision to convert to methanol is modelled as a decision node (square). Subsequently, the potential introduction of a CO_2-Ban is modelled as uncertainty (circle). Because the amount of time between the initial decision and the moment of conversion must be known for NPV calculation, the time span must be given as input.

First, the decision must be taken which level of DFC to add into a design. After a varying number of years, varying from five to twenty years, the decision must be taken to convert to methanol or not. And lastly, a potential ban on CO_2 is modelled as uncertainty node. The results of this experiment are shown in Figure 6.12. A sensitivity analysis is done again, to gain insights in the impact of the probability on the decision to prepare or not (Figure 6.12a), and subsequently whether a ship is converted or not (Figure 6.12b).



(a) The proposed DFC level.



(b) The decision whether to switch to methanol or not.

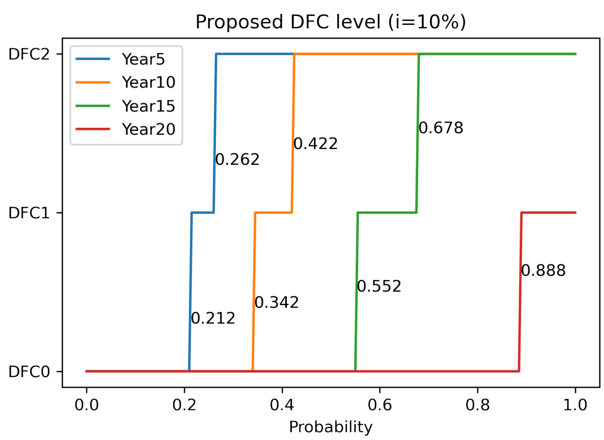
Figure 6.12: The impact of the probability of a potential CO_2-Pricing measure by policy-makers as part of regulatory uncertainty. The $DFC1$ level is not chosen in this case. Ships with a higher level of design preparation are converted earlier compared to the base level case $DFC0$. The used cash flows can be found in Table E.2, when a ships sails on MDO while a carbon ban is introduced it is assumed that the revenues are zero.

Figure 6.12a shows the same trend as the experiment of the carbon pricing measure as shown in Figure 6.9a. The DFC2 level is not choosen for conversions after year 20 and the DFC1 level is skipped for converting before year 15. However, the one thing that stands out is the fact that the probalities for which design preparation is expected to payoff, have shifted left. Lower probabilities of occurrence are needed for a carbon ban, compared to a carbon pricing measure, to prepare ships for methanol. Figure 6.12b follows the same trend.

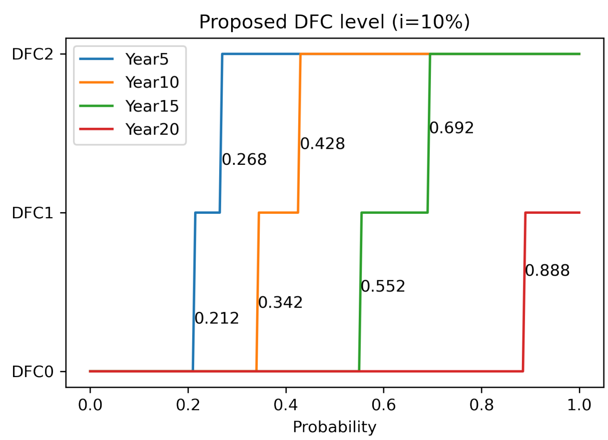
6.2.5 Reduced Autonomy

As part of operational uncertainty autonomy is reduced in the next set of experiments. The same sequence of decisions and uncertainties is modelled as in the experiment as discussed in section 6.2.1. As shown in Table 6.3, the costs of changes decrease if it was chosen to reduce the ship's autonomy. To assess the impact of reducing the autonomy on the proposed DFC level, these costs are used in the option model. The results are shown in Figure 6.13.

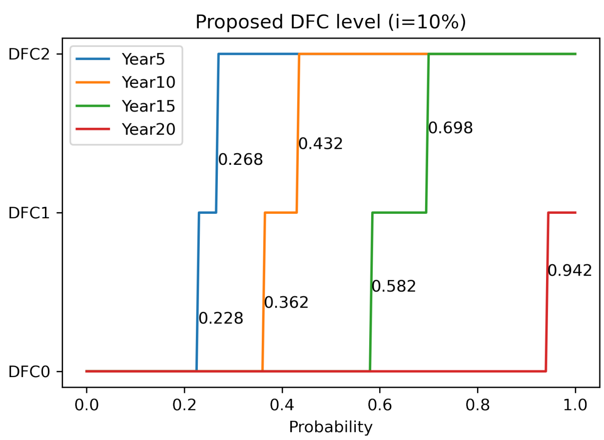
These experiments show only little impact of the changes in autonomy on the probabilities needed for a certain DFC level. Only for a conversion execution in year 20, the impact is significant. Reducing the autonomy to 80% shows a large shift in probability needed before DFC1 is proposed and for an autonomy of 70% design preparation becomes worthless again. Concluding, design preparations are less valuable if there is chosen to reduce the ship's autonomy.



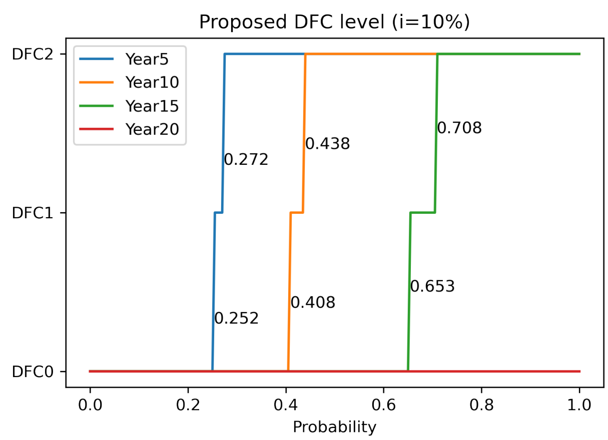
(a) 100% autonomy



(b) 90% autonomy



(c) 80% autonomy



(d) 70% autonomy

Figure 6.13: The impact of reducing the ship's autonomy on the proposed level of DFC when modelling the decision to convert or not as an uncertainty. The used cash flows can be found in Table E.2.

