Alternative Fuels for Short Sea Shipping in Europe

An agent-based study to explore future scenarios

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Image FrontPage: Paracas: "Poor man's Galapagos", Peru (L. Vogelsang 2016)

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By

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Preface

This master thesis is my final work to complete the Master's programme Complex Systems Engineering and Management at Delft University of Technology. This research has been carried out in collaboration with the Port of Rotterdam.

I would like to express my gratitude to my graduation committee for all the help during this thesis. Many thanks to my daily supervisor Igor Nikolic, for all the help, advice, and guidance during this process. Jan Kwakkel, I very much appreciate the effort you made and the time you spent into enabling the experiments to run, thank you for all the help. I would like to thank Prof. ir. Andrea Ramirez Ramirez for the help and insights she provided during the meetings. Furthermore, I would like to thank Aiara Lobo Gomez for the input she gave me on the topic and the fruitful discussions during this process. It was very enjoyable to have you as my supervisor at the Port of Rotterdam. In addition, I would like to thank all employees of the Port of Rotterdam who provided me with insights into the maritime shipping sector and therefore contributed to this research. Moreover, I would like to thank all the colleagues of the department Business Analytics and Intelligence for the pleasant and relaxing working environment.

I very much enjoyed working on this project for the past seven months and I hope you will enjoy reading it!

Leoni Vogelsang

Rotterdam, April 2019

Executive Summary

Increasing ship emissions are of big concern because they contribute to the effects of climate change and have an impact on the local and regional environment. Due to these concerns, stricter regulations are enforced upon the shipping sector by the International Maritime Organisation, the European Union and other regulatory or bodies. These regulations aim to reduce the emissions of vessels by limiting the allowable amount of SOx and NOx emissions. Special areas in the North- and Baltic Sea are assigned as Emission Control Areas (ECAs) for which even stricter regulations apply. These regulations have a major impact on short sea vessels spending most of their time in ECAs. To comply with regulations, vessels could either install after-treatment systems, which washes away the negative emissions from the exhaust gases or switch to alternative fuels.

However, since new regulations are enforced, stakeholders have been slow to react. A key reason why investments are not taking place is that of uncertainty in regulations and policy. Besides, the availability of bunker infrastructure in ports is key to the development of alternative fuels. However, ports are concerned about the loss of competitiveness and the additional costs of regulations. To stay competitive, ports could benefit from obtaining insight into how the system might change, so ports can prepare themselves for possible futures. Consequently, the following research question is formulated:

"What are the effects of port strategies on the deployment of alternative fuels for short sea shipping in Europe?"

The objective of this study is to obtain insight into what possible future scenarios for alternative fuels for the short sea shipping sector in Europe might arise and to give insight into the effects of different policies implemented by the Port of Rotterdam Authority on the emergence of alternative fuels. This study is performed by including several emission abatement technologies, namely: the use of scrubbers and SCR systems in combination with the consumption of HFO, the use of an SCR system in combination with the consumption of MGO, LNG propulsion technology, and methanol propulsion technology in combination with either a small or large fuel tank. Furthermore, this study explored the transition of the European short sea fuel system for a time horizon up to 2028.

Because the European short sea maritime fuel system is adaptive and assumes a bottom-up approach, an agent-based modelling approach is applied. Bas et al. (2017) created an agent-based model which represents the maritime fuel system: Maritime Fuel Policy Exploration Model (MarPEM). This model can be used to study the effects of policies on the development of alternative fuels. In this research, MarPEM is used to create a model that represents the European short sea sector.

This research illustrates how MarPEM can be reused to study the effects of policies on the transition towards the deployment of alternative fuels for the European short sea sector. The reuse of MarPEM gives valuable insights into the reuse of agent-based models. The conceptualization of the model is perceived to be more suitable to reuse than the source code. Besides, it is found that the scalability of the model is the paramount factor determining the reuse of the model rather than the agent's behaviour included in the model. Further, suggestions are made to improve the performance of the model. An agent-based model that represents the European short sea shipping sector is successfully created and considered to be a valid representation.

The European maritime fuel system is subjected to various uncertainties, such as fuel prices, investment costs, and regulations. To deal with these uncertainties and assess the impact of policies, an exploratory modelling and analysis approach is applied. This approach uses a large number of computational experiments to explore the implications of the assumptions that are made in the modelling process and the uncertainties to which the system subjected is. In this way, the uncertainty space and decision space can be identified and related to the output space.

Several port policy levers are identified in this study. The port policy levers included in this research comprise several ways of collaboration between European ports. The following three options of collaboration are implemented in the model: 1) ports providing methanol bunker infrastructure, 2) ports applying a discount on port dues for vessels operating with an LNG or methanol propulsion technology, and 3) ports applying a discount on port tariffs for vessels when bunkering bio methanol in the associated port.

Overall, this study provides insight into the dynamics of the adoption of propulsion technologies by short sea vessels in Europe. The outcomes of the model provide insight into the most influential uncertainties towards the deployment of propulsion technology and the and effects of port strategies, which enables to better understand where the system might go in the future. The outcomes show that the uncertainties in fuel prices are the most important uncertainties towards the deployment of emission abatement technology. The technological uncertainties explored in this study, such as space requirements and investments costs are not expected to have a significant impact on the adoption of emission abatement technologies. The study shows that being compliant is highly dependent on the HFO fuel price. Besides, regulation enforcement is a prominent uncertainty affecting the behaviour of ship operators. Nevertheless, the outcomes show that it is most likely that a transition away from non-compliant vessels will take place when regulations are enforced. However, the outcomes also indicate that when HFO prices remain low with respect to other fuel prices, scrubbers in combination with SCR systems are the most cost-effective option for ship operators to apply. However, whilst vessels are compliant with emission regulations when operating with scrubbers and SCR systems, it does not influence the amount of HFO fuel bunkered, since vessels continue to consume HFO, and thus CO2 emissions remain high.

In addition, key uncertainties influencing the deployment of the other emission abatement technologies are the HFO price and the associated fuel price of the technologies. Further, the enforcement of the regulations is recognised as an important factor that can steer the transition towards the deployment of LNG or methanol propulsion technologies. It is indicated that enforcement is needed to initiate the uptake of emission abatement technologies. However, when ship operators experience the pressure of emission regulation enforcement too early, ship operators are likely to make investments in the technologies with the least radical implications. Scrubbers and SCR systems are then often considered since vessels can continue to operate with cheap HFO, besides the fuel is available in all the ports. For this reason, it might be more beneficial to give vessels more time to make well-considered decisions towards the application of emission abatement technology.

Besides, when a transition to alternative fuels is more favourable than a transition towards the compliance of vessels, it is concluded that governing the fuel prices might be more effective than the enforcement of regulations. It is recognised that when the fuel prices for methanol or LNG are favourable and the HFO price is relatively high, the uptake of methanol or LNG propulsion is likely to take place. Besides, when HFO prices are high, it will be less attractive to invest in scrubbers and SCR systems. Further, it is not expected that vessels operating with a methanol propulsion technology shift to the consumption of bio methanol. Even when ship operators are willing to pay a little more for being more sustainable, the incentives are insufficient.

This study shows that some of the policies might be more effective than others. Firstly, it is expected that the discount given on port dues for vessels with a certain technology does not influence the investment decisions of ship operators. The cost savings of the discount will not add up to the total investment costs of LNG or methanol and the higher fuel prices. Similarly, the discount on port dues when bunkering bio methanol is not likely to contribute to the number of vessels operating with methanol propulsion technology, neither is it expected to have an influence on the amount bio methanol bunkered. Nevertheless, the availability of methanol infrastructure in ports is likely to have a significant effect on the deployment of methanol propulsion technology. It is expected that when more ports provide the methanol bunker infrastructure, more investments take place in methanol propulsion technology. The availability of methanol infrastructure directly lowers the risk of not being able to bunker. Methanol propulsion technology is more attractive in combination with a small fuel tank since the loss of cargo capacity can be kept to a minimum. This is especially observed for liner vessels due to the fact that more vessels can bridge the distances between ports in their rotation schedules without running out of fuel. Besides, the uptake of methanol prolusion technology in combination with a small fuel tank causes a vessel to bunker more often, which could be beneficial for ports and fuel suppliers.

The findings of this study were in accordance with findings in other studies. However, apart from solely focussing on the environmental, technological and economic performance of emission abatement technologies, this approach captured the mutual influence of the technical and social systems and therefore fundamentally different and provided new insights. ABM and EMA proved to be useful to actually analyse the problem because it captures the mutual influence of the technical and social systems.

The central issue concerning the results is the sustainability of certain pathways. Bio methanol has the potential to mitigate the effects of maritime shipping on climate change. However, bio methanol is not available in large quantities yet and therefore in order to start this transition the use of conventional methanol is required. Nonetheless, the use of methanol is less sustainable than the use of LNG. Hence, the transition to methanol might be less desirable.

Though the deployment of methanol as a maritime fuel across Europe is not likely to emerge in the upcoming years, it might be possible to establish such a transition on a smaller geographical scale. For this reason, it is advised to conduct further research and look for collaborations with ports serving similar line rotations and operating in a small geographical area. This might accelerate the uptake of methanol propulsion technology and reduces the risk for ports, bunker suppliers and ship operators.

Contents

List of Figures

List of Tables

List of Abbreviations

ABM	Agent-based modelling
CO2	Carbon dioxide
ECA	Emission Control Area
EMA	Exploratory Modelling and Analysis
EU-MarPEM	European Maritime Policy Exploration Model
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LNG	Liquid Natural Gas
MarPEM	Maritime Policy Exploration Model
MGO	Marine Gas Oil
NECA	NOx Emission Control Area
NOx	Nitrogen Oxide
NPV	Net Present Value
PoR	Port of Rotterdam
PRIM	Patient Rule Induction Method
SCR	Selective Catalytic Reduction
SECA	Sulphur Emission Control Area
SOx	Sulphur Oxide

1. Introduction

Sea transport is an important contributor to the world's economy, as it is the biggest carrier of freight around the globe, 90% of trade is transported by ship (Lister, Tsjeng, Cullinane & Lu, 2015; Mansouri, Lee, & Aluko, 2015). Although shipping is stated to be the least environmental harming mode of transport, it is not completely free of negative effects on the environment. It is responsible for 2,5% of global emissions, such as CO2, SOx and NOx emissions (Maritime Knowledge Centre, TNO & TU Delft, 2018). In 2015, about 298 million tons of fuel was consumed by global shipping, consisting of 72% heavy fuel oils, 26% distillate fuels, and 2% LNG (Lister, 2015; Olmer et al., 2017). The amount of fuel consumed is likely to get even worse due to increasing global trade. The expected rise in emissions ranges between 50% and 250% if no serious actions are undertaken (Maritime Knowledge Centre et al., 2018). The pollution and waste caused by sea shipping lead to environmental degradation and resources depletion. Solutions must be found if we wish to reduce the negative effects of sea shipping on the environment (Lai, Lun, Wong, & Cheng, 2011). Sustainable sea shipping is, therefore, a key challenge for the international community. Concerns are raised among stakeholders, ranging from shippers to governmental bodies and international communities (Lai et al., 2011).

Due to these concerns, stricter regulations are enforced upon the shipping sector by the International Maritime Organisation (IMO), the European Union and other regulatory or bodies. These regulations aim to reduce the emissions of vessels, by limiting the allowable amount of SOx and NOx emissions. Special areas in the North- and Baltic Sea are assigned as Emission Control Areas (ECAs) for which even stricter regulations apply (Mallidis, Despoudi & Dekker, 2018). Here, the local and regional environmental impacts are of more concern. Vessels are operating near coasts and close to populated areas; thus, the emissions could impact human health and ecosystems onshore (Svanberg, Ellis, Lundgren & Landälv, 2018). These regulations have a major impact on short sea vessels spending most of their time in ECAs, they need to reduce their emissions to be compliant with the stricter regulations. Short sea vessels generally operate in limited geographical areas on relatively short routes with port calls taking place frequently. Therefore, short sea vessels could use fuels which are only regionally available. In this research, the impact of these regulations on the short sea shipping sector is further investigated.

Regulations force the shipping industry to act. A combination of efficiency measures and the transition to alternative fuels or after-treatment installations (installations that remove the negative emissions from the exhaust gases) is therefore needed (Maritime Knowledge Centre et al., 2018). At present, heavy fuel oil (HFO) is the most commonly used fuel by deep sea and short sea vessels. However, HFO does not comply with IMO and EU regulations because it exceeds the maximum allowable NOx and SOx content. Marine Gas Oil (MGO) and Marine Diesel Oil (MDO) are fuels with a lower sulphur content. These fuels are available in most ports, but not much used due to its higher price (Gritsenko &Yliskylä-peuralahti, 2013). Besides, when NOx regulations come into force, additional measures should be taken since MGO does not comply with NOx regulations. MDO is a blend of MGO and HFO, and does in some cases comply with SOx regulations, but not with NOx regulations (Andersson & Salazar, 2015).

Examples of alternative fuels that can be used by the shipping sector are LNG, liquefied biogas (LBG), biodiesel, hydrogenated vegetable oil (HVO), (bio) methanol, or (bio) ethanol (Brynolf, Fridell & Andersson, 2014). However, these alternative fuels, except LNG, are still in an experimental stage, and thus niche markets for the shipping sector (Maritime Knowledge Centre et al., 2018). Currently, LNG and methanol are the most promising alternative fuels for shipping (Maritime Knowledge Centre et al., 2018). LNG and (bio) methanol do comply with regulations and have advantageous costs compared to other alternative fuels (Andersson et al., 2015). For this reason, this study will focus on these fuels as alternative fuels for the short sea shipping sector. In addition, after-treatment installations will be considered as an emission abatement option. However, from these emission abatement options, bio methanol is the only fuel that has the potential to mitigate climate change and therefore it is the most favourable fuel from a sustainable point of view (Brynolf et al., 2014). For this reason, in this research extra attention is paid to the development towards bio methanol as a fuel for maritime shipping. A more detailed description of these technologies is given in Chapter 3.

Table 1.1: Tank -to-propeller emissions of abatement options

	HFO	HFO + Scrubber/SCR	MGO + SCR	LNG	Methanol	Bio methanol
SOx (g/MJ)	1.33	0.049	0.047	0.0001	0	0
NOx (g/MJ)	1.6	0.28	0.28	0.12	0.28	0.28
CO2 (g/MJ)	79	79	75	57	69	69

* Reference: Brynolf, Magnusson, Fridell & Anderson, 2014; Brynolf, Fridell and Anderson, 2014

Table 1.1 shows the SOx, NOx and CO2 tank-to-propeller emissions of different abatement options. HFO is not compliant with current and future regulations, but the other abatement options do comply.

1.1 Problem description

Since new regulations are enforced, stakeholders have been slow to react. The uncertainty of fuel and shipping markets burden the take-off of investment decisions by the ship operators, fuel suppliers, and port authorities. A key reason why investment decisions are not taking place is that of uncertainty in regulations and government policy (Alphatanker, 2018). For example, for a long period of time, it was unclear if the implementation of the IMO sulphur cap would be delayed until 2025. In addition, technological replacement is slow, since the lifetime of a vessel is about 20-30 years, and so it is uncertain if regulations change in the meantime. Moreover, it is unknown how these regulations will be enforced and what the consequences are of not being compliant (Alphatanker, 2018).

Nevertheless, due to regulations, it is unavoidable that a shift in both fuel and shipping markets will take place. The emergence of an alternative fuel depends on regulatory authorities with respect to emission regulations and availability of bunker infrastructure in ports (Elgohary, Seddiek, & Salem, 2015). This emergence requires investments from both port authorities and ship operators. However, becoming more sustainable might become at the cost of being economically efficient. Shipping companies compete for profit and implementing abatement options is costly. Moreover, ship operators never adopt a fuel until it is cost-effective, easily available, and compatible with the existing and future technology. Furthermore, it requires the fuel to be compliant with current and future regulations (Svanberg et al., 2018). Ship operators need reliable and accurate information about the technologies, so the financial risks can be kept to a minimum. They need to have some certainty about the availability of fuels and the availability of bunker infrastructure in ports before committing to investments in alternative fuels (Maritime Knowledge Centre et al., 2018). Furthermore, bunker suppliers are worried about their ability to supply compliant fuels due to the lack of refinement capabilities. Moreover, they are afraid to lose market share due to the absence of standards and infrastructure (Gritsenko et al., 2013). Ports in Europe compete for shipping traffic. Therefore, local authorities and port authorities themselves are concerned about the loss of competitiveness and the additional costs of regulations (Zhang, Loh, Louie, Liu, & Lau, 2018). The regulations can influence the number of port calls and the operational rotation schedule of vessels. To stay competitive, ports could benefit from obtaining insight into how the system might change. It is important for ports to prepare themselves for possible future developments. However, since there are many stakeholders with different objectives, it is difficult to foresee how changes in a particular part of the system will influence the entire system. For this reason, ports must be adaptive because not responding in time to changes, could result in negative consequences for the ports itself. However, preparing for a wide range of possible futures is challenging. All components of the fuel supply chain are subjected to strong interdependencies. Therefore, it is possible that minor changes in one part of the system, result in a substantial change in the overall system (Halim, Kwakkel & Tavasszy, 2016).

1.1.1 The Port of Rotterdam

The Port of Rotterdam (PoR) is one of the port authorities dealing with this problem. The PoR is the biggest port of Europe and globally number 10. Moreover, it is the largest bunker port in Europe and is one of the top three largest bunker ports worldwide. The annual amount of fuel bunkered is about 11 million m3 (Port of Rotterdam, 2018). Due to the availability of refineries, all kinds of oil products are available and can be offered at a cheap price. Nevertheless, for the PoR, the transition to alternative fuels means a major change in bunker supply. PoR will be confronted with a loss in its role as a European oil hub (Acciaro, Ghiara & Inés, 2014). To remain competitive, it is important for the PoR to identify how the regulations influence the investment decisions of ship operators in the future, as well as the bunker behaviour of vessels. When getting insight into possible future scenarios for the emergence of the deployment of alternative fuels, the PoR can timely react and enable the required infrastructure. In this way, the PoR could reduce their risk, as well as the risks of ship operators and bunker suppliers. In addition, insight should be obtained into how certain port strategy could influence the emergence of alternative fuels to create robust strategies.

1.2 Literature review

This section entails a high-level overview of the literature related to emission abatement options and port strategies. In this way, the current state of knowledge and the lack of insight could be addressed.