6.3 Discussion of the results

This section aims to place the result obtained in the previous sections into perspective. First, the output of the ship model will be discussed in section 6.3.1. Subsequently, the output from the option model will be discussed. The various experiments will be discussed in section 6.3.2 - 6.3.4.

6.3.1 Costs of Changeability versus Costs of Changes

From the ship model, it can be concluded that less steel weight, piping and tank weight is added into a design when the autonomy is reduced. These three aspects are the main cost drivers of the new building and conversion costs, as well as the conversion planning. When an autonomy of 100% is evaluated it can be concluded that the costs of changeability are small compared to the reduction of the costs of changes, which are significant. From this, it can be concluded that the hypothesis is confirmed: By making small investments during the new building of a ship, the costs of converting a ship to methanol can be greatly reduced. However, as the decision to convert to methanol in the future is subject to uncertainty, it cannot be concluded that ships should always be prepared for conversion to methanol.

6.3.2 Conversion as Uncertainty

For this reason, the option model was used to model the decision of whether a ship will be converted to methanol in the future as an uncertainty. From this experiment is concluded that adding changeability to a ship design only has value when there is a probability higher than 0.342 that a ship will be converted to methanol. For probabilities between 0.342 and 0.422 a DFC1 level is proposed by the option model. For probabilities higher than 0.422 a DFC2 level is chosen by the model, which implies that both cofferdams and double-walled piping are installed during the new building phase.

Moreover, it can be concluded that the moment a conversion is executed significantly impacts the chosen DFC level because of the Net Present Value calculation. In addition, the chosen discount rate has a large impact as well, because of the same reason. The DFC levels need a lower probability of conversion for a discount rate of 5%. However, Design-for-Conversion to methanol has no value if a discount rate larger than 15% is used and the conversion is executed after year 15.

The last conclusion which is drawn from this set of experiments is that the DFC1 level only has limited added value. This is in line with what was expected by employees at Royal IHC. The DFC1 level is only chosen in small ranges of probabilities as the model switches almost immediately to DFC2.

6.3.3 Instigator

To better understand what factor may drive ship owners to convert their ships to methanol the costs and revenues of Sapura Onix were estimated. From this, it was concluded that in addition to the conversion costs, the VOYEX increase as well when a ship is converted to methanol because a larger amount of fuel is consumed. Therefore, an instigator is needed to drive ship owners to convert their vessels to methanol. Two different instigators were used in the experiments, a carbon pricing measure and a CO_2 ban.

Carbon Pricing

From this set of experiments, a couple of conclusions can be drawn. The first is that the sequence in which a decision whether to convert to methanol or not, and the uncertainty of a pricing measure is modelled, affects the outcomes of the experiment. Moreover, when the uncertainty is present after it must be decided to convert a vessel to methanol, the DFC1 level is not used, except for converting at year 20. In addition, it is concluded that the current price of CO_2 in the European Union of 85 [€/t] is not enough to drive ship owners to convert their vessels to methanol. Consequently, the effect of carbon and fuel prices was evaluated, which provided insights into when such a measure will become effective given the probability a pricing measure will be introduced.

Carbon Ban

If a carbon ban is introduced and a ship still runs on MDO, the ship's revenues are seriously affected. Modelling a potential introduction of a carbon ban showed that lower probabilities result in ships being prepared for methanol, compared to a pricing measure with 420 [€/t]. Again, the DFC1 level is skipped in most cases.

6.3.4 Reduced Autonomy

If autonomy is reduced, this results in a higher probability of conversion needed to give value to DFC levels. Moreover, for a conversion execution at year 20, DFC2 has only value when it is chosen to keep 100% autonomy. For an autonomy of 70% autonomy compared to sailing on diesel fuel, Design-for-Conversion to methanol is worthless, when converting at year 20.

7

Discussion

The aim of this section is to reflect on the choices made within this research and to put it into perspective. First, the assumptions made, with respect to the application of the method to a conversion to methanol, will be discussed in section 7.1. Thereafter, the limitations of both models will be discussed in section 7.2. Moreover, a couple of recommendations will be proposed in section 7.3. Subsequently, answers to the research questions as set out in chapter 1 will be provided in section 7.4. Finally, the broader applicability of this research will be discussed from different perspectives in section 7.5.

7.1 Assumptions

To better understand the considerations that influence the research's output, the assumptions made in the ship model and the option model are addressed below.

Ship model

Two of the most important assumptions, that significantly impact the results, are the cofferdam width and the plate thickness. A uniform plate thickness of 15[mm] is used for both horizontal and vertical cofferdams. Changing this value will impact the calculation of the steel weight significantly, resulting in a large difference in planning and costs. Moreover, a cofferdam width of 760[mm] is used according to MARPOL, however, a change in this value will result in less or more volume in a methanol tank. This potentially results in a different ship layout, as the algorithm might choose other spaces first. Furthermore, if this distance were decreased spaces in the double-bottom or double shell may become more favourable.

Next to these aspects, the assumption has been made that the tank-to-shaft efficiency of a ship operating on methanol is equal to the efficiency on MDO (Wärtsilä, 2022). However, if an increase in efficiency is obtained after more research is conducted on methanol technology, too many spaces are prepared as methanol tanks and will not be used in the future.

In addition, it was chosen to let the algorithm optimize for the minimal conversion costs at $DFC0$. It was found that the steel weight is the dominant cost driver, over the pipe length and the tank weight. So indirectly, the ship model optimises for the lowest amount of added steel. However, results may slightly differ if the choice is made to optimize for the total costs, which consist of new building costs, conversion costs and loss of income.

Option model

For the option model, a couple of assumptions are made, however, these assumptions only affect certain runs and not the model as a whole. The first assumption is that the fuel price of methanol is equal to that of MDO and set at 1050[€/t]. However, the price of methanol is slightly lower than that of diesel oil as shown in Figure 7.1 on the next page. Moreover, at this moment a coupling exists between the price of methanol and the price of diesel oil. However, in the future, this might change if most methanol is produced using green feedstock. This will affect the runs slightly because a ship conversion to methanol is less likely to be chosen as the fuel costs are estimated too high.

Figure 7.1: Price of methanol (Marine Methanol, 2022)

In addition, it has been assumed that the increase in ship lightweight does not affect the cargo carrying capacity of the ship. For a pipelay vessel, such as Sapura Onix, it is expected that this has a limited impact on the chosen DFC level. However, for ships whose revenues depend heavily on the cargo carrying capacity, such as dredging vessels, the impact could be more substantial. This is because each tonne of steel added into a ship for cofferdams results in lower revenues during the complete lifecycle of a ship. If this would be taken into account for the vessels for which it is relevant, design preparation is expected to become less valuable.

Moreover, the added weight to the lightship results in an increase in fuel costs. In addition, more weight for fuel needs to be taken into account when the ship is completely bunkered with methanol. The ship will have a larger draught, resulting in a higher resistance and hence higher fuel costs. The increase in lightship is approximately 2%, which has an impact during the complete life cycle of the ship, whilst the increase in deadweight due to the added fuel is 1.94 times the MDO weight.

7.2 Limitations

Now the assumptions made in the models are discussed, the limitations of both models will be discussed. These limitations need to be known to better understand what the models are capable of, and what not. In addition, the limitations of the set methodology, the combination of a Net Present Value calculation and a Real Options Decision Tree, will be discussed.

7.2.1 Ship model

The levels of design preparation used in the ship model were chosen out of deliberation with different staff members of Royal IHC. Preparing a ship for methanol by pre-installing cofferdams and double-walled piping was expected to have the most benefits from early implementation. However, the impact of the items that also need to be adjusted into the ship design, in terms of planning and costs, are roughly estimated. Therefore, it is difficult to reflect on the chosen DFC levels and whether the chosen levels were the correct ones.

Moreover, in the design phase, multiple parameters can be altered very easily, which is not done by the current ship model. Placing a bulkhead one frame forward or backward may result in another layout and fewer life cycle costs. Furthermore, changing parameters such as the ship's length or beam may result in different choices by the algorithm.

In addition, the current model is only able to place cofferdams inside a space. However, placing cofferdams outside a compartment could have advantages. This is because the volume of the space used for methanol would not have to be reduced by the area of the cofferdam times the cofferdam width, resulting in larger volumes. Consequently, fewer spaces may be needed because the volume set as the target for the algorithm could be met more easily by placing a few cofferdams outside the compartment, resulting in lower costs.

Lastly, methanol tanks can be placed inside the double-bottom by the algorithm while water ballast tanks are located there. Currently, the model has the freedom to fill these water ballast tanks with methanol. However, the model does not check whether the remaining water ballast capacity is sufficient to comply with the stability requirements. For the case study of Sapura Onix, this is not a problem, because only a few spaces inside the double bottom are selected but when more spaces are selected in the double bottom, additional stability checks are required.

7.2.2 Option model

One of the limitations of the Real Options Decision Tree is that consecutive uncertainties quickly result in a proposed $DFC0$ level. This is because the value of Design-for-Conversion to methanol depends on the probability a ship will be converted to methanol in the future. If this probability is low, because low probabilities are multiplied, no design preparation is proposed ($DFC0$). However, when assessing the uncertainties one by one, design preparations have more added value.

Moreover, the decision tree is composed of multiple branches. The probability that comes with uncertainty may vary for different branches of the tree. However, the current model is not capable of dealing with different probability values at the same uncertainty node for different branches of the tree. It is only capable of varying these probabilities at the same uncertainty node, for all branches of the tree. However, in this research, a decision does not influence the probability of consecutive uncertainties, so this is not a major limitation.

7.2.3 Methodology

One major limitation of the combination of a Real Options Decision Tree with a Net Present Value calculation is the fact that one does not double-count uncertainty. In a Net Present Value calculation higher discount rates can be chosen if uncertainty is high. However, because in the option model, the complete range of probabilities of occurrence is modelled, uncertainty may be accounted for twice. When choosing the discount rate one should be aware of this, as the discount rate as well as the probability significantly affects the results of the method.

7.3 Recommendations

Now the assumptions and limitations of both models are known, the last step is to propose recommendations for further research. These recommendations are discussed below.

7.3.1 Ship model

The first recommendation in terms of improving the ship model is to incorporate the stability check in the algorithm. In this way, additional constraints can be added, and no additional effort is needed for each run. These constraints should not only take into account the transverse GM, but also the trim and transverse balance. Moreover, multiple loading conditions need to be checked and the impact of the ballast tanks should be added. In addition, the Free Surface Moments (FSM) also have an impact on the stability, and therefore, should be added as well.

The second recommendation is about expanding the model to more types of ships. The first step is to check whether the model is also accurate for other pipelay vessels. If this is the case, the model can be tested for other offshore ship types, such as dredging ships or offshore supply vessels. The last step is to test the model for a completely different category of ships, such as dry bulk ships or container ships.