1.2.1 Emission abatement technologies

Literature has assessed the technological, economic, and environmental performance of abatement technologies. The main characteristics, and disadvantages and advantages of propulsion technologies are discussed in these studies. Abundant studies have been conducted in the past which assess the performance of conventional fuels and after-treatment systems, such as Ma, Steenberg, Riera-Palou & Tait (2012), and Winnes, Moldanová, Anderson & Fridell (2016). Besides, LNG is often included in these studies as promising alternative fuel. Examples of these are Brynolf et al., (2014) and Bengtsson, Fridell & Andersson (2015). In addition, recent studies on the performance of emission abatement technology for the shipping industry are more focused on the use of alternative fuels, and in particular (bio) methanol. For example, the performance of methanol as a maritime fuel was examined by Andersson et al., (2015) and Svanberg et al. (2018). The analyses showed that methanol is a technically viable option to reduce ship emissions. In addition, a comprehensive study on the use of ethanol and methanol as fuels for the maritime industry was performed by Ellis and Tanneberger (2015). Technical, economical, as well as the environmental performance of the two fuels, were assessed. Moreover, such a study was also performed by DNV GL (2016). This study showed that methanol is only a potential fuel under certain circumstances, stated that the MGO price is an important variable, as well as the time spent in ECAs. A comparison of the environmental and economic performance of methanol, ethanol, LNG and hydrogen is performed by Deniz & Zincir (2016). Brynolf et al. (2014) assessed the lifecycle performance of LNG, LBG, methanol and bio methanol. Further, Seddiek & Elgohary (2014) made a comparison between scrubbers, SCR systems, LNG and biofuels.

1.2.2 Port strategies

In addition, there is literature available about the port strategies to reduce their emissions. Adams, Pallis & Quinonez (2009), examine the drivers for ports to improve their environmental performance. By means of a survey, 5 drives have been identified: 1) Regulatory compliance, 2) social pressure, 3) corporate conscience, 4) improving operational performance, and 5) competitive advantages. Gritsenko et al. (2013), performed a qualitative analysis to explain how the change in ship emission reduction affects maritime governance. They identified the changing position and strategies of ports. Besides, they identified two strategies which are likely to be adopted by Baltic ports: 1) investment in compliant fuelling infrastructure and 2) supporting the attractiveness of shipping as sustainable transport. Acciaro, Ghiara & Inés (2014) identified the role of port authorities as an energy manager. Port authorities can support energy management by energy production, consumption, and the uptake of renewable energy. The uptake of innovative technologies, such as alternative fuels calls for more attention to energy matters within port management. They argue that energy management can contribute to the competitive position of ports. For example, the future use of biofuels might be beneficial for the development of bunker services, which was noticed for the development of LNG services. Gibbs, Rigot-Muller, Mangen & Lalwani (2014) investigated the role of UK ports to reduce emissions in the maritime transport supply chain. An analysis was performed on both the emissions by port activities and the operational behaviour of vessels. It was stated that emissions generated by vessels are significantly higher than the ones generated by port activities. For this reason, it was suggested that ports should focus on reducing ship emissions. Options for ports were identified to support this change. Besides, suggestions for future research include performing an assessment of the change in the propulsion technologies of vessels, stating that some of the abatement options may depend upon the availability of infrastructure in ports. Chang & Wang (2012) conducted a study on the effects on green port policy. The study was focussed on the effects of speed reduction of vessels to reduce fuel consumption and emissions, and the effect of supplying on shore power. Furthermore, it was concluded that the implementation of ECAs is difficult to achieve in the short term because it will increase the ship owner's costs by 36,2%.

1.3 Knowledge gap and research objective

In short, literature has assessed the technological, economic, and environmental performance of abatement technologies. Besides, literature has identified that the change in regulations can impose a different role upon port authorities and that port policy is essential for the development of alternative fuels. However, less attention has been paid to the effects of interactions between stakeholders on the transition to alternative fuels. It is not yet known what the impact is of policies enforced by international, European and national authorities in order to enable the transition of the shipping sector towards the use of sustainable fuels (Maritime Knowledge Centre et al., 2018). Bas, De Boo, Vaes-Van de Hulsbeek, & Nikolic (2017) performed a study that presents a comprehensive systems perspective of the maritime fuel system, an agent-based model was developed that can be used to study the effects of policy measures on the use of alternative fuels. This study was focused on the adoption of LNG for deep-sea shipping on a global scale. However, such a study is not yet performed for the short sea shipping sector. For this reason, this research tries to fill in this knowledge gap, based on the following research question:

"What are the effects of port strategies on the deployment of alternative fuels for short sea shipping in Europe?"

The objective of this study is to obtain insight into what possible future scenarios for alternative fuels for the short sea shipping sector might arise and to provide insight into the effect of different policy measured implemented by the Port of Rotterdam Authority on the emergence of alternative fuels. Based on the main research question and the suggested research approach, the following sub-questions are formulated:

1. Which abatement technologies are likely to be deployed by short sea operators in Europe?
2. How might the bunker behaviour of short sea operators in Europe change in the future?
3. Which port policies could support the deployment of alternative fuels by short sea operators in Europe?

Sub question 1, aims to give insight into the investment decisions of ship operators towards emission abatement technologies. Subsequently, the second sub-question examines the influence of these investments on the bunker behaviour of vessels. Finally, by means of the third sub-question, the effects of policy measures by the Port of Rotterdam on the investment decisions and bunker behaviour is explored. An answer to the main research question follows from answering the sub-questions. In this way, long and short-term robust strategies that support the adoption of alternative fuels for short sea shipping in Europe could be developed.

This study considers the uncertainties to which the system is subjected and takes into account the interests of the stakeholders involved. The scope of this research is bounded to short sea shipping in Europe. This means that only vessels and ports operating in Europe will be considered, as well as the institutions that are relevant to this region. Besides, this study analyses the transition of the European short sea fuel system up till 2028.

1.4 Relevance to the CoSEM master's programme

The development of more sustainable fuels for shipping involves complex decisions and various actors. Moreover, economic, social, and environmental responsibilities are important aspects. The transition to alternative fuels faces multifaceted challenges, such as technical and organizational barriers, market and policy implications and social acceptance (Mansouri et al., 2015). This research will look at the problem from a socio-technical perspective. This means that there will be assessed what kind of technologies are needed, as well as how the use of these technologies could be stimulated. Both the multi-actor environment of the shipping sector in which each actor has its own interests, and the technical and institutional complexity, makes that the system under investigation is a complex socio-technical system, and therefore a relevant research within the CoSEM master's programme.

1.5 Thesis outline

Chapter 2 describes the research approach and methods that are applied in this study. In chapter 3, the results of the analysis of the European maritime short sea fuel system are presented. The regulations, operational aspects of the abatement technologies, the different aspects of the supply chain of the fuels and fuel markets are discussed, as well as the actors involved in the short sea shipping network. Chapter 4 introduces MarPEM and subsequently discusses the conceptualization and formalization of the model, as well as policy options applied to the model. The reusability of the model is discussed in chapter 5. Next, chapter 6, presents the outcomes of the model verification and stochasticity analysis. Chapter 7 entails the parameterization of the model and model validation. Afterwards, in chapter 8 the experimental design is presented. Chapter 9, reflects on the outcomes of the experiments. The discussion, and conclusions and recommendations are given in respectively chapter 10 and 11.

2. Research approach

The objective of this chapter is to explain the research approach and methods that are applied in this study. First, an introduction to complex adaptive systems is provided and how this motivates the choice to apply an agent-based modelling approach. Subsequently, the reason for using exploratory modelling and analysis as a second research approach is clarified. Finally, the research methods are discussed.

2.1 Research approach

In this section, a suitable research approach is described based on the main research question. Hereto, first, an introduction to complex adaptive systems (CAS) is provided. Subsequently, the agent-based modelling and exploratory modelling and analysis as research approach are explained

2.1.1 Complex Adaptive Systems

In this research, it is argued that the system under investigation, namely the European short sea fuel system, is a complex adaptive system. John H. Holland has defined the following definition of a CAS (Nikolic, 2009):

> *"A dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behaviour in the system, it has to arise from competition and cooperation among the agents themselves. The overall behaviour of the system is the result of a huge number of decisions made every moment by many individual agents."*

CAS are characterized by the fact that they must be able to be represented by multiple formalisms and the system behaviour emerges from bottom-up interactions between many heterogeneous, but related components. Besides, CAS are adaptive in a sense that they evolve over time in reaction to their environment (Ashby, 1968). In addition, according to Nikolic (2009), three system levels can be identified in a CAS-system. The first level, the lowest level, is the agent level. This level consists of the smallest system components, namely the agents. All system behaviour emerges from the characteristics and interactions of these agents and their environment. The stakeholders in the maritime fuel systems, like vessels, ports, and bunker terminals are defined on this level. The second level, the network level, describes the structures of these interactions, so in which way do these stakeholders interact with each other and influence each other's behaviour. The third level corresponds to the system level. The overall behaviour of the system results from the decisions made by all agents. The emergent system properties could be obtained through the system level.

The European short sea maritime fuel system is a socio-technical system consisting of technical subsystems, such as operating vessels, fuel production plants and bunker infrastructure. These technical systems are influenced by a complex network of many social systems, such as regulations of authorities and fuel markets. Many actors, like ship operators, regulatory authorities, and fuel producers are involved in different segments of the value chain of maritime fuels, each having its own goals, means and assets. The behaviour of these actors is adaptive in the sense that they learn and adapt their behaviour over time on the basis of their own status and their environment, such as fuel prices and regulations.

In this system, the transition to alternative fuels will emerge over time in which the interactions between external factors and actor behaviour are dynamic and complex. It involves both the changes in physical infrastructure, such as bunker infrastructure and vessels, and institutions that govern the behaviour of stakeholders. The interactions between technical and social systems can lead to emergent and co-evolutionary behaviour. For this reason, it is hard to understand and predict the outcomes of these interactions (Chappin & Dijkema,.2008). In addition, the maritime fuel system is subjected to path-dependency, meaning that options in the future are influenced and limited by decisions taken today and in the past, such as the investments in vessels by ship operators, the investments in bunker infrastructure by ports and fuel suppliers, and the investments in refineries by fuel producers. For this reason, there is a need for a clear understanding of the effects of policy measures. Besides, there is a need to test the different policies with the uncertainty involved in the system to evaluate the impact of these policies.

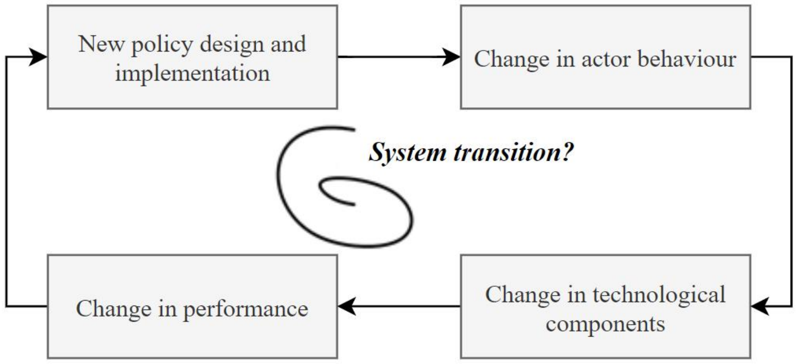

Figure 2.1: Transition of energy systems

2.1.2 Agent-based Modelling

Because the European short sea maritime fuel system is adaptive and assumes a bottom-up approach, it is important that the selected approach can deal with those properties. Traditional top-down models and economic optimization are not capable of this because they imply underlying implicit assumptions, such as the homogenous of actors (Chappin et al., 2008). Agent-based models can model the three characteristics of a CAS. An ABM conceptualises the system as interactions of many heterogeneous entities, represented by agents. The individual behaviour of the agents is determined by a set of rules which it must follow. Agents interact with each other and in this way, the overall behaviour of the system emerges. ABM is thus using a bottom-up approach (Nikolic, 2009).

In this study, ABM is used to map potential future states to examine where the European short sea maritime fuel system might go. The model is used as an exploratory tool to identify future scenarios towards the deployment of alternative fuels. In this way, insight can be obtained into the effects of interactions of the social and technical systems. Besides, agent-based models have some advantages as a support tool for policy making: ABM is easy to understand for those that are not familiar with this approach, the models are relatively transparent, and the models can deal with the complexity of interactions between the institutional environment and the individual behaviour of agents. Moreover, agent-based models are often used to analyse how transitions of systems may be facilitated (Van Dam, Nikolic & Lukszo, 2013). For these reasons, an agent-based approach will be used in this research

Bas et al. (2017) created an agent-based model which represents the maritime fuel system: Maritime Fuel Policy Exploration Model (MarPEM). This model can be used to study the effects of policy on the development of alternative fuels. The assumptions and the source code have been published. Therefore, it is possible to use the model for other studies as well. In this research, MarPEM is used to create a model to analyse the effects of policy measures on future scenarios for the European short sea maritime fuel system. However, to make the model useful for this particular purpose, adjustments to the model should be made. This requires a better understanding of the system's behaviour and interactions, as well as the system represented in MarPEM.

2.1.3 Exploratory Modelling and Analysis

Models are often used to predict system behaviour. However, this could be misleading when models are subject to deep uncertainty. Instead, models subjected to highly uncertain values should be used in a more exploratory way (Kwakkel, 2017). Exploratory modelling could be used to reason about systems subjected to deep uncertainty (Bankes, 1993). When insufficient knowledge or uncertainties exist when creating a model, a model cannot be taken as a reliable representation of the actual system and makes it difficult to validate the outcomes. However, exploratory modelling and analysis (EMA) could provide useful insights even when validation is impossible. Exploratory modelling uses many computational experiments to explore the implications of the assumptions that have been made in the modelling process. By doing so, the uncertainty space and decision space of the model can be identified and related to the output space. Two types of exploration approaches can be distinguished: 1) open exploration, e.g. a systematically sampling through the decision and uncertainty space, and 2) directed search, e.g. a search through the output space by using optimization approaches (Kwakkel, 2017). In this study, an open exploration will be used to understand the mapping of the uncertainty space and decisions space to the outcome space. In this way, more insight can be provided into possible outcomes, the uncertainties and the effects of policies.

2.2 Research methods

In the previous sections, the research approach to answer the research questions is discussed. It is discussed that a combination of an ABM and EMA approach is a suitable approach. This section describes which methods are used. The research can be divided into three phases: system analysis, model development, and experimentation and analysis. This section elaborates on these three phases.

2.2.1 System analysis

The system analysis aims to obtain insight into the characteristics of the European short sea maritime fuel system. The technical and physical aspects of the system are determined, as well as the social and economic aspects of the system. To perform the system analysis, scientific literature and experts are consulted to gain insight into how the European short sea maritime fuel system performs. Contact with these experts is set up via the PoR. The variety of experts consulted are specialized in different aspects of the system, ranging from advisory bodies, universities, authorities, and other involved companies to get a complete overview of the technical system, social interactions, and policy options. Another important source of knowledge is data obtained through the PoR. By means of analysing the data, main structures and behaviour of the system are identified.

2.2.2 Model development

An advantage of reusing MarPEM is that a lot of mechanisms and structures are already created. Therefore, it takes less effort to make a model that includes profound interactions. However, it is important to understand the full source code when adjusting the model and it is important to understand the differences between both systems. Moreover, you must deal with the existing structure of the model which could make it more difficult or even impossible to implement certain structures efficiently. This model is built in NetLogo, which is a free program and allows for easy implementation of agent-based models.

To be able to use MarPEM, first, a better understanding of the European short sea systems needs to be developed. More insight into the different agents, their behaviour and the relationships and interaction between these agents are obtained through the system analysis. A new system conceptualization is presented which makes the difference in the structure of both of the systems explicit. Assessed is whether MarPEM could be reused to represent the European maritime short sea fuel system and what is needed to enable the reuse of the model. After it is determined which parts of the source code can be reused, the model conceptualisation is implemented in MarPEM. During the implementation, the model is intermediary verified. This means it is checked if the model is implemented in the right way. Furthermore, the code should enable to test different policy options. After all adjustments were implemented in the model code, parameters had to be set. The data required for this is obtained through the PoR, scientific literature and reports. Besides, a stochasticity analysis and model validation are performed.

2.2.3 Experimentation and analysis

For the experimentation and analysis of the model outcomes, the EMA Workbench is used, an open source library implemented in Python which can connect with NetLogo models (Jaxa-Rozen & Kwakkel, 2018). The EMA Workbench can support decision making under deep uncertainty. There are other tools which can be used for EMA. However, an advantage of the EMA workbench is that it can work with simulation models which use the file system, which is the case for MarPEM. Another advantage of the workbench is that it allows for running experiments in parallel on a high-performance cluster (Jaxa-Rozen et al., 2018). Since the model has long computational times, the model has run on a high-performance cluster.

The workbench is based on three key concepts. Firstly, the XLRM framework which describes, exogenous or external factors (X), policy levers (L), relationship within the system (R), and performance metrics (M). This framework is used to structure relevant information. Uncertainties should be described as external factors (Kwakkel, 2017). Figure 2.2 illustrates this framework.

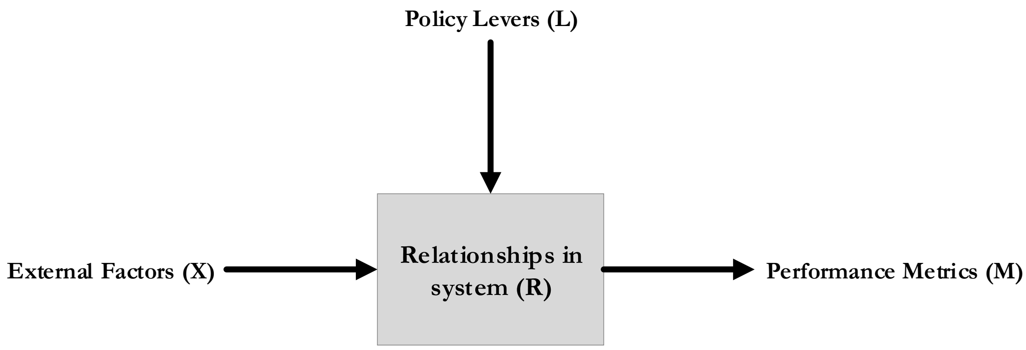

Figure 2.2: XLRM framework

Secondly, the workbench is based on the idea that the simulation model is running as if it is a function, $M = f(X, L)$. The third idea where the workbench is based on is a taxonomy of robustness frameworks (Kwakkel, 2017). So, to use the workbench, policy lever, external factors, and performance indicators must be defined for the experimental setup, as well as the number of replications, warm-up period and the time horizon. Replications of the experiments should be performed to deal with stochasticity present in the model. The PoR controls the model, e.g. they are the ones applying policies. All policies from other stakeholders will become external factors. To define policy levers, experts of the PoR are consulted.

The EMA workbench provides several techniques to perform analysis of the model outcomes. Feature scoring and scenario discovery are methods that are used to explore the uncertainty and decision space. Feature scoring is used to identify the most relevant features. Also, less important variables are identified by means of feature scoring. Scenario discovery is used to identify regions of interests and uncertain factors by means of analysing experiments. These regions are called scenarios. Dimensional stacking is applied to make the outcomes of scenario discovery more visual by means of creating a pivot table, using the most influential uncertainties (Kwakkel & Jaxa-Rozen, 2016). After analysing the data, it is possible to understand the mechanisms and interaction of the system as well as the uncertainties of the model outcomes. Furthermore, it is possible to identify policies and strategies to stimulate the use of alternative fuels for short sea shipping in Europe

3. System analysis

This chapter entails the relevant outcomes of the systems analysis. The system analysis is performed by means of desk research, consulting experts, and by analysing data. First, in section 3.1, the regulations related to ship emissions and the development of biofuels are discussed. Section 3.2 discusses the characteristics, advantageous and disadvantageous of each of the abatement technologies. Afterwards, in section 3.3 an overview of the supply chain of maritime fuels is given and the main differences between the different kind of fuels are discussed. Finally, in section 3.4, the European short sea shipping network will be explained.

3.1 Regulations

This section discusses the stricter regulations which are imposed upon the maritime sector. By means of these regulations, regulatory authorities aim to reduce the emissions of the maritime shipping industry. Besides, regulations towards the use of biofuels are discussed as well.

3.1.1 International Maritime Organization

Due to environmental concerns, maritime shipping emissions are increasingly regulated. The IMO, an agency of the United Nations, is responsible for the safety and security of shipping, and the prevention of environmental pollution by the shipping sector. Their main task is to establish a regulatory framework that is adopted globally (IMO, 2019). The maritime pollution convention (MARPOL) and the International Convention for the Safety of Life at Sea (SOLAS) are the two most important treaties of the IMO related to this research. The former sets minimum safety standards for the design and operation of vessels. MARPOL introduced Annex VI Prevention of Air Pollution from Ships which entered into force on in 2005 and was revised in 2008 (IMO, 2019). MARPOL Annex VI limits SOx and NOx emissions from maritime shipping. Up from 2020, a global maximum allowable sulphur content of 0.5% will be set. Currently, this cap is 3,5%. Besides, since 2015, specific SOx emission control areas (SECAs) are designated for which a cap of 0.1% sulphur content holds (Svanberg et al., 2018)

Figure 3.1: Emission Control Areas (Andersson & Salazar, 2015)

Further, the MARPOL Annex VI limits NOx emissions of vessels with engines of more than 130 kW output, dependent on the rotation speed and the age of the engine. The age of the engine determines whether Tier I, II or III is applicable. Tier I applies to vessels built between 2000 and 2011, Tier II for vessels built after 2011, and Tier III for vessels built after 2016 and sailing in NOx emission control areas (NECAs) (DNV GL, 2016). Currently, these NECAs are only in force in North America and the Caribbean area. However, in 2021, the North Sea and Baltic sea will be assigned as NECAs as well (Turner, Hassellöv, Ytreberg, & Anna Rutgersson, 2017). In addition, vessels need to have an Engine Air Pollution Prevention (EAPP) certificate and the International Air Pollution Prevention certificate (IAPP), which state that a vessel satisfies the MARPOL and Tier requirements (Elgohary et al., 2015).

Furthermore, the IMO developed a greenhouse gas reduction plan, which aims to reduce CO2 emissions with at least 50% by 2050 compared to 2008 (IMO, 2019). This plan will be implemented in 2023 and is mainly focussed on efficiency measures. Another regulation of the IMO to reduce emissions is the Energy Efficiency Design Index (EEDI). The EEDI requires a minimum energy efficiency level for new build vessels (IMO, 2019).

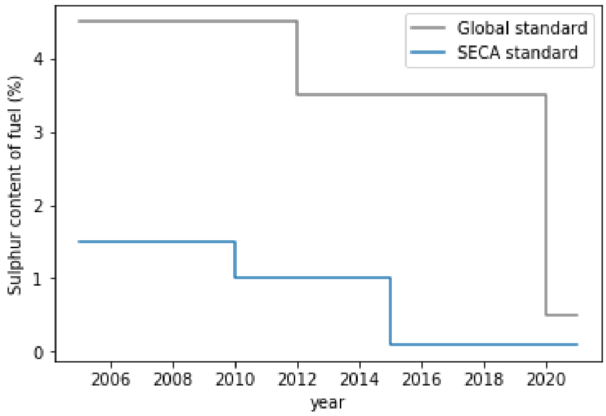

Figure 3.2: Allowable sulphur content

Table 3.1: Tier requirements

	Installation year of engine	NOx limit (g/kwh) *		
		n < 130	130> n < 2000	n>2000
Tier I	From 1 January 2000 to 1 January 2011	17,0	45*n^-0,2	9,8
Tier II	After January 2011	14,4	44* n^-0,23	7,7
Tier III	After January 2016, operating in NECA	3,4	9*n^-0,2	2,0

*n = engines rate speed (rpm). Reference: (CE Delft & TNO, 2017)

3.1.2 European regulations

Aside from the regulations set by the IMO, the European Union (EU) sets some stricter targets towards the reduction of ship emissions. The EU Marine Sulphur Directive implements MARPOL Annex VI with additional requirements. For vessels at berth in European ports, it is prohibited to use fuels with a sulphur content higher than 0.1%. Besides, from 2018 on, vessels making use of EU ports must report their emissions (DNV GL, 2016).

Another EU directive that limits the amount of emissions from the shipping industry is the Renewable Energy Directive (RED) which promotes the production of energy from renewable energy sources. It states that by 2020 at least 20% of the total energy demand needs to come from renewable energy sources. Moreover, the RED states that member states must ensure that at least 10% of their transport fuel comes from renewable energy sources by 2020 (Phillips, Flach, Lieberz, Rossetti, 2018). Biofuels can help to achieve these targets. The RED contains biofuel sustainability criteria to ensure that they are produced in a sustainable and environmentally friendly way. For this reason, in 2015 the indirect land use change (ILUC) directive came into force which complements the RED and the Fuel Quality Directive (FQD) (Phillips et al., 2018). While biofuels are an important mean to reduce greenhouse gas emissions, the production of biofuels typically takes place on agricultural land which is used to produce food or feed, or is produced on grasslands and forests, the latter is known as ILUC. Grasslands and forest are absorbing large amounts of CO2. When using these biofuels, the relative amount of CO2 reduction decreases (European Commission, 2019). Based on the feedstock, three types of biofuels can be distinguished:

- First-generation biofuels: these biofuels are produced from oils, sugar, starches from food crops such as sugar cane, corn, rapeseed, and soybeans. At present, most biofuels, such as bioethanol and biodiesel, are produced from first-generation biomass due to the maturity of technologies and the lower production costs. Nevertheless, concerns about these fuels are raised since they compete for land with food production and might affect the food prices (Yue, You & Snyder, 2014). For this reason, the ILUC directive limits the share of first-generation biofuels to 7% by 2020 (Phillips et al., 2018).
- Second-generation biofuels: these are made from lingo-cellulosic biomass, which can be produced from forest or agricultural residues. This group does not have an impact on the food supply because they are non-starchy, non-edible and non-food feedstock (Yue et al., 2014). A major drawback of second-generation biofuels is that it is hard to convert the lingo-cellulosic biomass into sugars. This makes it more difficult to produce some of the biofuels, like bio-ethanol, in a cost-efficient way (Yue et al., 2014). The ILUC directive sets a target of 0.5% for these advanced biofuels (Phillips et al, 2018).
- Third generation biofuels: this group of biofuels is produced from algae. Algae can grow on water and therefore do not use any valuable agricultural land and do not compete with food production (DNV GL, 2018).

3.2 Emission abatement technologies

Solutions are available for ship operators to reduce ship emissions and to be compliant with the stricter regulations. Promising emission abatement technologies considered in this research are after-treatment systems, LNG, and methanol. This section discusses the main characteristics, advantages, and disadvantages of each of these technologies.

3.2.1 After-treatment systems

After-treatment systems are installations on board of vessels that remove negative emissions from the exhaust gases. By installing after-treatments systems, conventional fuels can continued be used to comply with regulations (Ellis & Tanneberger, 2015). This section describes two types of after-treatment systems, namely: scrubbers and selective catalytic reduction (SCR) installations.

3.2.1.1 Scrubbers

Sulphur emissions can be reduced by using HFO in combinations with a sulphur scrubber. A scrubber washes the sulphur from the exhaust gases. However, they are not suitable to reduce NOx emissions or CO2 emissions (Alphatanker, 2018; Andersson et al., 2015). Therefore, scrubbers are an abatement method that does comply with the sulphur restrictions but does not comply with the Tier regulations. Thus, additional measures should be taken when operating in ECAs (Ellis & Tanneberger, 2015).

Scrubbers have high capital and operational costs, but in contrast with other abatement options, it is possible to use low-priced HFO. There are two kinds of scrubbers: 1) open-loop scrubbers, which use seawater, and 2) closed-loop scrubbers, which use chemicals to abstract the sulphur from the emissions

(Bengtsson et al., 2015). The scrubber installations require additional space onboard and add to the total weight of a vessel (Ellis & Tanneberger, 2015). Furthermore, operating with a scrubber increases the fuel consumption, 3% for seawater scrubbers and 1% for closed-loop scrubbers (Andersson et al., 2015). The use of open-loop scrubbers is less suitable to be used for vessels operating in brackish water, such as the Baltic Sea. Closed-looped scrubbers do not have this restriction but use sodium hydroxide which requires safety measure (Andersson et al., 2015). Another option is to use hybrid scrubbers (Bengtsson et al., 2015).

The instalment of scrubbers has been slow. In 2017, about 370 scrubbers were installed worldwide. However, it is expected that the number of installed scrubbers will increase rapidly (Alphatanker, 2018). Currently, most installed scrubbers are open-loop scrubbers. When ship operators own several vessels of the same type, the same scrubber design can be used which reduces the costs significantly. Besides, scrubbers are not expected to be installed on vessels with a lifetime of over 10 years (Alphatanker, 2018). Further, the instalment of scrubbers is more cost-effective when installed on larger vessels due to the loss of freight capacity. However, in the past, scrubbers have been installed on small vessels as well. Open-loop scrubbers are the cheapest scrubbers to install and to operate. Hybrid systems are the most expensive to install, but cheaper to operate than closed-loop scrubbers. Hybrid and close- loop scrubbers require caustic soda to remove the sulphur, this increases the operational costs (Alphatanker, 2018). The economic attractiveness of a scrubber highly depends on the HFO and MGO prices. When the difference between the two increases it could be more attractive to install scrubbers and use HFO instead of switching to MGO (Alphatanker, 2018).

3.2.1.2 SCR systems

To be able to use HFO or MGO in NECAs, NOx emissions could be reduced with SCR systems, emulsification, humid air, engine tuning, and exhaust gas recirculation. An SCR system is the only option that gives more than an 80% reduction (namely 95%) and will therefore be considered in this research (Seddiek et al., 2014). The installation converts NOx in nitrogen gas and can be installed in combination with any type of engine. However, to be used, the exhaust gas requires a minimal temperature of about 300°C. Therefore, these systems are less effective at low load and for two-stroke engines. During the start-up, the SCR cannot be used at all (Bengtsson et al., 2015).

It is possible to install an SCR system in combination with a scrubber to satisfy the sulphur and nitrogen regulations (Ellis & Tanneberger, 2015). Investments costs of a scrubber and an SCR installation are in the same range of the investment costs of methanol propulsion technology. The extra operational costs of after-treatments installations are typically between 4 to 6 euros/MWh (Andersson et al., 2015). Both after-treatment options require additional space on board of vessels. This might reduce the capacity for freight (Ellis & Tanneberger, 2015). An advantage of using after treatment options is that vessels are not dependent on the availability of fuels and bunker infrastructure in ports.

3.2.2 Liquefied natural gas propulsion technology

LNG could be a promising fuel for short sea shipping (Bengtsson et al., 2014). It is the cleanest conventional fuel available. It is free from sulphur emissions and the nitrogen emissions are extremely low DNV GL, 2018). Nevertheless, it is still made from non-renewable energy sources and the methane slip from the engines when using LNG contains greenhouse gases (Brynolf, Magnusson, Fidell & Andersson, 2014).

Currently, LNG is already used as a fuel for the maritime sector. The number of vessels using LNG is about 154 of which 113 operating in Europe (DNV GL, 2019). The EU supports the development of LNG bunker infrastructure in 144 ports across Europe, which supports the deployment of LNG (Martínez-Ló Pez, Caamañ O Sobrino, Chica González, & Trujillo, 2018.).

LNG is produced by cooling natural gas to -162 °C, at which it becomes liquid. Besides, it is also possible to produce LNG from biogas, known as liquefied biogas. The compressed gas has a decrease in volume by a factor more than 600 (Elgohary et al., 2015). Nevertheless, storage of LNG is more space consuming compared to diesel fuels since it has a lower energy content. This might have an influence on the amount of capacity available for cargo (Bengtsson, Fridell & Andersson, 2014). The fuel consumption will slightly increase, from 0.057 for diesel fuels to 0.059 kWh/ton cargo per kilometre for LNG fuels (Bengtsson et al., 2014).

The use of LNG requires major modifications to a vessel, such as the engines (valves, piston and fuel injector), LNG storage capacity, the fuelling systems, gas detection systems, and the exhaust ventilation system (Seddiek et al., 2014) The modifications needed depend on the type of vessel. Retrofitting does not seem to be a viable option. Thus, uptake is expected to take place especially amongst newly build vessels (TNO & CE Delft, 2017). The estimated costs of a vessel conversion are between the $7million and $24 million depending on the ship size (Elgohary et al., 2015). The high costs of the vessel conversion could be compensated by the low fuel costs of LNG compared to other alternative fuels. In addition, the use of LNG requires the availability of infrastructure in ports, such as bunker barges or LNG terminals. Therefore, vessels operating on fixed routes are more likely to invest in LNG because the vessels must be sure of being able to bunker fuel (Alphatanker, 2018).

3.2.3 Methanol propulsion technology

It is shown that methanol is a viable alternative fuel for improving the environmental performance of shipping (Maritime Knowledge Centre et al., 2018). Methanol is free from sulphur emission and produces a low level of nitrogen oxide. For this reason, it is compliant with sulphur regulations and Tier III (Andersson et al., 2015).

Methanol is the simplest alcohol with the lowest carbon content of any liquid fuel. It is a liquid at standard temperature and pressure. For this reason, it is less difficult to consume and distribute than LNG (Brynolf et al., 2014). Methanol can be produced from several kinds of feedstock. At present, it is often produced by the conversion of natural gas or coal gasification. However, more sustainable resources could be used for the production as well, such as biomass, renewable electricity, or hydrogen (Brynolf, Taljegard, Grahn & Hansson, 2018).

As a transport fuel, methanol has been tested and used in the automotive industry. Nevertheless, the shipping sector has little experience with methanol as a fuel (Bengtsson, Fridell & Andersson, 2012). However, the interests in methanol as a shipping fuel has started with the Swedish project Effship in 2009 (Svanberg et al., 2018). Since then, other projects have been executed, such as the Stena Germanica methanol ferry, Spireth, and Summeth (Ellis & Tanneberger, 2015). These projects have proven that the technology is available and viable. However, according to SOLAS, fuels with a flashpoint below 60°C are not allowed to be used by vessels. Methanol has a flashpoint below 60°C and therefore a risk assessment should be executed to assure that the fuel has an equivalent level of safety (Maritime Knowledge Centre, TNO & TU Delft, 2017). Methanol is biodegradable and therefore, in case of a spill, it will be less environmentally harmful compared to conventional fuels (Kasmuri, Rozaimah, Abdullah, & Hasan, 2016). Nowadays, there are 12 methanol-fuelled vessels operating globally (DNV GL, 2019).

Because methanol is liquid at standard temperature, it can be stored in the same fuel tanks as HFO. The energy content of methanol is about half the energy content of oil. Therefore, methanol fuel tanks require about 2,5 more space on board compared to oil tanks (DNV GL, 2018). For these reasons, ship owners should make the choice between increasing the volume of the fuel tank or to bunker more often. The latter is depending on the trade route of the vessel (Ellis & Tanneberger, 2015). The investment costs for methanol are significantly less than for LNG (DNVGL, 2016).

When considering the full supply chain of methanol produced from natural gas, the total CO2 emissions are slightly higher than the emission corresponding to conventional fuels. When methanol is produced from coal it has twice as much CO2 emissions compared to natural gas (DNVGL, 2016). However, methanol produced by coal gasification mainly takes place in China and is not exported to Europe (Andersson et al., 2015). The combustion of methanol in the engine reduces the tank-to-propeller emissions. The well-to-tank emissions from bio methanol are significantly less than the well-to-tank emission of methanol produced from natural gas (DNVGL, 2016). Besides, bio methanol has significantly lower greenhouse gas emission compared to conventional fuel oils (Maritime Knowledge Centre et al., 2018). This percentage depends on the feedstock that is used for the production of methanol (Svanberg et al., 2018).

3.3 Maritime fuels

The Maritime fuel system consists of two parts. On the one side there in the supply side of bunker fuels and on the other side the demand side of bunker fuels. The former comprises the supply chain of the fuels, the latter consist of the short sea shipping network. Within the supply chains of maritime fuels, many stakeholders are active. These stakeholders are interacting with each other by means of physical product flows and markets, each trying to minimize its costs and maximize it revenues. Figure 3.3 depicts the supply chain of marine fuels. This section discusses the characteristics of the fuels considered in this study in more detail and reflects on the differences in supply chains of the fuels.