Moreover, it is recommended to expand the ship model for other alternative fuels. As mentioned earlier in this study, there is much uncertainty about whether ships will run on methanol in the future, seeing as there are also other alternative fuels such as ammonia or hydrogen. However, the current model can still be used, as design preparation may still have value when a ship is converted to another fuel. For example, double-walled piping may also have value when a ship is converted to ammonia, for which double-walled piping is required as well.

7.3.2 Option model

The option model can be used to generate a lot of scenarios by combining consecutive uncertainty and decision moments. There is no limit to the number of scenarios which can be generated. However, because the probability of occurrence of certain options at an uncertainty node is unknown, this probability is varied between 0 and 1. As the Decision Tree is solved for every probability, the computational time increases exponentially when adding more nodes. More research is recommended on the most effective way to solve the tree.

A second recommendation is to conduct more research into the uncertainties that need to be modelled in the decision tree. The model's output is as good as the way consecutive uncertainties and decisions are defined as model input. By means of a thorough analysis of the uncertainties involved in the problem, the results may become more realistic. Nonetheless, the used approach remains suitable to deal with these uncertainties.

7.4 Answering the Research Questions

The research is structured according to six research questions, which provided guidance in answering the main research question: *"How to determine the value of Design-for-Changeability under uncertainty to find the optimal DFC level when preparing for conversion to methanol?"* This section will discuss the answers to the various sub-questions, that together provide an answer to the main question.

1. How is Design-for-Changeability used to deal with uncertainty during a ship's lifetime so far?
This uncertainty can be dealt with by facilitating changes in the future by taking changeability into account during ship design, so-called Design-for-Changeability. However, the application of these principles into a ship design result in additional investment costs, also known as the 'Cost of Changeability'. Moreover, the potential benefits of Design-for-Changeability are unknown because of uncertainty. It is expected that the 'Cost of Changes' can be reduced when designing for changeability. A methodology is needed to assess the optimum amount of changeability that should be incorporated in ship design, for ships subjected to uncertainty, resulting in the lowest life-cycle costs.

2. How can the value of options be expressed for designs over their lifetime?
To do so, additional research was needed to quantify the benefits of Design-for-Changeability for the IHC case. This is done by looking into methods that are capable of determining the value of options during their lifetime. Net Present Value, Filtered Outdegree, Normalised Fuzzy Pareto Trace, Multi-Criteria Valuation, and the Black-Scholes formula were reviewed as potential valuation methods. The comparison as shown in Table 2.2 has shown that a Net Present Value calculation is the most suitable valuation method.

3. How can the value of Design-for-Conversion be calculated under uncertainty?

Subsequently, methods capable of determining the value of options under uncertainty, so-called modelling methods, are reviewed. Epoch-Era Analysis, Real Options Analysis and the Markov decision process have been studied as potential modelling methods. The comparison as shown in Table 2.3 has shown that Real Options Analysis is the most suitable method, it shows the value of flexibility based on possible future outcomes when uncertainty is resolved (Gregor, 1994). Especially a Real Options Decision Tree is well suited for modelling uncertainty and decision-making, including the sequential nature of these two aspects. Moreover, this method is capable of modelling multiple options.

4. Which factors drive the design, production and conversion costs when preparing for or converting to methanol?

Section 3.3 discussed the cost drivers which drive the design, production and conversion costs. It is concluded that these costs are based on three main parameters: the amount of added steel weight, the amount of piping needed, and the methanol tank weight.

5. What are the additional costs of Design-for-Changeability during new building, and how does the level of DFC impact the cost of changes?

Using the cost drivers, both the costs of changeability, as well as the costs of changes, were calculated for the preparation for and conversion to methanol fuel for the Sapura Onix. The incurred costs of changeability for the different DFC levels are €0.0M, €1.7M, and €2.2M, for DFC0, DFC1, and DFC2 respectively. On the other hand, the costs of changes, which consist of both conversion costs and loss of income, are €20.1M, €6.9M, and €4.0M, for DFC0, DFC1, and DFC2 respectively.

6. What DFC level is most valuable when designing an offshore ship for conversion towards methanol while facing uncertainty?

Which level of DFC is to be added to the design depends on the probability that a ship will be converted to be powered with methanol in the future. However, a couple of aspects are identified to be considered when choosing the right DFC level, such as the discount rate and the moment the conversion will be executed. When considering conversion in the first 10 years of a ship's lifetime, Design-for-Conversion is more likely to have value compared to conversions later in the ship's life cycle. Moreover, the used discount rate for NPV calculation greatly affects the value of Design-for-Conversion. Because of uncertainty a discount rate of 10% is chosen, for which the DFC levels still have value.

7.5 Broader Applicability

Section 1.1 discussed the relevance of this research from various perspectives. This section will reflect on the contribution of this research to new insights for the stakeholders and will show the broader applicability of this research. Because two separate models were built, a ship model and an option model, both can easily be used for different purposes. For example, verification of the option model was done using a decision tree which modelled the decisions and uncertainties when exploiting a goldmine.

Relevance for Industry

In section 1.1.2 ship owners, ship operators, and shipbuilders were identified as relevant stakeholders. This research provides new insights for ship owners, as the investments in Design-for-Conversion are found to be more likely to pay off if a vessel is converted early in its life cycle rather than later. Ship operators can benefit from the research outcomes as ships can be changed faster by means of Design-for-Conversion, allowing operators to better serve a changing market. Lastly, shipbuilders, such as Royal IHC, can use this study's outcomes to provide clients insight into whether to make investments in design preparations or not.