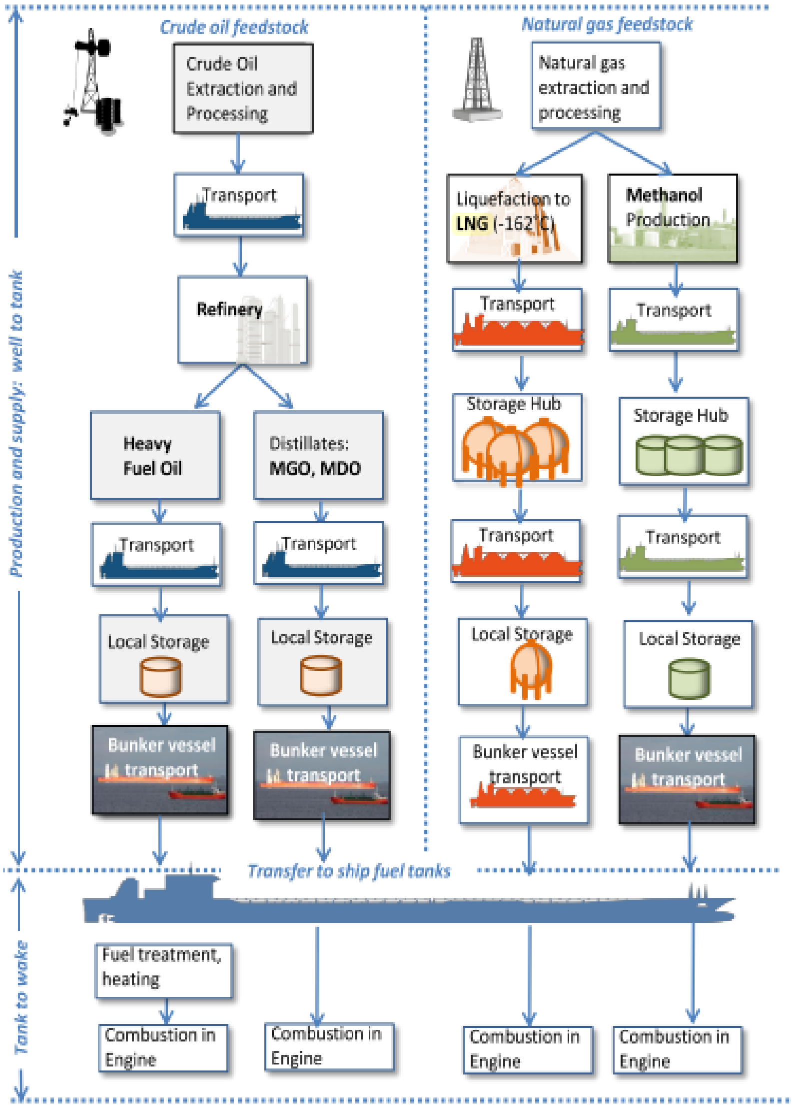

Figure 3.3: Supply chain of maritime fuel (Ellis & Tanneberger, 2015)

3.3.1 Conventional fuels

HFOs and MGO are produced in refineries all over the world. These fuels have been used as bunker fuels since the 1960s. HFOs are produced from residual crude oil. Distillate fuels, such as MGO and MDO can be obtained when processing crude oil in refineries. The HFO produced nowadays is mostly produced with a high sulphur content. HFO, with a low sulphur content of 1% is only produced in a few refineries (Alphatanker, 2018). However, to satisfy the SECA requirements, the sulphur content should be further reduced. Reducing the sulphur content is technically possible but requires more processes within the refineries, such as catalytic cracking and hydro skimming. Currently, refineries do not have the capacity to do this (Alphatanker, 2018). Moreover, the refinery industry is unable to prepare themselves, due to the long lead times of refinery projects. Thus, for refineries, it is often too late to respond to the stricter regulations of the IMO to opt for 2020, since the construction of new build low sulphur production units takes a minimum of 8 years to be realized and installing new units as cookers or hydrocrackers could take 5 years (Alphatanker, 2018). The large investment costs by refineries that must be made to produce low-sulphur fuels, causes that low-sulphur conventional fuels are associated with higher costs (Stikkelman, Minnée, Prinssen, & Correljé, 2011).

3.3.2 Liquefied natural gas

In 2017, the global trade amounted 293,1 million tonnes (Chevron, 2018). The natural gas sector is expected to be able to supply sufficient quantities of LNG and the infrastructure for inland waterways and short sea shipping (Bengtsson et al., 2014, DNV GL, 2018). In Europe, LNG competes with natural gas. 10% of the natural gas market consists of LNG and amounts approximately 320 m t/a and is expected to increase to 460 m t/a by 2020 (DNVGL, 2016). By liquefying natural gas, natural gas can be transported over long distances (TNO & CE Delft, 2017). Due to new producers, such as Australia and the US, the supply of natural gas is higher than the demand. This results in a relatively low gas price and which is interesting for the maritime fuel markets. Besides, the high oil prices over the past few years make LNG more attractive (Alphatanker, 2018). LNG bunker prices are depending on the LNG import prices. The import prices highly depend on the capex of the liquefaction plants, the amount of gas reserves, the capacity of LNG infrastructure, and demand for LNG (TNO & CE Delft, 2017). When comparing LNG prices on a calorific value, they are often less than HFO bunker fuel prices. The advantage of these costs depends on future oil prices (Maritime Knowledge Centre, 2018).

3.3.3 Methanol

The global methanol production amounts to approximately 75 million metric tons per year (Maritime Knowledge Centre et al., 2018). Worldwide the methanol capacity is about 144 million tons, of which most located in China, South America, and North America. The methanol production capacity in Europe amounts approximately 4 million tons (Argus, 2018). The only large-scale methanol plant in Europe is located in Norway (Ellis & Tanneberger, 2015). Today, about 80% of the methanol production is produced from natural gas and 17% is produced by coal gasification (Iaquaniello, Centi, Salladini & Palo. 2018). About 60% of the global methanol demand is consumed in China, where the demand has been increased rapidly in de past few years. Methanol is an important feedstock for the chemical industry and used for products as plastics, paints, and coatings (DNV GL, 2018). Formaldehyde, active acid, and olefins are important building blocks for these products are produced from methanol. (DNV GL, 2016) It is predicted that the current methanol production is able to supply enough methanol to cover the demand of the shipping sector till 2030 since it is assumed that the use of methanol as a bunker fuel is growing slowly (DNVGL, 2016). The feedstock used to produce methanol accounts for approximately 90% of the production costs. Therefore, the production of methanol takes mainly place at locations where there is access to low-cost feedstock (Iaquaniello et al., 2018). Moreover, when natural gas has been used as feedstock, production plants are often located close by the well, since it is easier and cheaper to transport the liquid methanol fuel than to transport the gas.

The costs of methanol depend on the type of feedstock, nowadays natural gas is mainly used for the production of methanol. Therefore, the methanol price is usually coupled with the natural gas price and for this reason higher than the natural gas price (DNVGL, 2016). Prices might be lower when methanol is produced from coal (DNVGL, 2016). Moreover, the competitiveness of methanol depends on the oil prices for heavy fuel oils (HFO) and marine gas oil (MGO) and natural gas prices (Ellis & Tanneberger, 2015). The methanol price is normally between HFO and MGO prices (DNVGL, 2016). Moreover, in recent years, the exploitation of shale gas in North America led to an increase of methanol production in North-America with production costs close to the methanol produced in South-America.

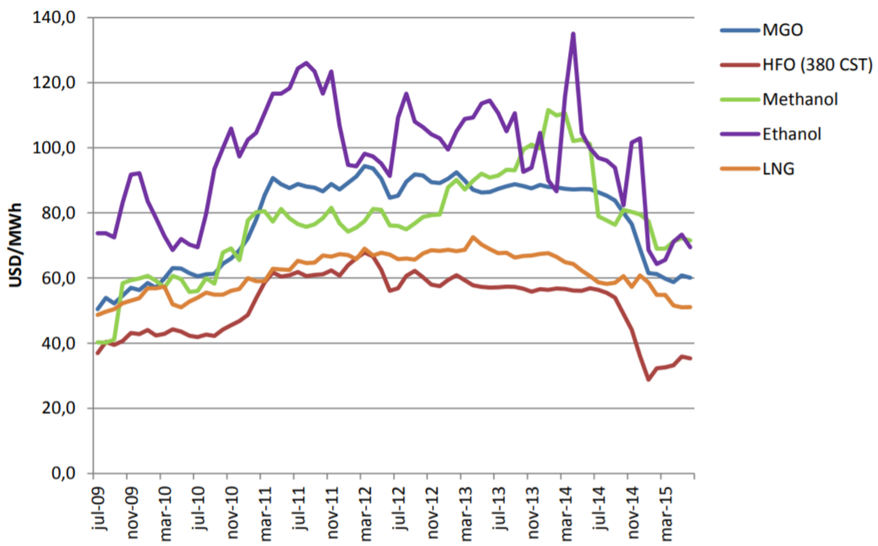

Figure 3.4: Historical fuel prices (Ellis & Tanneberger, 2015)

3.3.4 Bio methanol

Bio methanol is produced from biomass, which is organic material from plants or animals, such as agricultural crops or forest residues. Biofuels are often considered as carbon neutral since the CO2 released during production and consumption is captured during the growth of the biomass (Ellis & Tanneberger, 2015). Therefore, biomass is expected to play an important role to mitigate climate change (Bengtsson et al., 2012). In comparison with conventional fuels, biomass is fast to grow and can be replaced without depleting natural resources. However, the availability of biomass is limited and per different per region. The growth of biomass is seasonal from nature and this causes an annual variability of supply (Iakovou, Karafiannidis, Vlachos, Toka &Malamakis, 2010).

Using biomass as feedstock can decrease the dependence on conventional energy sources and can therefore contribute to the energy security and independence of countries not possessing conventional resources. Furthermore, biofuels might create employment opportunities and income, and enhance economic developments (Tyrovola, Dodal, Kalligeros Zannikos & 2017). The use of biomass for the heating and electricity sector might be more cost-effective than using it for the transportation sector. Moreover, the petrochemical industry makes a large range of products from oils, which could be substituted by biomass as well (Yue et al., 2014). For this reason, policy measures are thus required to allocate the biomass resources in an efficient way (Bengtsson et al., 2012).

3.3.4.1 Production process

Different kinds of biofuels can be produced from biomass, such as biodiesel, bio-oils, biogas, or alcohols. The production of these fuels takes place in biorefineries. In these refineries, the biomass is converted into biofuels, power, or chemicals. Two often used conversion technologies are biochemical and thermochemical technologies (Yue et al., 2014). The thermochemical pathway to produce methanol is basically the same as that of the conventional production of methanol. By means of gasification, biomass can be converted into syngas. Through the catalytic conversion of the syngas, methanol can be produced (Shamsul, Kamarudin, Rahman, & Kofli, 2014). The following reactions take place:

$$CO + 2H2 \rightarrow CH3OH \tag{1}$$

$$CO + 3H2 \rightarrow CHC3OH + H2O \tag{2}$$

$$CO2 + H2 \rightarrow CO + H20 \tag{3}$$

The conversion requires high pressures and/or low temperatures and the use of a chemical catalyst. This makes the production of methanol rather expensive (Yue et al., 2014). Another way of producing methanol in a thermochemical way is by direct oxidation of methane via the reaction $2CH_4 + O_2 \rightarrow 2CH_3OH$.

By means of biochemical processes, biogas could be produced through anaerobic digestion of biomass which could serve as a replacement of LNG when liquefying it. The biogas can be used as fuel; however, biogas is difficult to store and transport (Yue et al., 2014). By converting the biogas into bio methanol or bioethanol, these problems can be solved. The production of bio methanol has a higher thermal efficiency and lower carbon emissions than the production of bioethanol and is therefore preferred. For example, one metric ton of wood can be converted into 510 L methanol or 290 L ethanol (Hasegawa, Yokoyama & Imou, 2010). When considering the costs of producing bio methanol and bioethanol produced from second-generation feedstock, the costs for bioethanol are estimated to be about 1000 to 13000 euro/ton and the costs of bio methanol about 200 to 400 euros per ton. However, the energy content of bio methanol is lower than the energy content of bioethanol. So, if the energy unit costs are compared than the costs of bio methanol are about 0.2-0.3 times lower than the costs for bioethanol (Iaquaniello et al., 2018).

The selection of these conversion technologies is an important decision because of the capital and operation costs and is dependent on the kind of feedstock. The cost-effectiveness of different production processes might vary per location (Yue et al., 2014).

3.3.4.2 Bio methanol production plants

The availability of bio methanol is limited and restricted per area. It is currently only produced at a few locations in small quantities (Svanberg et al., 2018). Bio methanol could be produced from a wide range of biomass feedstock. At present, municipal and industrial waste, biomass, and carbon dioxide are used as feedstock for methanol. In this section, the production locations of methanol are discussed.

BioMCN - Netherlands

BioMCN, located in the North of the Netherlands, was the world's first company to produce bio methanol at a commercial scale. The production plant of BioMCN produces about 450.000 ton/y methanol (Balegedde Ramachandran, Oudenhoven, Kersten, van Rossum & van der Ham, 2013). When biodiesel is produced by means of transesterification, the by-product glycerol is produced as well (Almeida, Andrade & Santos, 2017). Since glycerol can be used for many applications in the chemical industry, it is a valuable product and cannot be considered as a waste product. BioMCN uses glycerol to produce bio methanol. Glycerol is converted into biogas which can be converted into bio methanol (Almeida et al., 2017). Balegedde Ramachandran (2013), performed a cost analysis of the BioMCN plant in the Netherlands. A techno-economic analysis showed that with a natural gas price of 0.2 euro/ton and an assumed glycerol price of 200 euro/ton, the costs of the production of bio methanol would be approximately 433 euro/ton, which is 75 euro/ton more than when methanol is produced via natural gas (Balegedde Ramachandran et al., 2013).

Enerkem - Canada

Enerkem is a Canadian company which produces bio methanol from waste. The first commercial-scale methanol production plant came in operation in 2015. The plant converts municipal waste into syngas, which subsequently is converted into methanol. Per year 100.000 dry ton of municipal waste is converted into 38 million litres/y of methanol (Enerkem, 2019). The use of municipal waste to produce fuels can significantly improve sustainability. The advantage of using municipal waste is that it is a waste produced and must be processed anyway, the costs of the feedstock are therefore relatively cheap. For example, forest residues are considered costlier because they need to be harvested, transported and pre-treated for gasification (Iaquaniello et al., 2018). Aside from the advantages of using waste as a feedstock, securing the supply of waste could be challenging (Yue et al., 2014). Besides, the efficiency of waste incineration is often low, about 35%-40 % (Iaquaniello et al., 2018). The emission reduction of methanol from waste compared to the emissions from methanol produced from natural gas are about 1.2 kg CO2 versus 2.18 kg CO2, including the emissions from production and consumption. Iaquaniello et al., 2018 made a cost assessment of methanol produced from waste. The estimates costs were about 110 euro/ton for a 300 ton/day plant.

Demonstration projects - Sweden

Bio methanol can be produced from forest residues or black liquor from pulp mills. Black liquor has been identified as an interesting feedstock for renewable energy because it is worldwide available in large quantities. Worldwide, every year, approximately 400 million tons of pulp is produced. The production of one ton of pulp comes with the production of about seven tons of black liquor (Maritime Knowledge Centre et al., 2018). Several demonstration projects with small scale plants are performed in Sweden. A pilot plant in Pitea tested the production of methanol from black liquor (Ellis & Ramme, 2018). Besides, VarmlandsMetanol AB has developed a process that converts biomass into methanol by means of the gasification of forest residues. However, this plant is still not in operation. It is expected that the plant can produce 300 t/d methanol and deliver thermal heat water to households (Shamsul et al., 2014). In addition, a project has started to produce methanol from CO2 of biomass origin and electricity in 2017. These projects did not lead to scale-ups, due to the uncertainty in regulations (Ellis et al., 2018).

Carbon Recycling International - Iceland

In Iceland, CO2 captured from a geothermal plant is used to produce methanol. The CO2 is reconverted into syngas by means of an electrolysis process. The plant produces about 4000 metric ton/year. The methanol is certified as a renewable fuel from a non-biological origin (Ellis & Tanneberger, 2015). The technology used to recover the CO2 has been developed by Mitsubishi Heavy Industries (Andersson et al., 2015).

Waste-to-Chemicals - Rotterdam

The Waste-to-Chemicals project, now under development in Rotterdam, will convert waste into methanol. The plant will process 360.000 tons of municipal waste into 220.000 tons of methanol. It is estimated that the plant will reduce CO2 emissions by approximately 300.000 tons per year. Also, the plant reduces SOx and NOx emissions. The technology of Enerkem will be used to convert the waste into synthesis gas by a thermochemical process. Air Liquide and AkzoNobel will supply the oxygen and hydrogen needed for the conversion. The methanol can be used by the industry and transport sector (Port of Rotterdam, 2019).

3.3.4.3 Distribution

The processes within the supply chain of marine fuels, such as collection, production, storage, and consumption, take place at different locations. The low-energy density of the bio methanol feedstock requires considerable collection and transport efforts. Biomass is the only renewable energy sources that can be stored easily until needed and provides an alternative for transportation fuels (Yue et al., 2014). However, the larger volumes due to the low-energy density of the feedstock make that larger storage facilities are required. Production takes mostly place close to the source of the feedstock. When designing a biofuel supply chain, a trade-off should be made between the costs of transportation and the capital costs of production plants. Transportation costs, such as collecting and transporting the biomass to the production plants, account for a significant part of the total fuel costs. When comparing the biofuel supply chain with the conventional fuel supply chains, the transportations costs of biofuels are much higher and take a larger part of the total costs (Yue et al., 2014). When looking to refineries, there is a clear rule of economies of scale, however, this is not always the case for bio refineries. Production costs could be lowered by building larger production plants. However, the costs of supply could increase as transport distances will increase. Further, some locations for production plants are more favourable because of the availability of feedstock. Moreover, costs can be reduced by integration or co-location with other industries. After production, the fuels are stored, often in larges industrial hubs. Afterwards, the fuels are transported to local storage hubs for further distribution. Transportation can take place by vessel or truck (Yue et al., 2014).

3.4 Short sea shipping network

The previous section has discussed the main characteristics of the supply side of each maritime fuel. However, the demand for bunker fuel is determined by the short sea shipping network. This network consists of ports, shipping lanes and vessels operating in the coastal waters of Europe. The different aspects of the shipping network are explained in this section.

3.4.1 Ports

The European short sea network consists of more than 200 destinations for short sea shipping. These ports are located in Europe, or non-European countries located at the Mediterranean and the Black Sea. Ports vary in size, institutional structure, and environmental strategies.

3.4.1.1 Role of port authorities

Over the last decades, port authorities shift from a public organization to more privatized bodies. This shift is taking place to enhance port performance and competitiveness. Ports have a meaningful role in regional economic developed by facilitating maritime trade and economic activities, which creates employment and investments (Wang & Notteboom, 2015). Furthermore, traditionally, port authorities had the role of landlord, regulator, and operator. However, the operator role, such as cargo handling has been shifted to private operators. The landlord function consists of management maintenance and development of the ports area, as well as the facilitation of infrastructure (Wang & Notteboom, 2015). Apart from these functions, ports develop policies and strategies related to the exploitation of the port area. Corporate social responsibility is getting more attention and becomes part of port's strategies. Therefore, more attention has been paid to social and environmental aspects as well. Port authorities could benefit from the facilitation and promotion of innovative technologies. These innovative technologies could help the ports to achieve their green and sustainability goals (Wang & Notteboom, 2015). Sustainable strategies require ports to be adaptive to regulations and quickly responds to customer demands. Four actions could be undertaken in order to enhance their sustainability; developing renewable energy, using onshore electricity for vessels at berth and electrification of other port-related processes, the promotion of sustainable model split for hinterland distribution, and providing alternative fuels for vessels (Wang & Notteboom, 2015).