Although the case study is performed on Design-for-Conversion to methanol for offshore vessels the ship model can also be used for other ship types. By means of a ship model, the layout of a complex offshore vessel was modelled, so it is expected that it can also be used for other ship types, such as offshore supply vessels, container vessels, or dry bulk vessels. Moreover, the ship model can be adjusted to assess design-for-Conversion for other alternative fuels. Although different aspects of the ship design may be changed when converting to other alternative fuels, the layouts generated by the ship model can still be used.

Besides ships, many other systems could benefit from Design-for-Changeability, according to Reinhardt et al. (2001). The mention that systems that could benefit from changeability should have a stable core functionality but variable secondary function, long life cycles and fast technological developments, high complexity, and high development and maintenance costs. That is why the established methodology is expected to apply to systems that meet these criteria. Examples of such systems could be spacecraft, specialized aircraft or chip machines.

Applicability for Policy-making

This research has shown that an instigator is needed before ship owners will decide to convert their ships to methanol. Two measures that can be taken by policy-makers have been researched, a carbon pricing measure and a carbon ban. Moreover, various other measures may be researched by means of the option model. Because it was found that design preparations do not require significant investments, a subsidy on Design-for-Conversion would also be an interesting research topic. Furthermore, Design-for-Conversion to methanol would also benefit if regulatory uncertainty is limited by policymakers.

New Scientific Insight

Figure 1.2 showed that Fricke et al. expected that a static optimum exists, in which the cost of changeability and the cost of changes result in the lowest life-cycle costs (2000). However, this study showed that the cost of changes should be considered to be the expected cost of changes because they are subject to uncertainty. Moreover, these costs should be discounted by means of a Net Present Value calculation because ships are long-term assets. These new insights are visualised in Figure 7.2.

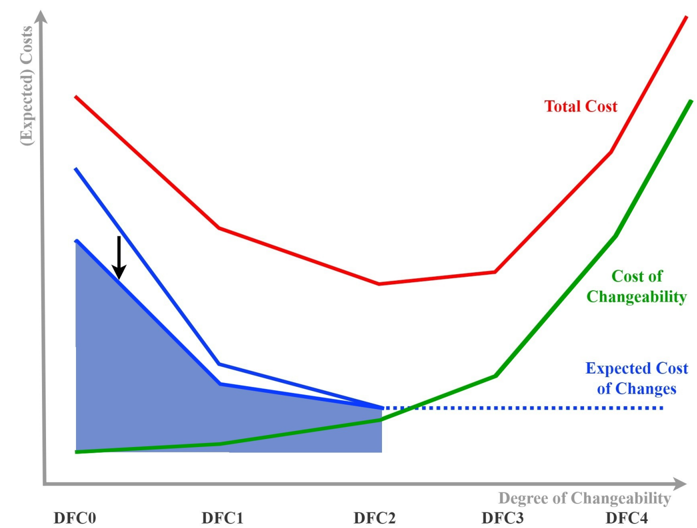


Figure 7.2: New insights as a result from the application of a Real Options approach in conjunction with a Net Present Value calculation to determine the value of Design-for-Conversion under uncertainty.

The cost of changes is discounted, to account for the time value of money. This causes the blue line to shift downward, as indicated by the black arrow. For higher discount rates or conversions in the later stages of a ship's life, the line shifts further down. Second, the blue line becomes an area, which illustrates the whole range of expected cost of changes which are subject to uncertainty. Because of the expected value calculation, the values of these costs can vary between 0, for a probability of 0, and the discounted values of the costs of changes. Subsequently, the optimum as described by Fricke et al. is dynamic instead of static, due to the uncertainty behind executing and the timing of a change event (2000).

8

Conclusion

The aim of this research is covered in the main research question: *"How to determine the value of Design-for-Changeability under uncertainty to find the optimal DFC level when preparing for conversion to methanol?"*

The technical impact of Design-for-Conversion is quantified by incorporating Design-for-Changeability principles in a ship model. The valuation of Design-for-Conversion under uncertainty is determined by means of a Real Options decision tree and a Net Present Value calculation. By combining both models, a methodology is established that can be used to determine the optimal level of DFC under uncertainty. This methodology is used to conduct a case study on preparing a pipelay vessel for future conversion to methanol. It was found that the costs of changes can be significantly reduced when designing for conversion, but uncertainty negatively impacts the added value of design preparation. Consequently, waiting with the execution of conversion to methanol results in a decreasing added value of Design-for-Conversion. Moreover, it was found that the Discount Rate used for the Net Present Value calculation significantly impacts the choice of whether to prepare a ship for methanol. In addition, it can be concluded that an instigator is needed so that ships are converted to methanol. Two instigators have been researched, a carbon pricing measure and a ban on CO_2 emissions. A carbon pricing measure is only effective if the right price is established, whilst a ban is highly effective as ships are converted immediately, and hence design preparations pay off. Lastly, technological and operational uncertainty is assessed through a reduction of autonomy, which had only a limited effect on the chosen DFC levels.

From these results, it can be concluded that the methodology can be used to find the optimal level of DFC while facing uncertainty. However, accurate modelling of uncertainties, time span, and discount rate is necessary to obtain accurate model output. The theory of Fricke et al. as shown in Figure 1.2 has been partially confirmed by the ship model, as small investments in changeability drastically decrease the cost of changes. However, as shown in Figure 7.2 there is no static optimum that results in the lowest life-cycle costs, due to uncertainty and the time value of money.

It is expected that the ship model can also be used to assess the technical impact of Design-for-Conversion for other ship types. Moreover, with some adjustments in the ship model, the same approach can be used for Design-for-Conversion to other alternative fuels. Furthermore, through the use of Real options Analysis, the method also allows to assess the impact of uncertainty. In addition, the Real Options Decision Tree allows for assessing uncertainty in a variety of other complex and capital-intensive systems, which have similar characteristics to offshore ships such as spacecraft or sophisticated aircraft. Hence, the method can serve as a basis for decision-making on design preparation to help the maritime industry to be better prepared for the uncertainty faced in the energy transition.

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A

[Confidential] Design Modifications for Methanol

B

[Confidential] Costs Parameters

C

[Confidential]
Bulkheads and Decks
Sapura Onix

D

Ship Model Verification

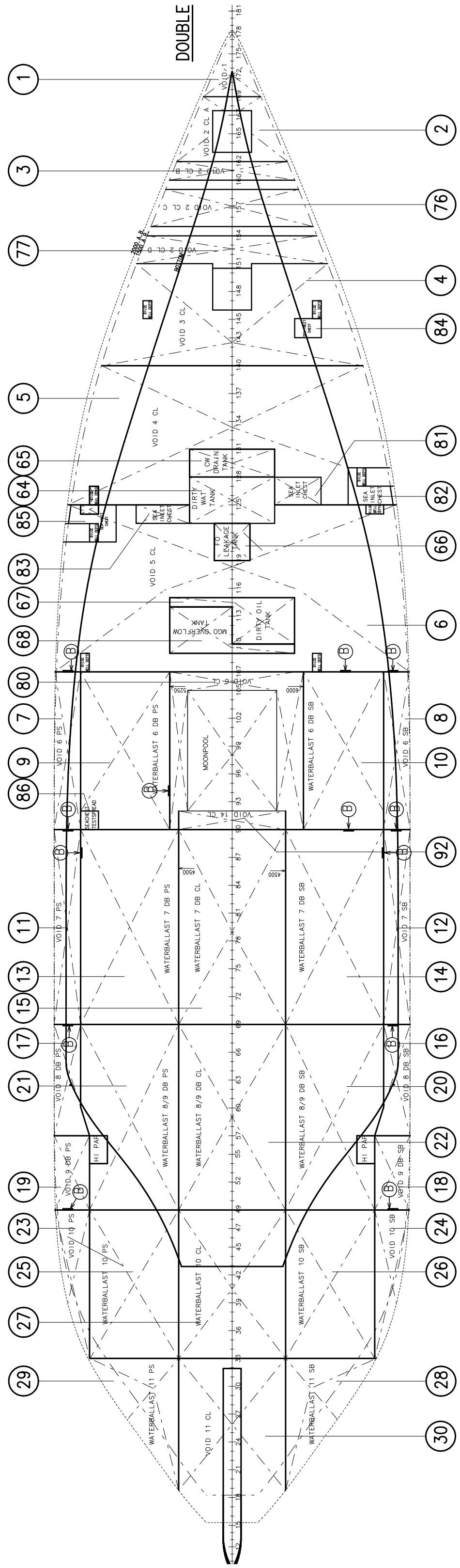


Figure D.1: Overview of the double bottom of Sapura Onix at z=0.0[m]

Table D.1: Match list of volumes used for verification.

Frames	**Model**		**Sapura Onix**	**Space name**
15-33	1	58	28	WATERBALLAST 11SB DB
15-33	2	59	30	VOID 11CL
15-33	3	60	29	WATERBALLAST 11PS DB
33-49	4		24	VOID 10SB
33-49	5		26	WATERBALLAST 10SB DB
33-49	6		27	WATERBALLAST 10CL DB
33-49	7		25	WATERBALLAST 10PS DB
33-49	8		23	VOID 10PS
49-69	9		18	VOID 9SB DB
49-69	10	15	20	WATERBALLAST 8/9SB DB
49-69	11	16	22	WATERBALLAST 8/9CL DB
49-69	12	17	21	WATERBALLAST 8/9PS DB
49-69	13		19	VOID 9PS DB
49-69	14		16	VOID 8SB DB
49-69	18		17	VOID 8PS DB
69-90	19		12	VOID 7SB
69-90	20		14	WATERBALLAST 7SB DB
69-90	21		15	WATERBALLAST 7CL DB
69-90	22		13	WATERBALLAST 7PS DB
69-90	23		11	VOID 7PS
90-107	24		8	VOID 6SB
90-107	25		10	WATERBALLAST 6SB DB
90-107	26		80	VOID 6CL
90-107			-	MOONPOOL
90-107			92	VOID 14CL
90-107	27		9	WATERBALLAST 6PS DB
90-107			86	Other
90-107	28		7	VOID 6PS
107-125	29		64	DIRTY WATER TANK
107-125			66	FUEL OIL LEAKAGE
107-125			83	SEA INLET CHEST PS
107-125			85	SEA INLET CHEST PS
107-125			67	DIRTY OIL
107-125			68	MGO OVERFLOW
107-125			6	VOID 5CL
125-140	30		5	VOID 4CL
125-140			64	DIRTY WATER TANK
125-140			65	COOLING WATER DRAIN ER DB
125-140			81	SEA INLET CHEST SB
125-140			82	SEA INLET CHEST SB
140-151	31		4	VOID 3 CL
140-151			84	SEA INLET CHEST SB
151-162	32		3	VOID 2CL B
151-162	32		76	VOID 2CL C
151-162			77	VOID 2CL D
162-179	33		1	VOID 1CL
162-179			2	VOID 2CL A