3.4.1.2 Port regulations

To enhance the attractiveness of a port, it can be beneficial for a port to differentiate themselves from other ports, for example through the availability of alternative fuels in a port. Port authorities can undertake several actions to promote the use of these alternative fuels. Firstly, a port could invest in bunkering infrastructures, such as bunker terminals and bunker barges. Secondly, ports could play a role in the assessment of the safety risks of alternative fuels. In this way, they could develop bunker standards and guidelines which should be included in the corresponding Port by Laws. Thirdly, Port Authorities could stimulate collaboration and knowledge sharing between stakeholders. Finally, financial support schemes, such as the Environmental Ship Index or Green Awards could stimulate the use of alternative fuels. Both measures affect the port dues for vessels and have already been implemented by some European ports. It will have a bigger influence when more ports are implementing this system to create a common system (Stikkelman et al., 2011). Ports also have the possibility to implement a distance related emission charges system. In such a system, the charges are depending on the distance travelled before entering a port. However, the problem is that vessels might travel extra kilometres to avoid or reduce the charges, which could lead to extra emissions. Therefore, this system only works when more ports are applying this system (Stikkelman et al., 2011).

Furthermore, ports could apply for subsidies from the EU, national or local governments to support investments in infrastructure or lobbying and assisting these authorities to enforce emissions standards (Stikkelman et al., 2011). Taxation of emissions is another measure which can reduce emissions. However, this measure could not be implemented by the ports themselves but should be enforced on a national or European level. Another way of taxation is by charging taxes on the bunkering of conventional fuels (Stikkelman et al., 2011). This will make conventional fuels less attractive and make alternative fuels more competitive. Further, emission trading could be an alternative to reduce the emissions from vessels. Ample policy measures are available for the reduction of maritime emissions. However, for some of the policies, ports are highly dependent on governmental regulations.

3.4.1.3 Availability of bunker infrastructure in ports

The rise of alternative fuels as a bunker fuel has been described as the "Chicken and the egg problem". The absence of bunker infrastructure in ports could be a barrier for ship operators to invest in alternative fuels. Therefore, it is important that a network of bunker facilities is available. This was an important requirement for LNG to become an attractive fuel (Svanberg et al., 2018). Port authorities play an active role in the facilitation of alternative fuels. However, ports need to have some certainty that investment by ship operators will take place and the infrastructure will be used.

Nevertheless, several port authorities have taken responsibility for the development of LNG infrastructure. LNG is globally available and the availability of infrastructural assets, such as LNG bunker vessels and terminals, is increasing rapidly. Gas producers have started to invest LNG bunkers infrastructure to speed up the transition to LNG. In 2017, LNG bunker vessels became available in key locations, such as Rotterdam, Amsterdam, and Antwerp, the North Sea region, and the Baltic Sea (DNV GL, 2018). However, due to the high costs, the LNG development in small and medium-sized ports is lagging. For this reason, some ports chose to invest in bunker barges that obtain the LNG from close by LNG terminals instead of building their own LNG facility. Currently, the distribution of LNG is taking by vessels or road. However, not practiced yet, distribution by rail is also possible (DNV GL, 2016).

The bunker infrastructure for methanol is not well developed yet. However, storage and supply of methanol are available at many places due to the use of methanol by the chemical industry, for example in the Port of Rotterdam (PoR) and Antwerp (Ellis & Tanneberger, 2015). Therefore, the costs of infrastructure investments are relatively low compared to LNG and only minor adjustments are needed to provide methanol. The investment costs of a small methanol bunker facility are estimated at around 400.000 euros and the conversion of a bunker barge to carry methanol costs approximately 1,5 million euro, compared with 50 million euro to build an LNG terminal and 30 million euro to build a new LNG bunker barge (Jordan & Hickin, 2017).

3.4.2 Ship operators

The European short sea sector is characterized by many parties operating in these waters. Two types of operating vessels could be distinguished, liner vessels and charter vessels. These parties transport different kinds of cargo from one port to another port located in Europe. This section describes the analysis that has been performed to obtain insight into the operating behaviour of these vessels, such as ports calls and trade routes. This analysis is conducted by analysing data of the PoR and the EuroStat database.

3.4.2.1 Liners

The short sea shipping network consists of many ports, ranging from world-class gateway ports to small regional ports. An analysis has been performed on the number of short sea shipping calls per port for container liners. In Europe, there are about 161 fixed shipping lines for the transport of containers, on which in total 350 vessels are operating. 82 of these shipping lines are operating in the ECAs with a total of 173 vessels. These vessels are so-called liners, which means that they operate in a fixed route. Shipping operators decide based on the demand which routes they operate. These routes are generally fixed for half a year, after which is determined if the rotation is still economically feasible or whether the rotation should be adjusted. Ship operators generally make their decisions to change the shipping routes based on economics. Factors that influence the decisions is the change in length of the routes, bunker quality, the price of bunker fuel, amount of bunker needed, type and size of a vessel, amount of freight, time in port, pilotage and terminals and port dues (Stikkelman et al., 2011). The schedules for containers are weekly routines departing ones every 7, 14, or 21 days. The number of vessels operating per line differs from 1 to 6 vessels per line and mainly depends on the duration of a line routine. For example, on a one-weekly routine, often one ship is operating, and on a two-weekly routine, often two ships are operating, in such a way that one vessel departs every week. Figure 3.5 depicts the European short sea container liner network of vessels operating in ECAs, including the 30 most called ports.

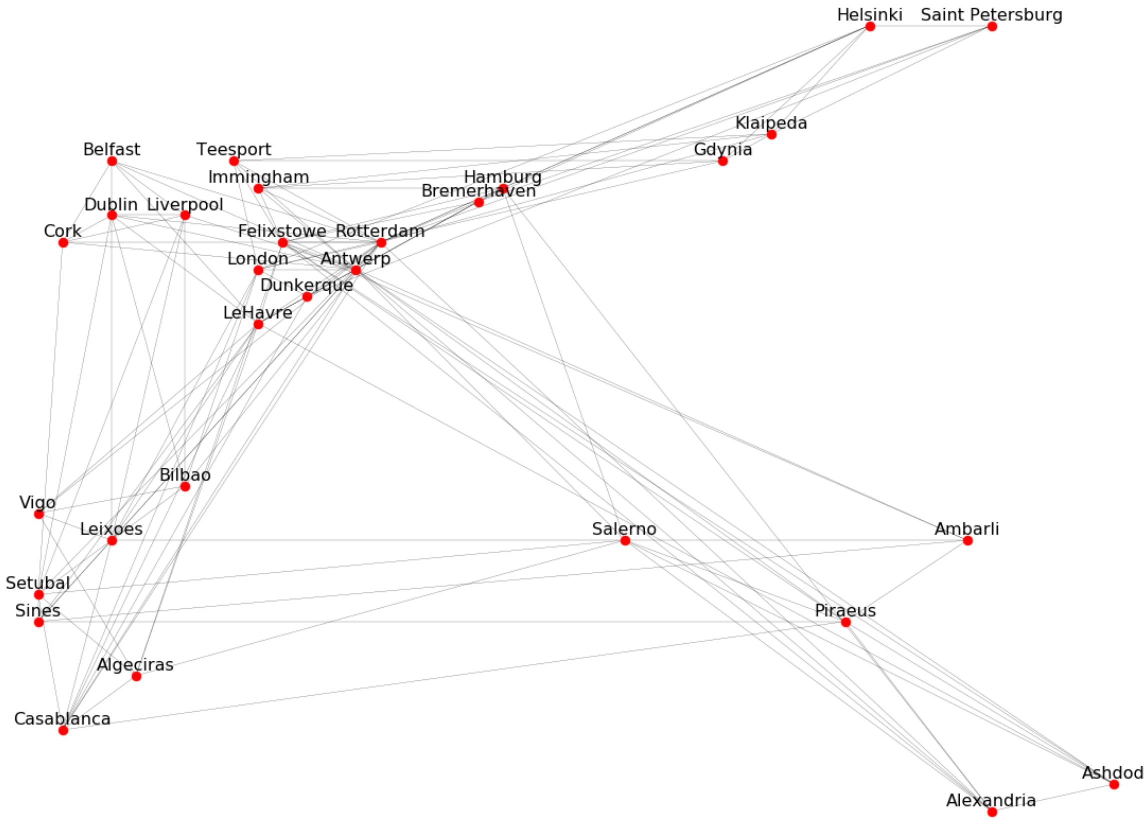

Figure 3.5: Short sea container liner network operating in ECAs

The analysis showed that the port calls are quite equal distributed over the ports. Figure 3.6 shows that there is a large group of ports which is called between the 0 – 75 times a month. Figure 3.7 illustrates the number of calls per port in a descending manner, with on the left side the port of Rotterdam. On a global scale, there are a few ports in the world which cover a significant part of the global shipping industry. However, this is not the case for the European short sea network. When considering deep-sea shipping, ship operators have a limited choice of ports they could call due to the size of the vessels. For short sea operators, the characteristics of a port are less dominated for the selection of a port because the vessels are small and therefore do not have these restrictions. Furthermore, since the large number of port calls of vessels, the fuel prices and port dues play a minor role in the selection of ports. Moreover, the vessels operating short sea have more choice in choosing their bunker port, since they call ports frequently.

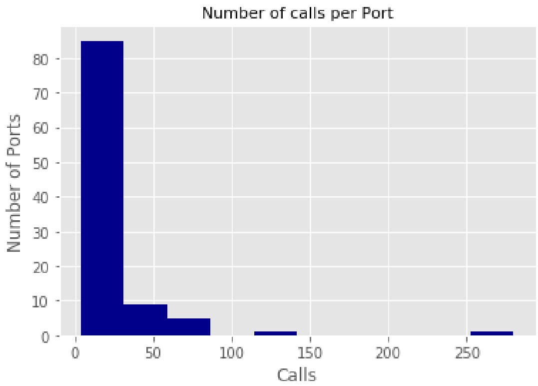

Figure 3.6: Histogram port calls per month

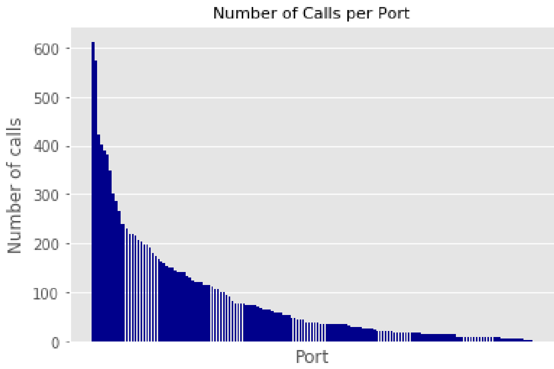

Figure 3.7: Number of port call

In this study, only the line rotations including ports located in ECAs are considered, since these vessels are confronted with stricter regulations. The thirty ports that are called most frequently by the container liners of these line rotations are included in this research. These liners represent over 70% of the total port calls. For this reason, it is assumed that they represent over 70% of all bunker calls, and therefore considered as a good representation of the short sea shipping network.

3.4.2.2 Charters

Charters vessels are hired by ship owners and do not sail in fixed routes but sail according to the demand. There are several ways in which chartering takes place. In some cases, the vessel operator becomes fully responsible for the ship, including fuel bunkering, maintenance and port dues. However, it is also an option that the vessel and crew are hired, and the maintenance and fuel costs are for the vessel owner. Other kinds of variations are also possible. Chartering finds mostly place in the liquid bulk segments which include the transportation of oils and chemicals.

3.4.2.3 Cargo segments

Four main cargo segments can be distinguished, liquid bulk, dry bulk, general cargo, and containers. Containers are mostly transported by liner vessels Besides, there is a difference between vessels that transport cargo of which the origin and destination of the cargo are located in Europe, and vessels that transport cargo of which the origin or destination is not necessarily located in Europe, these vessels are called feeders. Feeders generally transport the cargo from smaller ports to a larger port, where the cargo is loaded on a deep-sea vessel to be transported to other regions in the world, or the other way around.

Figure 3.8 shows the number of calls for each port per cargo segment. Data for this analysis is obtained via the Eurostat database. Only short sea calls by vessels with a maximum of 20.000 dwt are considered. Besides, the container calls are split into containers liner calls and container charter calls. In addition, no data was available of the ports not located in Europe. For these ports, assumptions are made based on the number of container calls and the region.

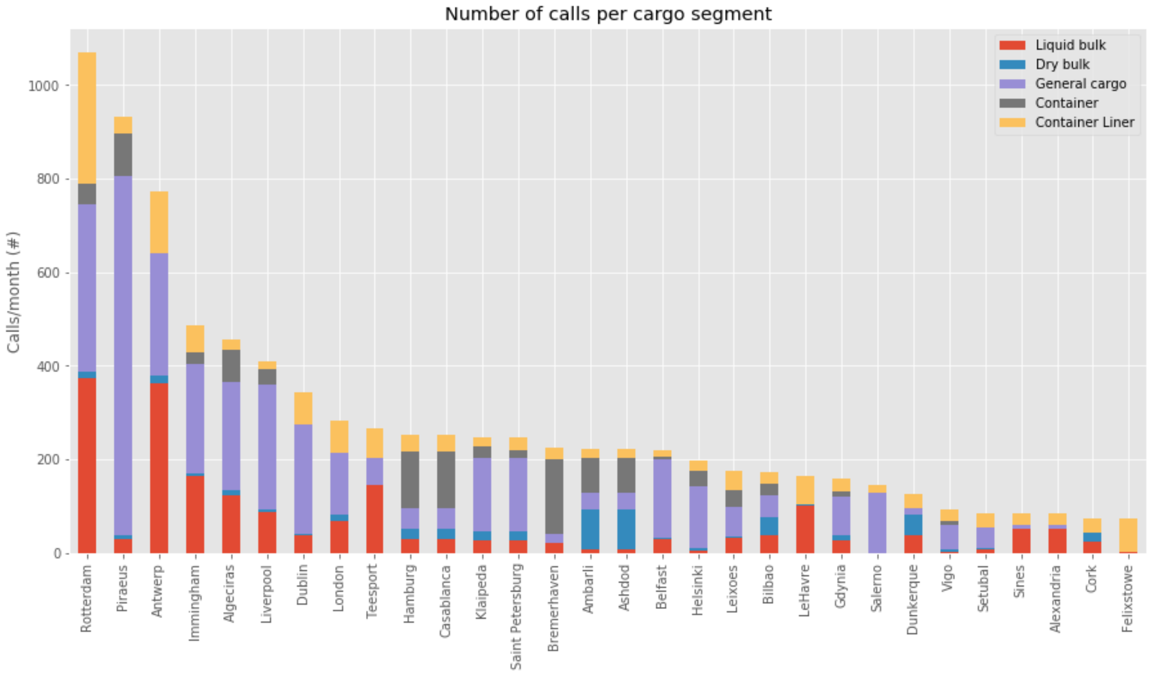

Figure 3.8: Short sea port calls per cargo segment

Figure 3.9 shows the percentage of trade of each port with each sea region. Eurostat provides data about the amount of short sea trade between countries and sea regions. This data is used to make assumptions about the amount of trade between the ports and sea regions.

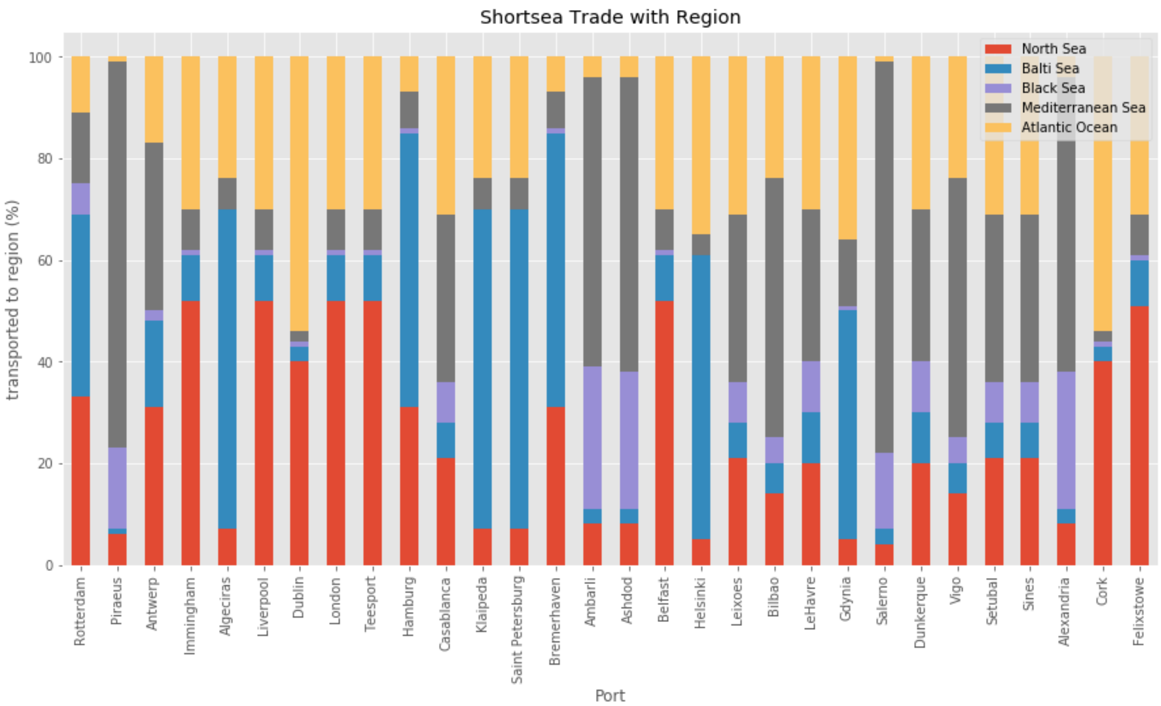

Figure 3.9: Short sea trade with regions

4. Model development

The previous chapter provided insight into the European maritime fuel system, which is used to build a conceptual model of this system. The goal of this chapter is to provide insight into the structures and agent behaviour captured in the model, as well as the underlying assumptions of the model. Hereto, first, a high-level description of MarPEM is given from which model structures are used to model the maritime fuel system for short sea shipping in Europe (from now on referred to as EU-MarPEM). Subsequently, a conceptual model of EU-MarPEM is created. The model agents are identified and relations between these agents are illustrated in the model ontology. Afterwards, the model formalization is discussed e.g. model assumptions, model narrative and model flowcharts are presented.

4.1 Maritime Fuel Policy Exploration Model

Bas et al. (2017) created an agent-based model that represents the maritime fuel system: Maritime Fuel Policy Exploration Model (MarPEM). This model could be used to study the effects of policies on the development of alternative fuels. The model can provide insight into how a maritime fuel system may develop subjected to different policy instruments. Although the model is a representation of the global maritime fuel system with a focus on LNG, the creators argued that the model can be used for different maritime fuel systems as well. The model enables to capture the mutual influences of supply and demand for maritime fuels on a global scale. The mode behaviour consists of the operational behaviour of vessels sailing between ports, the supply of fuels bunker terminals, the fuel supply and pricing decision of LNG liquefaction plants and LNG terminals, and the price setting and fuel supply by fuel markets. Besides, the model includes the investment decisions in emission abatement technologies made by ship operators to be compliant with emission regulations. Further, the model allows for testing with different policy options to observe their effects on the adoption of maritime fuels. Three different types of policy options are implemented in MarPEM.

- Enforcing emission regulations by varying the inspection probability.
- Stimulating the availability of LNG infrastructure in the ports by creating four scenarios with fuel availability in ports.
- Stimulating investments in abatement technology.

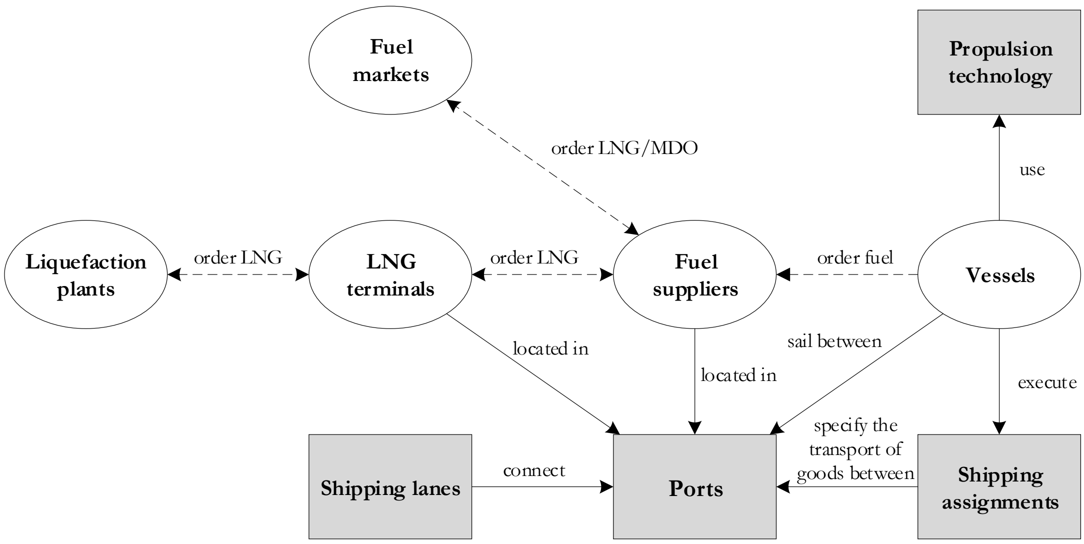

Figure 4.1: Conceptualisation of MarPEM

4.2 Model conceptualization EU-MarPEM

This section presents the conceptualisation of EU-MarPEM. First, the main structures of the European short sea network which are included in the model are discussed, as well as their characteristics. These components are modelled as agents. Hereafter, the relations between these components are depicted in the model ontology.

4.2.1 Model environment

The system under consideration is the European short sea maritime fuel system. EU-MarPEM is a simplified representation of the short sea shipping network of Europe. The model includes ports located in Europe and non-European counties, countries bordering the Mediterranean and the Black Sea. This model captures the behaviour associated with the supply of fuels to vessels operating in this area and the operational behaviour of vessels. Besides, IMO and EU regulations are represented in the model.

4.2.2 Model agents

The agents in the model represent stakeholders and the physical component, which form together the maritime fuel system. In this section, a brief description of the properties of the agents is given. In appendix A, a more detailed list of all characteristics of each agent can be found.

4.2.2.1 Vessels

The vessels are representing a set of aggregated vessels. Two types of vessel are present in the model, namely: charters and liners. The difference between the two types of vessels is that liners are operating in a fixed rotation schedule whereas charters select shipping assignments on demand. After delivering a shipping assignment, a charter will select a new shipping assignment. The vessels can carry a specific cargo type, which determines which shipping assignments they can transport. Besides, vessels sail at a certain speed. A vessel has a certain propulsion technology which determines which kinds of fuels it can consume, the amount of fuel it consumes, and what kinds of emissions and the amount of emissions the exhaust gases contain. Other technical characteristics a vessel possesses are the carrying capacity, type of engine and the bunker capacity. Characteristics which influences the investment decisions of a vessel are the age, economic lifetime (age above which the vessel starts considering retrofitting), technical lifetime (age at which the vessel is replaced), discount rate and risk aversion.

4.2.2.2 Ports

Ports are hubs where demand and supply of maritime fuels come together. Ports are located at a specific geographical location, and several fuel suppliers could be located in a port. Furthermore, ports have a capacity which determines the available space in the port for vessels to moor. Moreover, ports have a number of port calls per month and a number of bunker calls per month.

4.2.2.3 Bunker terminals

In the model, the fuel suppliers and bunker traders are considered as one agent, the bunker terminal. The bunker terminals are located in a port and supply the bunker fuel to vessels. A bunker terminal has one specific type of fuel it can supply. Each bunker terminal has a willingness to accept, e.g. the minimum price of the bunker terminal at which it sells the bunker fuel, determined by the market price and the fixed costs of the bunker terminal. In addition, bunker terminals can have a set of fuel orders.

4.2.2.4 Fuel market
Each fuel market is represented by an agent. The fuel market has four characteristics, a fuel type, a market price, a supply curve, and a set of orders. The supply curve determines the quantity the market can supply for a certain price. The market price determines the price at which the order is sold.

4.2.2.5 Propulsion technology
Vessels operate with a certain propulsion technology. The propulsion technology determines which types of fuel can be consumed. Furthermore, it determines the fuel consumption, the ship emissions, the required space on board, as well as the loss of bunker capacity. When vessels want to invest in new propulsion technology, they can either chose to retrofit the vessel or to replace the vessel, both options are subjected to different costs.

4.2.2.6 Shipping assignments
Shipping assignments are executed by vessels. Vessels deliver the shipping assignment from the port of origin to the port of destination. Therefore, the port of origin is defined, as well as a set of destination ports. When de shipping assignment is executed by a charter, there is only one destination port defined. A shipping assignment executed by a liner can contain several destination ports (the rotation schedule). The rotation of the shipping assignment is determined by its port of origin and a set of port of destinations. The shipping assignment has a certain type, which determines which type of vessel could transport the shipping assignment. Besides a vessel has a line number which determines which vessels are can execute the shipping assignment and the shipping lanes that can be sailed.

4.2.2.7 Shipping lanes
Vessel sail between ports in order to execute shipping assignments. These ports are connected through shipping lanes. The shipping lanes have a port of origin, a port of destination, distance, and a line number. Further, it is specified whether the shipping lane is located in an ECA or not.

4.2.2.8 Orders
An order is sent by the bunker terminals to the fuel market. The order has a type of fuel, a purchaser, a supplier, a quantity, a net price e.g. price obtained by the fuel market, and a gross price e.g. price paid by the bunker terminal.

4.2.3 Model ontology
Figure 4.2 shows the model ontology of EU-MarPEM. This ontology shows the relation between the agents which are identified in section 4.2.2. The relation between these concepts is indicated by means of an arrow. The arrows show the direction of the relation and can be two-sided.

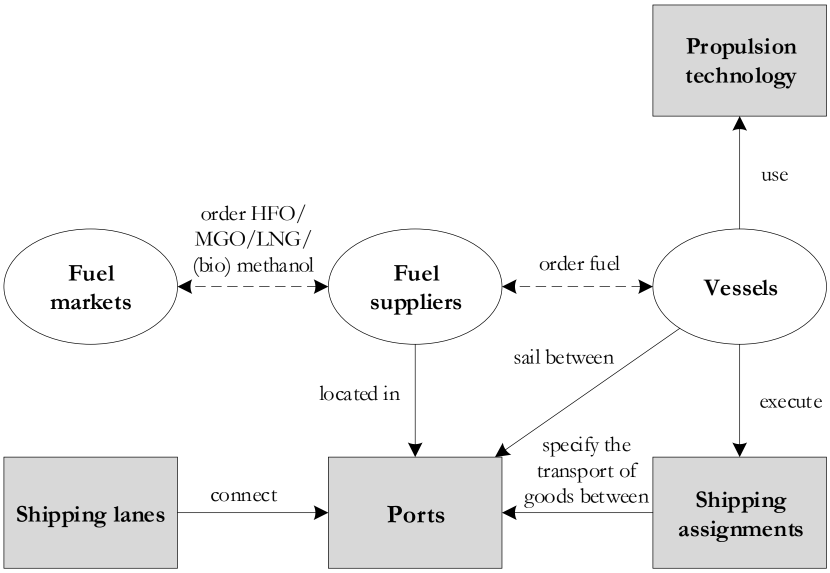

Figure 4.2: Ontology of EU-MarPEM

Fuel markets and bunker terminals are trading fuel with each other. The fuel markets set a price at which it sells the fuel to the bunker terminal. The fuel markets supply the fuel orders to the bunker terminals. Bunker terminals are located ports. Vessels moor and sail between ports via shipping lanes in order the execute shipping assignments. The shipping assignments must be transported from one port to another port. The vessels order fuel from a bunker terminal. The vessels operate with a certain propulsion technology which among other things determines which fuel they should order from the bunker terminals.

4.3 Model assumptions

During the conceptualization of the model, many assumptions are made to capture the European maritime fuel system in an agent-based model. The main assumptions are:

- The model includes only vessels that might operate in ECAs. So, the model includes liners containing ports in their rotation schedules which are located in ECAs, and charter vessels.
- The line rotations of vessels are static and will not change over time. This study does not incorporate the optimization of liner schedules.
- The model does not include multimodal transport modes.
- The model does not consider hinterlands connections. Therefore, the choice of calling another port which serves the same hinterland will not be considered in this model. Since short sea operators are often responsible for door-to-door service, changing ports will probably cause extra hinterland connection costs, and therefore not likely to happen.
- Vessels bunker only in the port of origin or port of destination of their shipping assignments. Thus, vessels will not call ports for bunkering only.
- The optimization of bunker behaviour is not taken into account, e.g. vessel bunker full capacity. In reality, this might not be the case because of credit restrictions or optimization of fuel consumption. Carrying fuel on board adds to the total weight of the vessel and therefore to the total fuel consumption.
- The time to bunker and moor is in ports is not explicitly present in the model. However, this time is considered in the distance vessel sail per day.

- The model does not consider the optimization of fuel use by vessel. For example, slow steaming to save fuel.
- The use of dual fuel engines is not taken into account. A vessel uses one type of fuel. The use of multiple fuels is less common for short sea vessel than for deep sea vessels due to the shorter distances and time spent in coastal areas.
- The following emission abatement technologies are included in the model:
  - No emission abatement technology,
  - scrubber/SCR,
  - SCR,
  - LNG,
  - Methanol in combination with a small fuel tank.
  - Methanol in combination with a large fuel tank
- The following assumptions are made about the consumption of bunker fuels
  - When using no emission abatement technology, vessels consume HFO.
  - When vessels operate with a scrubber/SCR system, vessels consume HFO.
  - When vessels operate with an SCR system, vessels consume MGO.
  - When vessels operate with an LNG propulsion technology, vessels consume LNG.
  - When vessels operate with a methanol propulsion technology with either a small or large fuel tank, vessels are able to consume methanol or bio methanol.
- It is assumed that LNG is supplied in every port due to the availability of LNG terminals or bunker barges.
- Methanol bunker suppliers are not located in ports. Several "what if" scenarios are considered with the availability of methanol in ports.

4.4 Model narrative

This section entails the model narrative, which describes what actions take place in every time step of the model run. The flowcharts presented in this section provide insight into how the model behaviour is translated into software structures. The blue diamonds in the flowcharts represent the decisions made, and the rectangles represent the actions which are included in the model. First, a high-level flowchart of the model is discussed (figure 4.3). Afterwards, the processes described in this high-level overview are discussed in more detail.

4.4.1 Time scale

One time-step in the model represents one day, meaning that everything that takes place in one tick in the simulation model happens in one day in real-life. This time step is chosen because the operational behaviour of vessels takes place at a daily basis such as decisions towards bunkering and port calls. This chosen time step does not allow the vessels to call more than one port a day. However, taking a smaller time step would increase the run-time of the model.

4.4.2 High-level overview

The high-level flowchart (figure 4.3) describes the decisions and actions that are considered each tick of the model in a chronological way. First, the model is initialised during the set-up. Afterwards, the go-procedure is repeated for a certain number of ticks. The go-procedure starts with saving the current state of the model to produce model output. Subsequently, variables are updated and every thirty ticks, new shipping assignments are created. Afterwards, the operational behaviour of vessels sailing between ports is taken place, which consists of the behaviour of vessels; moor, select shipping assignments, make bunker decisions and bunker. Afterwards, bunker terminals place fuel orders and the fuel market supplies the fuel. Vessels decisions toward investments in propulsion technology take place on a yearly basis. Finally, every thirty ticks, bunker terminals set a new fuel price based on the revenues of the previous month.

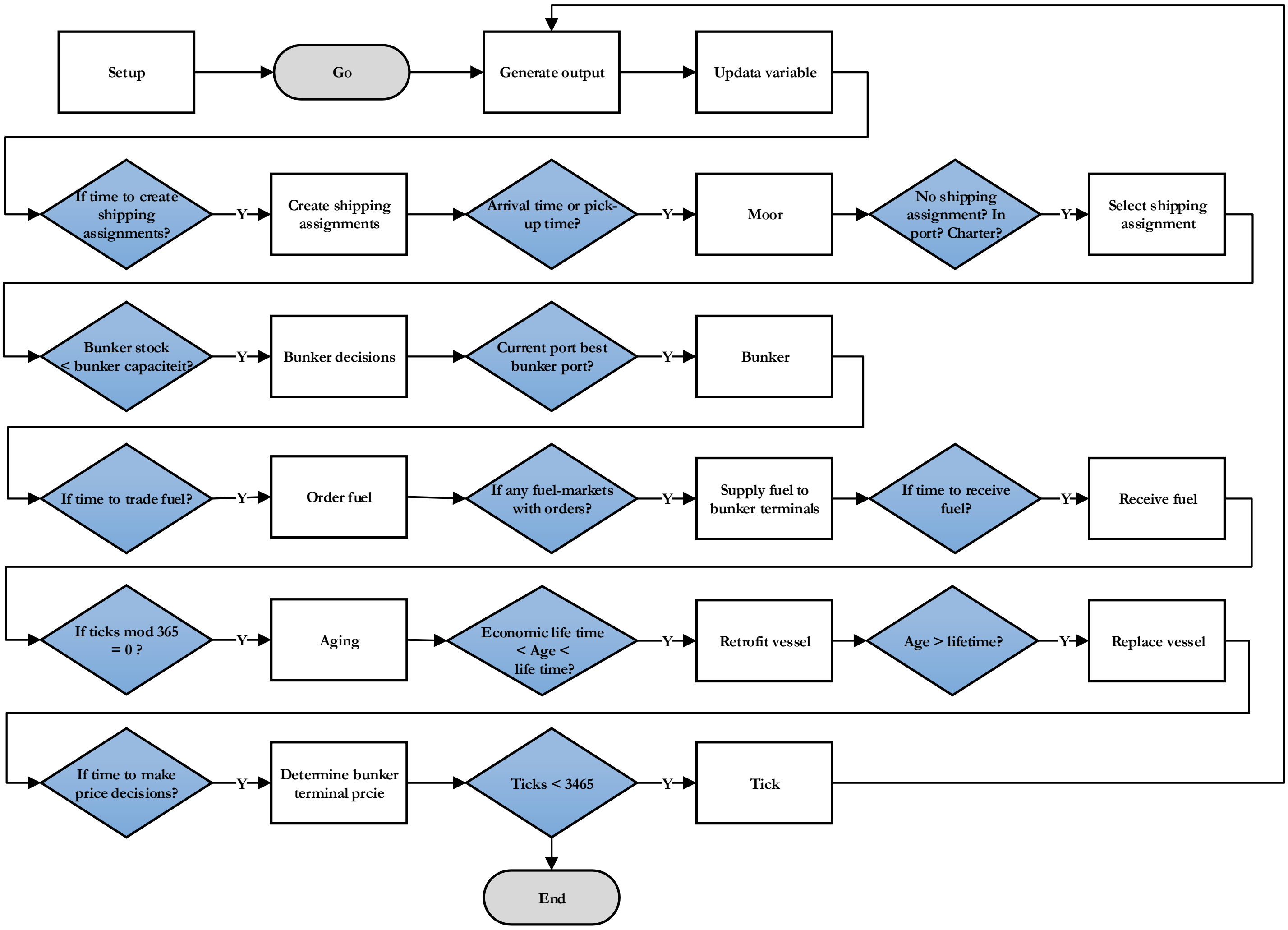

Figure 4.3: Flowchart of high-level model behaviour

4.4.3 Model initialisation

The model is initialised at the beginning of each model run and considers four steps: creating agents, creating shipping assignments for vessels, assigning shipping assignments to liners, and identifying the sets of possible shipping assignments, routes, and ports for vessels.

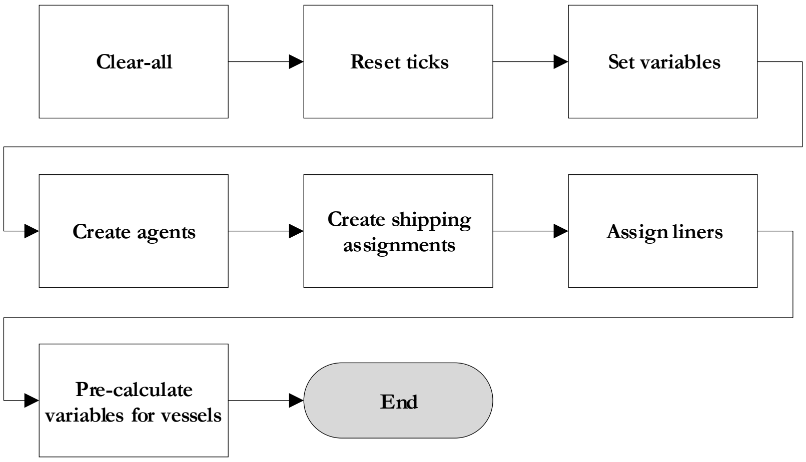

Figure 4.4: Flowchart model initialisation

4.4.3.1 Creating agents

Firstly, the agents are created. This is done by means of loading different files into the model which contain the values of the properties of the agents. The model starts with creating the ports. The location and capacity will be specified, as well as whether the port applies a discount. Secondly, the bunker fuel markets are created. Each of the fuels has its own fuel market. This market determines the price of the fuel. Subsequently, bunker terminals are loaded into the model. These bunker terminals are assigned to a specific port and supply one type of fuel. So, in each port, several bunker terminals can be located. Afterwards, propulsion technologies are created. Hereafter the vessels are created, followed by the ports determining which bunker terminals are located in the port. Subsequently, the shipping assignments are created and it is specified which shipping assignments and vessel are liners and charters. Finally, the shipping lanes are loaded into the model.