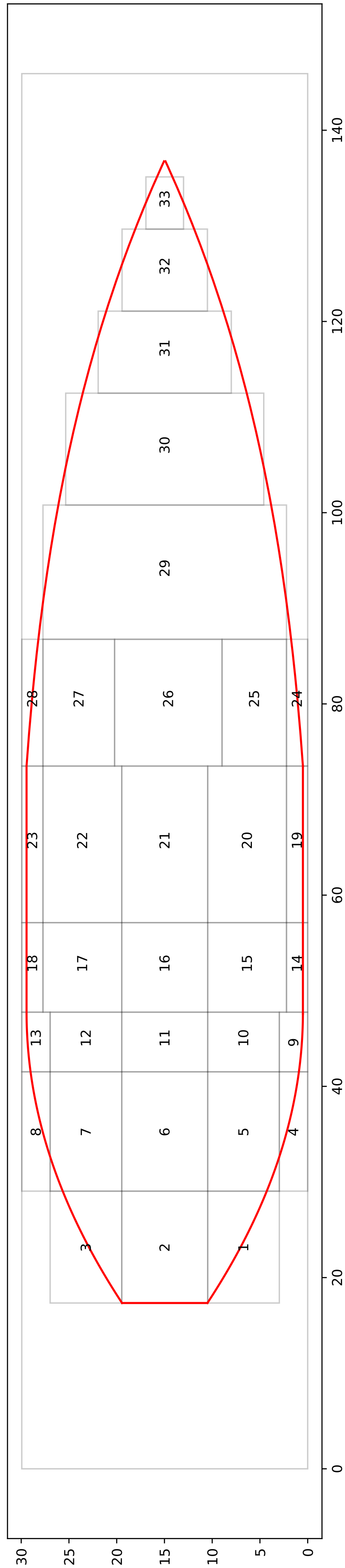


Figure D.2: Overview of the double bottom of ship model output at z=0.0[m]

E

Results

E.1 Ship Model

E.1.1 Tank List

space	Function	volume [m^3]	LCG [m]	TCG [m]	VCG [m]
35	Cargo Hold	7397.3	54.63	14.97	7.25
64	Cargo Hold	82.5	21.87	14.97	4.00
66	Cargo Hold	4843.3	32.40	14.97	7.50
76	Cargo Hold	144.5	21.87	14.97	9.50
87	Engine Room	235.0	132.42	14.03	9.50
53	Engine Room	36.2	1.50	2.11	4.00
54	Engine Room	1028.4	0.60	14.05	4.00
55	Engine Room	36.2	1.50	27.83	4.00
68	Engine Room	186.0	1.50	1.68	9.50
69	Engine Room	2318.9	1.50	14.66	9.50
70	Engine Room	186.0	1.50	28.26	9.50
42	Engine Room	779.7	74.13	23.97	5.50
86	Engine Room	475.7	126.39	14.48	9.50
95	Engine Room	341.1	74.13	23.97	11.25
93	Engine Room	307.0	74.13	5.60	11.25
89	Engine Room	143.0	16.02	28.46	11.25
91	Engine Room	190.7	32.40	28.46	11.25
96	Engine Room	100.9	74.13	28.83	11.25
99	Engine Room	106.9	87.78	28.83	11.25
73	Engine Room	722.4	14.85	14.97	9.50
85	Engine Room	1121.5	119.37	14.43	9.50
56	Engine Room	169.3	8.10	14.97	4.00
83	Engine Room	87.8	110.79	3.35	9.50
84	Engine Room	87.8	110.79	26.59	9.50
45	Engine Room	1578.9	87.78	14.97	3.75
78	Engine Room	1228.0	87.78	14.97	7.75
98	Engine Room	1228.0	87.78	14.97	11.25
48	Engine Room	1887.8	104.94	14.57	3.75
49	Engine Room	83.2	100.65	26.48	3.75
47	Engine Room	83.2	100.65	3.46	3.75
51	Engine Room	223.5	126.39	14.38	3.75
52	Engine Room	75.3	131.82	14.43	3.75
80	Engine Room	257.3	100.65	2.57	9.50
81	Engine Room	2996.6	104.94	14.97	9.50
82	Engine Room	257.3	100.65	27.37	9.50
50	Engine Room	578.5	119.37	14.27	3.75
63	MeOH Tank	176.5	19.53	23.22	4.00
57	MeOH Tank	108.2	16.02	1.53	4.00
62	MeOH Tank	136.5	19.53	6.72	4.00
61	MeOH Tank	139.9	16.02	28.41	4.00
60	MeOH Tank	183.6	12.51	23.22	4.00
59	MeOH Tank	278.0	14.85	14.97	4.00
58	MeOH Tank	143.6	12.51	6.72	4.00
40	MeOH Tank	551.6	74.13	5.60	5.50
75	MeOH Tank	58.2	16.02	28.46	7.75
25	MeOH Tank	131.6	74.13	5.60	0.75
24	MeOH Tank	28.6	74.13	1.48	0.75