Assign liners

After creating the model agents, the line rotations are assigned to vessels. First, a basic assignment will be hatched into a shipping assignment. The port of origin and the ports of destination are assigned to the shipping assignments, so the port rotation schedule of the shipping assignment is known. Subsequently, the shipping lanes which are needed to execute the rotation schedule are assigned to the shipping assignments and the total distance of the port rotation is calculated. Next, liners select a shipping assignment of which the line number corresponds to their own line number and the vessel is assigned as the executor of the shipping assignment. The vessels move to the port of origin of the shipping assignment and determine the time of arrival in the next destination port. Besides, the risk-aversion (which determines how reliant vessels are in investing in new technology based on the availability of bunker infrastructure in the ports) of the liners is determined based on the number of times a vessel has to bunker, taken into account the bunker capacity, the fuel consumption and speed of the vessel. For liners, either a risk aversion towards methanol propulsion technology of 1 or 0 will be assigned. A risk aversion of 1 means that the vessel is not hesitated to invest in the technology, and a risk aversion of 0 means that the vessel is not able to invest in the propulsion technology because it cannot complete its line rotation without running out of bunker stock. When it is possible to complete the full rotation without running out of full, the risk aversion will be set to 1.

Make shipping assignments

The shipping assignments for charters are created by hatching a basic assignment. The port of origin and the port of destination are determined, as well as the possible shipping lanes of the shipping assignment.

Assign possible shipping assignments, routes, and ports to vessels

In the last step of the model initialisation, vessels identify the shipping assignments they can execute, the ports they can call, the ports with discounts they can call, the shipping lanes ports they can sail, the number of non-ECA and ECA shipping lanes they can sail, and the mean distance of the shipping lanes they can sail. By means of this step, some of the calculations are made at the beginning of each run, which can be used at a later moment during the model run. In this way, the computational time of the model has decreased significantly.

4.4.4 Agent behaviour

The interactions between agents can be divided into four groups, which are all taking place at different time scales: 1) the operational behaviour of vessels sailing between ports and the bunker behaviour of vessels takes place at a daily basis, 2) the update of model variables and the generation of output variables, as well as the creation of shipping assignments every thirty days, 3) The interaction between the bunker terminals and the fuel markets, as well as price decisions made by bunker terminals, take place on a monthly basis, and 4) Vessels make their investment decisions towards new technology on a yearly basis.

4.4.4.1 The operational behaviour of vessels sailing between ports

To moor

A vessel can either pickup or deliver a shipping assignment in a port. When the arrival time or the pickup time of a vessel is equal to the number of ticks, the vessels will moor. First, the vessel moves to the port. The total number of port calls of the current month will be updated with the aggregation of the vessel. Subsequently, the distance travelled of the vessel will be determined and the bunker stock will be updated by considering the distance travelled and the fuel consumption of the vessel. When the number of ticks is equal to the arrival time of the vessel and the vessel is a charter, the shipping assignment will be removed from the vessel. Liners update their rotation, by setting the port of origin the current port and setting the port of destination the next port in the rotation. The next shipping lane of the vessel will be determined, as well as the time of arrival in the next port. Subsequently, charters will select a new shipping assignment.

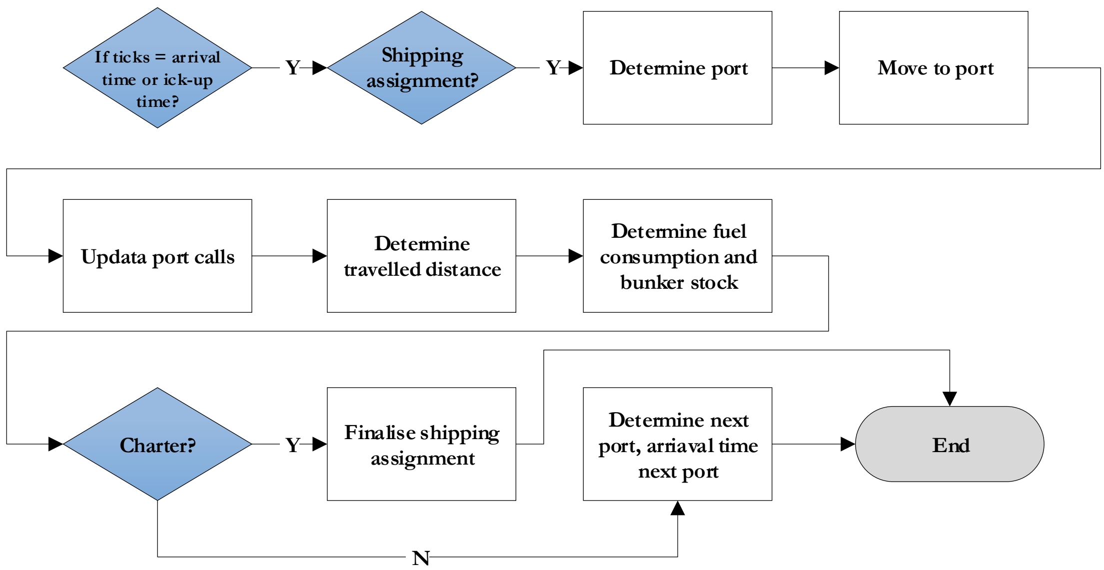

Figure 4.5: Flowchart vessel to moor

To select a shipping assignment

First, a vessel determines whether the fuel it consumes is available in the current port. If this is not the case and the bunker stock is less than the bunker-consideration percentage of the vessel, it will determine what the maximum distance is it can sail with the current bunker stock. A shipping assignment will be selected based on the following criteria: the distance of the shipping assignment should be less than the maximum distance the vessel can sail with the current bunker stock, the next port of the vessel supplies the fuel, and the type of cargo corresponds with the type of vessel. Besides, the shipping assignment should not already be executed by another vessel or already be executed in the current month. If the current port can supply the fuel, the vessel's new assignment does not have to satisfy the requirement of the availability of fuel in the port of destination. From all the shipping assignments that could be executed by the vessel, one will be selected. If possible, a shipping assignment with the origin equal to the current port of the vessel, otherwise based on the minimal distance to the vessel. If the port of origin of the shipping assignment is not the current port of the vessel, the vessel should determine the shipping lane it has to sail to the port of origin of the shipping assignment. This shipping lane will be added to the route of the shipping assignment. The vessel follows the route of the selected shipping assignment. In addition, the time of arrival in the next port should be determined.

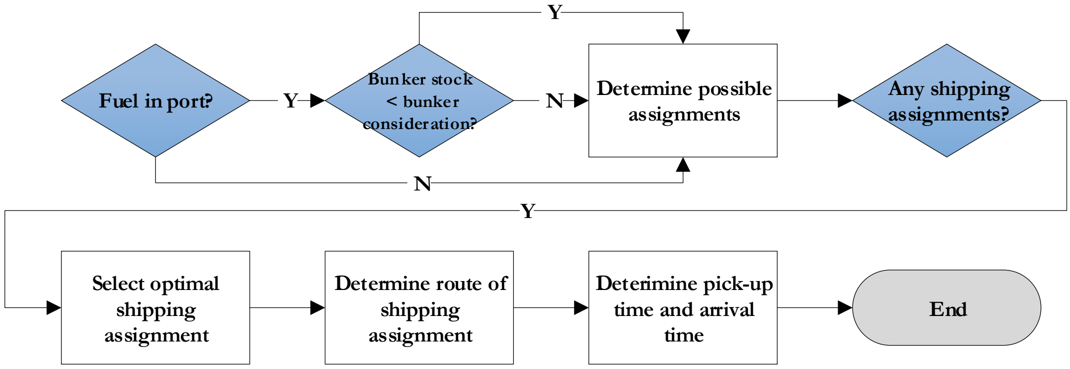

Figure 4.6: Flowchart vessels selecting a shipping assignment

To make a bunker decision

After the vessel has selected a shipping assignment, it decides whether it will bunker in the current port. The decisions process differs between liners and charters. Charters first determine if there is a bunker terminal available in the port which supplies the required fuel and if its bunker stock is less than the fuel consideration percentage. If so, the vessel determines if the fuel will be supplied in the next port. If this is true, the vessel determines the fuel consumption to the next port. If the fuel consumption is more than the bunker stock, the vessel will bunker in the current port. If the fuel consumption is less than the fuel stock, it will compare the fuel prices in the current and the next port. If the current port's fuel prices are less than the fuel prices in the next port, the vessel decides to bunker in the current port. Liners determine first if the required fuel is available in the current port and whether they are able the execute a full rotation without bunkering. When this is not the case, the vessel determines which ports are attainable with the current bunker stock. When the current bunker terminal is the cheapest attainable bunker terminal, the vessel will decide to bunker in the current port.

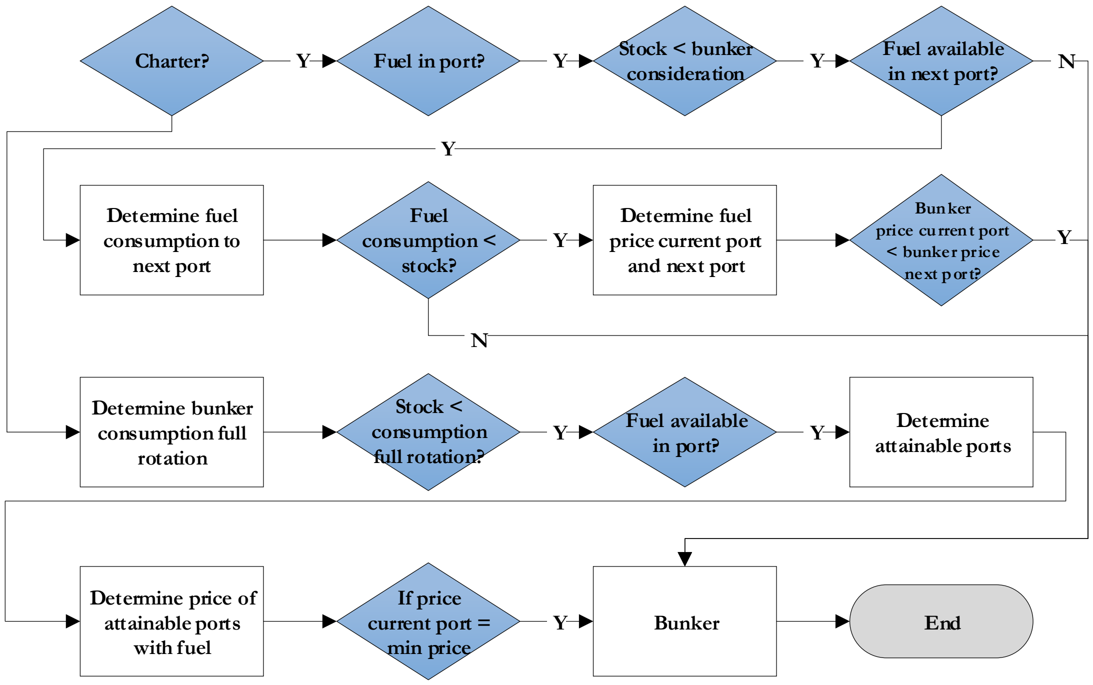

Figure 4.7: Flowchart bunker decisions vessels

To determine fuel prices

When the vessel consumes another fuel than methanol, the fuel prices will be determined by the by bunker terminal price and the applied CO2 price per MWh. When the required fuel is methanol, a comparison of prices between the bio methanol and methanol terminal is made. The fuel price is determined by the price of the bunker terminal, the CO2 price, and the willingness to pay for bio methanol. When the port applies a discount to vessels bunkering bio methanol, the discount will be taken into consideration as well.

To bunker

The vessel determines its demand by subtracting the bunker stock from the bunker capacity, so it will bunker full capacity. The fuel demand is multiplied by the aggregation of the vessel. The bunker terminal in the port with the required fuel will increase its fuel demand with the demand of the vessel. The port and the bunker terminal will keep track of the total bunker calls in the current month by increasing the bunker calls with the aggregation the vessel. The bunker stock of the vessel will be increased to the bunker capacity.

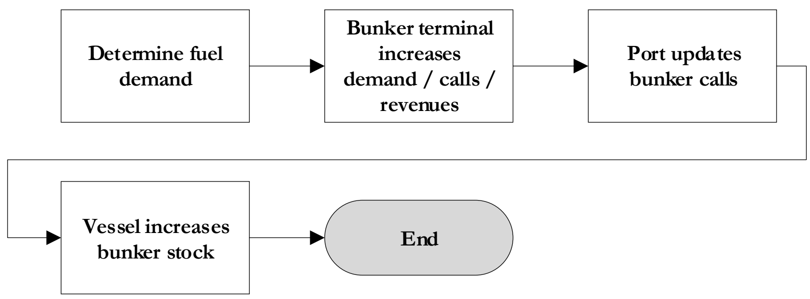

Figure 4.8: Flowchart bunkering

4.4.4.2 Fuel order and supply (monthly)

To order fuel

Every month, bunker terminals order bunker fuel from the fuel market. First, bunker terminals determine their willingness to pay for the fuel by subtracting their costs from the price at which they sell the fuel to the vessels and the gross price of the order will be set to the willingness to pay of the vessel. The bunker terminal creates an agent-set containing orders. The bunker terminal adds these orders to its own fuel orders and to the orders of the fuel market.

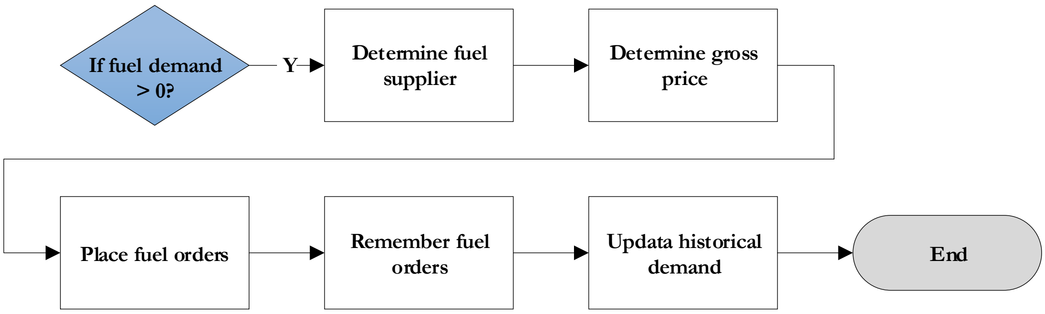

Figure 4.9: Flowchart order fuel

To supply fuel

After the fuel orders are placed, the fuel markets supply the fuel to the bunker terminals. Hereto, the fuel market composes first a demand curve, based on the gross prices and the associated quantities of the order. The market is explored to see if there is a price at which demand equals supply. When this applies, the market price will be set. The quantities that will be supplied per order will be determined and the fuel will be supplied to the bunker terminals. Consequently, the demand of the bunker terminals is reduced.

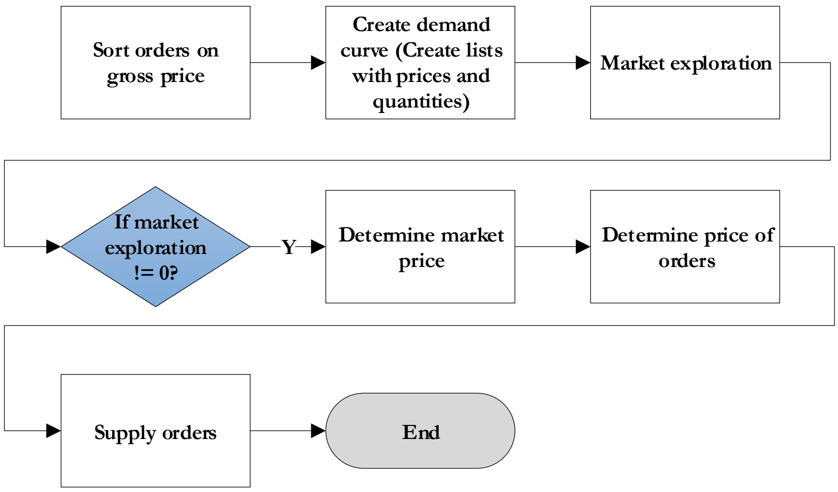

Figure 4.10: Flowchart supply fuel

To receive fuel

If there are any fuel orders supplied to the bunker terminal, the bunker terminal will reduce its bunker demand with the amount of fuel it received and calculate its total expenses.