space	Function	volume [m^3]	LCG [m]	TCG [m]	VCG [m]
3	MeOH Tank	44.6	17.19	22.02	1.00
2	MeOH Tank	142.1	17.19	14.90	1.00
1	MeOH Tank	44.6	17.19	7.92	1.00
74	MeOH Tank	450.5	16.02	23.22	9.50
39	MeOH Tank	93.7	74.13	1.75	5.50
41	Moonpool	1169.5	74.13	14.60	5.50
94	Moonpool	511.7	74.13	14.60	11.25
26	Moonpool	219.3	74.13	14.60	0.75
4		28.0	29.28	2.05	1.00
5		164.8	29.28	6.73	1.00
6		198.1	29.28	14.97	1.00
7		164.8	29.28	23.21	1.00
8		28.0	29.28	27.89	1.00
9		31.0	38.64	1.70	1.00
10		91.7	38.64	6.72	1.00
11		110.1	38.64	14.97	1.00
12		91.7	38.64	23.22	1.00
13		31.0	38.64	28.24	1.00
14		30.6	46.44	1.11	0.75
15		113.5	46.44	6.35	0.75
16		123.9	46.44	14.97	0.75
17		113.5	46.44	23.60	0.75
18		30.6	46.44	28.83	0.75
19		53.4	59.31	1.11	0.75
20		198.6	59.31	6.35	0.75
21		216.7	59.31	14.97	0.75
22		198.6	59.31	23.60	0.75
23		53.4	59.31	28.83	0.75
27		146.2	74.13	23.97	0.75
28		28.6	74.13	28.46	0.75
29		525.7	87.78	14.84	0.75
30		360.2	100.65	14.97	0.75
31		217.1	110.79	14.74	0.75
32		118.9	119.37	14.82	0.75
33		37.3	126.39	14.72	0.75
34		234.2	46.44	1.11	7.25
36		234.2	46.44	28.83	7.25
37		409.8	59.31	1.11	7.25
38		409.8	59.31	28.83	7.25
43		223.7	74.13	28.19	5.50
44		84.3	87.78	1.49	3.75
46		84.3	87.78	28.45	3.75
65		408.7	32.40	1.49	5.75
67		408.7	32.40	28.46	5.75
71		143.0	16.02	1.49	7.75
72		722.4	16.02	6.72	9.50
77		103.7	87.78	1.84	7.75
79		103.7	87.78	28.10	7.75
88		143.0	16.02	1.49	11.25
90		190.7	32.40	1.49	11.25
92		100.9	74.13	1.11	11.25
97		106.9	87.78	1.11	11.25

E.1.2 Stability check

The ship model performs a stability check, as discussed in section 5.1.4. The check is performed in arrival conditions with 10% consumables as this condition is expected to be the most critical in terms of stability.

Table E.1: Stability check performed in arrival condition, 10% consumables at summer draught.

T_{old}(10% cons.)	7.05	[m]
TPI(T=7.05[m])	37.00	[t/cm]
W_{added}	240.3	[t]
T_{new}(10% cons.)	7.12	[m]
$KM(T_{new})$	15.11	[m]
KG_{new}	11.55	[m]
GM_{new}	3.56	[m]

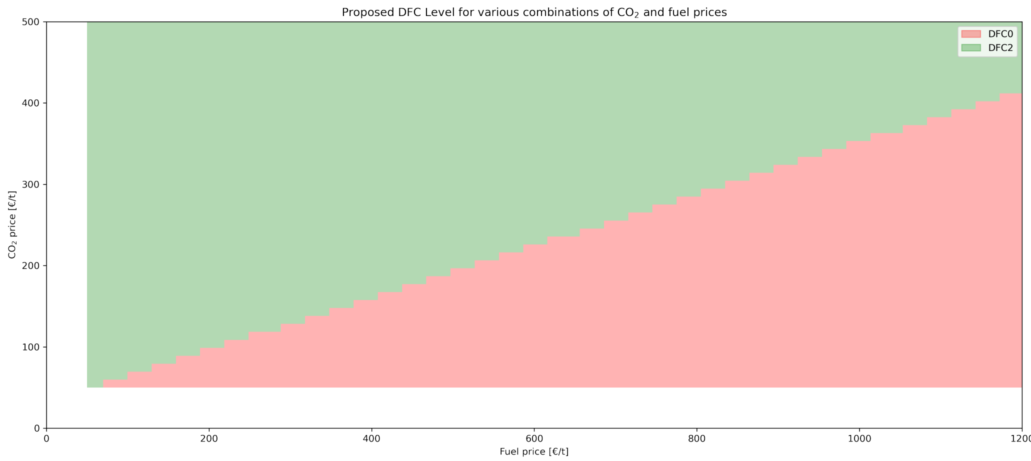
E.2 Option Model

E.2.1 Cash flows used in experiments

Table E.2: Cash flows used in the experiments of section 6.2

Run nr.	Experiment: Run name	Reference:	Conversion Costs Tab. 6.3	Loss of Income Tab. 6.3	Fuel Costs Eq. 5.31	Carbon Pricing Eq. 5.32	CAPEX Eq. 5.33	OPEX Eq. 5.34	Revenues Eq. 5.28
Run 1	Decision as uncertainty	Fig. 6.2 & Fig. 6.3	x	x	x				
	Instigator (No conversion)	Fig. 6.4a			x		x	x	x
	Instigator (Conversion Y10)	Fig. 6.4b	x	x	x		x	x	x
Run 2a	Carbon Pricing 85[€/t]	Fig. 6.6	x	x	x	x			
Run 2b	Carbon Pricing 420[€/t]	Fig. 6.7	x	x	x	x			
Run 2c	Carbon Pricing 420[€/t] decision and uncertainty reversed	Fig. 6.9	x	x	x	x			
Run 2d	Carbon & Fuel price (P=0.5)	Fig. 6.10	x	x	x	x			
Run 3	Carbon Ban	Fig. 6.12	x	x	x				x
Run 4a	Autonomy 100%	Fig. 6.13a	x	x	x				
Run 4b	Autonomy 90%	Fig. 6.13b	x	x	x				
Run 4c	Autonomy 80%	Fig. 6.13c	x	x	x				
Run 4d	Autonomy 70%	Fig. 6.13d	x	x	x				
Run 5a	Carbon & Fuel price (P=0.9)	Fig. E.1a	x	x	x	x			
Run 5b	Carbon & Fuel price (P=0.5)	Fig. E.1b	x	x	x	x			
Run 5c	Carbon & Fuel price (P=0.1)	Fig. E.1c	x	x	x	x			

E.2.2 Carbon price versus fuel price



(a) P=0.9

(b) P=0.5

(c) P=0.1

Figure E.1: Impact of fuel price and CO_2 price on the decision of a ship owner to prepare a ship for a future conversion.