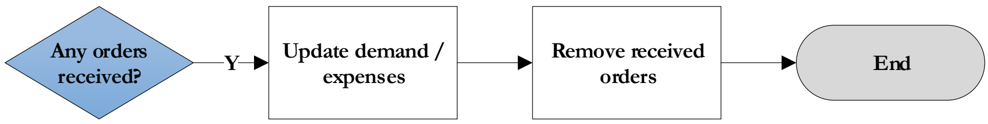

Figure 4.11: Flowchart receive fuel

4.4.4.3 The pricing decisions of bunker terminals (monthly).

The pricing decisions consider the update of the fuel prices of the bunker terminals. Every month, the bunker terminals evaluate whether their revenues are increased or decreased. A bunker terminal has two strategies: 1) it can increase its price, and 2) it can decrease its price. When the revenues of a bunker terminal are increased in comparison with the previous month, it applies the same strategy as it did last time. When the revenues are decreased it will choose to apply the opposite strategy as their last strategy. However, bunker terminals are not able to set a price below their minimum price (the price at which they buy the fuel from the market + their fixed costs) or above the maximum willingness to pay by the vessels for the fuel. The difference in price dependents on the success of the last strategy and the market price. If the success of the last strategy is relatively high, a relatively high price difference will be applied, and the other way around, according to the following equations:

$$Price = price + e^{\frac{revenues(t)}{revenues(t-1)}} * \ln(market\ price) \tag{1}$$

$$Price = price - e^{\frac{revenues(t)}{revenues(t-1)}} * \ln(market\ price) \tag{2}$$

$$Price = price - e^{\frac{revenues(t-1)}{revenues(t)}} * \ln(market\ price) \tag{3}$$

$$Price = price + e^{\frac{revenues(t-1)}{revenues(t)}} * \ln(market\ price) \tag{4}$$

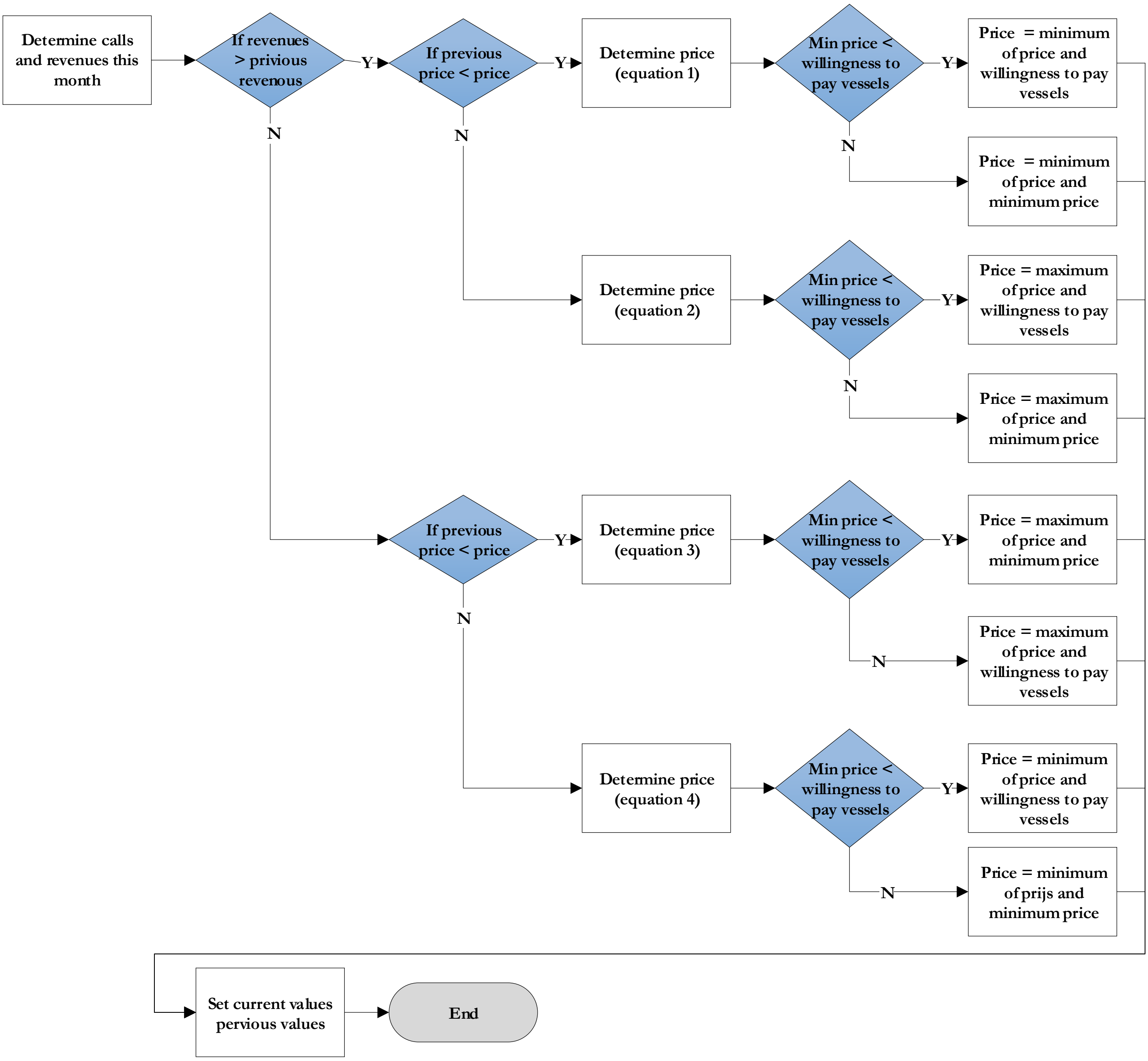

Figure 4.12: Flowchart price decisions bunker terminals

4.4.4.4 Invest decisions vessels (yearly)

Retrofitting vessel

When a vessel passed its economic lifetime, it will consider retrofitting the vessel. First, a selection of possible propulsion technologies in which the vessel can invest is determined. This selection dependents on the maximum distance a vessel should be able to sail (based on the line rotation). Next, the vessel determines the Net Present Value of each propulsion technology. If the propulsion technology with the lowest NPV is not the current propulsion technology of the vessel, the current propulsion technology will be replaced.

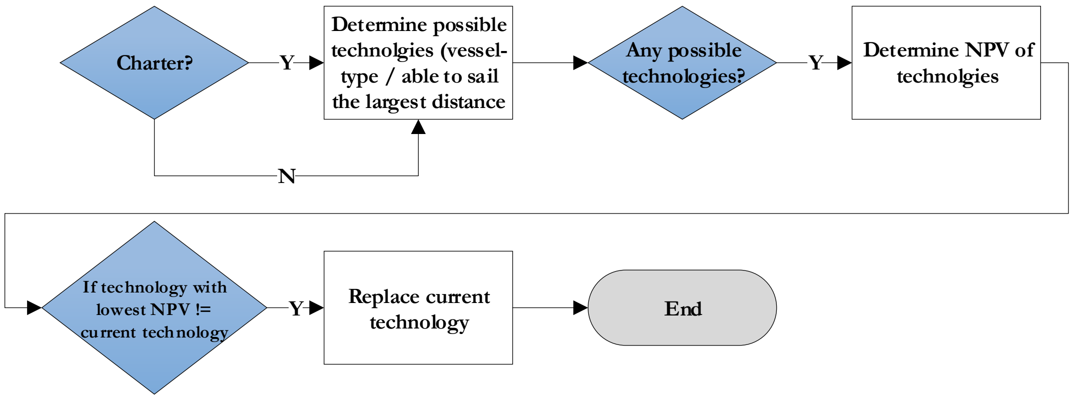

Figure 4.13: Flowchart retrofitting vessels

Replacing vessel

The decision to replace a vessel is made once a vessel has passed its technical lifetime. First, the age of the vessel is reduced to 0. Subsequently, the propulsion technology is selected in the same way as the selection of a propulsion technology for retrofitting a vessel. However, for the initial investment costs of the propulsion technology, different costs are used.

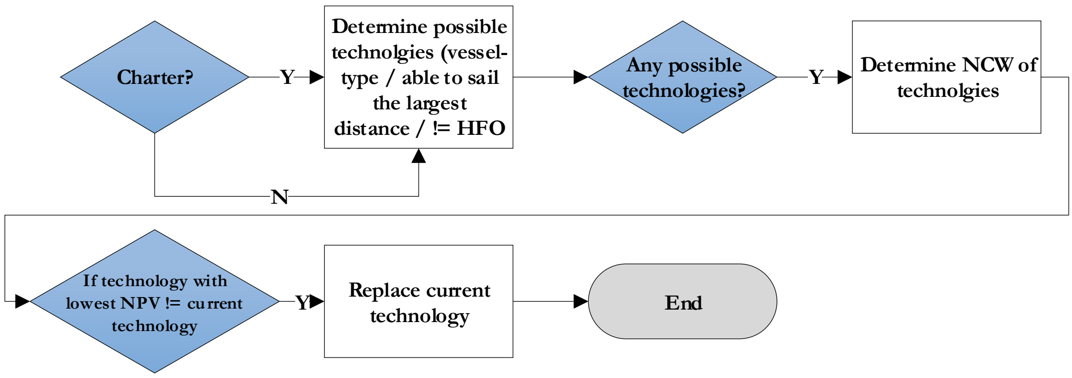

Figure 4.14: Flowchart replacing vessels

Determine Net Present Value

First, the initial investment costs are determined based on the size of the engine and the investment costs of the propulsion technology. Secondly, the yearly fuel costs of the vessel will be determined based on the yearly travelled distance, the fuel prices, and fuel consumption, as well as the CO2 price. When considering methanol propulsion technology, a comparison between the fuel costs of methanol and bio methanol should be made. The comparison will consider the CO2 price, the willingness to pay for bio methanol and the bunker discount it will receive when bunkering bio methanol. The most costs favourable price of both of these fuels will be taken when calculating the fuel costs. Subsequently, the yearly expected fine will be determined. First, the vessel counts the number of shipping lanes at which it offences the maximum allowable SOx and NOx emissions based on the emissions of the propulsion technology. The age of the vessel will be considered when assessing the allowable NOx emission in the ECAs and non-ECAs. Based on the fine, the control percentage, the percentage of offended lanes and the average number of shipping lanes the vessel sail, the amount of the fine is determined. Next, the costs of the lost cargo capacity of the propulsion technology are calculated, considering the space of the technology, costs of lost cargo capacity, and the capacity of the vessel. In addition, the yearly discount the vessel is expected to receive when using the propulsion technology will be determined. This considers the percentage of ports with discount, the total number of port calls, the capacity of the vessel and the type of vessel. Finally, based on the yearly expected fuel costs, fines, costs of the lost cargo capacity and discount, the yearly costs are determined. Based on the initial investment costs of the propulsion technology, the remaining lifetime of the vessel, the yearly costs, and the discount rate, the NPV is calculated. This NPV is corrected for the risk of not be able to bunker in ports based on its risk aversion of the vessel.

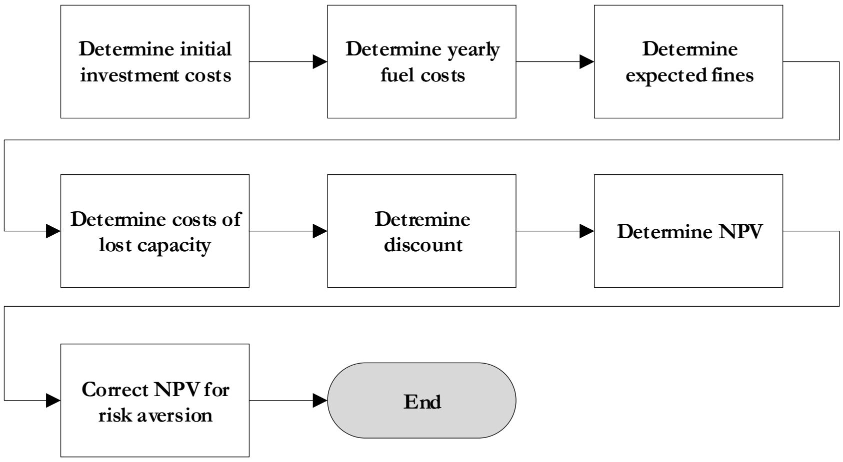

Figure 4.15: Flowchart determine NPV

4.5 Collaborative port strategies

In chapter 3, several policy options are identified to stimulate the use of alternative fuels. However, not all these options can be implemented by the ports themselves. MarPEM considers regulation of ship emissions by means applying fines and the frequency of controlling vessels on their compliance with emission regulations. In EU-MarPEM, these policies are treated as an external regulatory uncertainty since the port cannot control them. The PoR has identified that applying a discount on port dues for vessels with certain propulsion technologies is one of the options they can implement that might stimulate the use of certain technologies. Additionally, the port can give discount on port dues for vessels which bunker a certain fuel in the port. Moreover, the port can provide the methanol bunker infrastructure in the port

However, only one port applying one of the above-mentioned strategies might not induce an uptake of a certain technology. Collaboration between ports might be more effective and could be advantageous in many ways: 1) By sharing market and promotion costs, 2) shared costs for development of infrastructure, 3) shared risk among ports, 4) smaller ports could achieve a stronger position by collaborating, and 5) collaboration could strengthen ports against outsiders (Mclaughlin & Fearon, 2013). Collaboration between ports has been performed in the past. An example is a collaborative agreement between the port of Stockholm and the port of Turku. These ports cooperate by means of facilitating the infrastructure for LNG and investigating the possibilities of supplying electricity onshore (Gritsenko & Yliskylä-Peuralahti, 2013). However, ports should seek the right balance between competition and collaboration in order to be successful. The PoR has indicated to be interested in knowing what impact collaboration between European ports has on the deployment of alternative fuels. Therefore, policy options evaluated in this research comprise several ways of collaboration between European ports. The following three options of collaboration are implemented in the model:

1) **Availability of methanol bunker infrastructure in the port.**
   This policy option is represented by means of several scenarios. In each scenario, a different number of ports have methanol infrastructure available in the port. In this way, the scenarios represent the collaboration between ports deciding upon the availability of methanol bunker infrastructure in the port.

2) **Applying discount on port dues of vessels with certain technologies.**
   This policy option is already implemented by some European ports for the use of LNG. However, such a policy could be extended for vessels which are using methanol. When a vessel with an LNG or methanol propulsion technology is calling a port, it will receive a discount on the port dues. In the model, vessels take this discount into account when making investment decisions for new propulsion technology.

3) **Applying discount on port dues of vessels bunkering bio methanol.**
   This policy does not only stimulate the use of certain technologies but does also stimulate the use of bio methanol. To reduce CO2 emissions, the use of bio methanol is more preferred than the use of methanol. For this reason, a discount could be applied for vessels using bio methanol. However, it is difficult to assess whether a vessel is using methanol or bio methanol. New digital services being developed allow ports to determine which fuel is bunkered by a vessel in the port. Thus, a distinction could be made between vessels which bunker bio methanol in the port and vessels bunker conventional methanol. This policy relies on the idea of applying an additional discount on port dues of vessels which bunker bio methanol. This policy could only be applied when methanol infrastructure is available in the port. In the model, vessels take into account the bunker discount when deciding in which port to bunker, as well as when making investment decisions for new propulsion technology.

All these policy options are represented in the model by means of scenarios. In each scenario, a different group of ports applies a discount and provides the methanol bunker infrastructure in the ports. In this way, the collaboration between the ports is represented.

5. Model reusability

Several successive steps were taken to create EU-MarPEM based on MarPEM. This section reflects on the process of creating the model. During the implementation and experimentation phase, several hurdles had to be overcome. For this reason, a reflection on the reusability of the model is given, as well as suggestions for the future use of the model.

5.1 Reusability of agent-based models

Computationally intensive models generally suffer from the lack of reusability and therefore the development of models take often place from scratch (Van Dam, 2009; Manuel, Tirado-ramos & Puga, 2017). However, building simulation models could be extremely time consuming and expensive, since a lot of effort is put into building the model. For this reason, the reuse of models and knowledge can save a lot of time. Therefore, reusability is an often-mentioned concept in the field of simulation (Zhu, Yao, Li & Tang, 2019). However, reusability is often difficult, especially between different modellers, since there are no standards that govern the development of reusable models (Van Dam, 2009). Long & Zang (2014) describe the reusability of models as the reusability of the quality whereby a simulation model can be reused for other simulation models after small changes are made. The reusability of models can take place at various levels. Namely, it could consider the reuse of the conceptual model, the reuse of only a small part of the code, a component or the complete model (Zhu et al., 2019).

5.2 Reusability of conceptualisation of MarPEM

This section describes the reusability of the conceptual model of MarPEM by reflecting on the reusability of the model ontology, model scalability, and model behaviour.

5.2.1 Model ontology

The first step of the creation of EU-MarPEM was the conceptualisation of the model. When comparing the two ontologies of both models, it is recognised that both systems contain similar foundations. The major components and the relations between the systems are present in both systems. The exclusion of the LNG supply in EU-MarPEM is one of the major modifications that was made. The reason for this is that on a global scale different markets and production locations for LNG exist. However, when considering a European scale, the difference in LNG production locations does not influence the European LNG market. For this reason, the different production locations for LNG are not taken into account.

5.2.2 Model scalability

Another concept, though closely related to model reusability, is model scalability. According to Long et al., scalability refers to the capability of the model to represent different supply chains and scales of a single supply chain and thus refers to the diversity of the model. After identifying the main components of the model and the relations between these components, the difference in scale of the model was identified. The European short sea network considers a smaller geographical scale than MarPEM. Nevertheless, the smaller geographical scale of the system requires a higher level of detail.

The European short sea network consists of many ports, with no small group of ports representing a significant part of all port calls. Therefore, to make a representation of the European short sea network, significant more ports, vessels, bunker terminals, shipping lanes and shipping assignments must be included in the model. However, this leads to more frequent agent interactions between ports, vessels and bunker terminals. For example, the distances between ports are smaller, which causes vessels to call ports more frequently and to make bunker decisions more often. Therefore, a reduction in the number of included agents is required, and a selection of ports is made.

Hence, the reduction in the number of ports should not neglect the distance sailed by between ports not included in the model because the distances sailed between these ports add up to the total fuel consumption of vessels. To allow for this difference, adjustments in the structure of the model must be made, especially for liner vessels. The example presented below explains the change in structure. It requires to assign line numbers to shipping assignments, shipping lanes, and vessels. The line numbers indicate for each vessel which shipping assignments it can execute and which shipping lanes it can sail. Besides, the number of ECA and non-ECA ports in the shipping lane should be assigned to each shipping lane. Nevertheless, the number of ports included in the model is still significantly more than in MarPEM.

Example:
There are two shipping lines: A-B-C-D and A-B-D.
Distances are as follows: A-B=1, B-C = 2, C-D=3, B-D=4

We want to include port A and D in the model and exclude port B and C. However, we want to include the distance travelled from A to B, from D to C, and from C to D for line 1, and from A to B and B to D for line 2. This means that the total distance travelled between port A and D should be summed. So, the distance A-D for line 1 becomes 6. The distance for A-D in line 2 becomes 5. The model should thus allow for changes is distances of the shipping lanes.

5.2.3 Model behaviour

When considering the model behaviour, most of the actions take place in both systems, such as vessels sailing, mooring, and bunkering, and bunker terminals supplying and ordering fuel. On the one hand, some of the behaviour of the model represented in MarPEM was not of interest in order to answer the research questions, such as the availability of hinterland connections and the behaviour of the LNG liquefaction plants. On the other hand, more detailed behaviour is added to the model. Examples of these are the possibility to bunker in the port of origin of the shipping assignment, or the way in which bunker decisions are made by liner vessels. Furthermore, in MarPEM, liner vessels only sail between two ports. However, during the system analysis, the liner rotation schedules were analysed and these had to be included in the model. However, these rotation schedules, include more than two ports. Thus, several modifications are made to allow for this difference. This change also relies on the use of line number, since every rotation gets an own line number assigned. In addition, the addressed problem and research questions required to include more fuels and propulsion technologies into the model. Including bio methanol and conventional methanol into the model requires some adjustments, since vessels with a methanol propulsion technology have the choice of bunker bio methanol and methanol. The model should thus allow for making a distinction between those fuels.

Further, the EU-MarPEM must allow for policy testing. Testing with the availability of infrastructure of ports is possible in MarPEM and is therefore not of a concern for the implementation in EU-MarPEM. However, modifications are made to allow for testing with the policies related to the discount on port dues for vessels operating with a certain propulsion technology and when bunkering bio methanol. These changes are made in the calculation of the NPV and in the bunker decision procedures.

Aside from the above-mentioned changes, the European regulations applicable to the short sea sector are incorporated in EU-MarPEM. MarPEM includes the SOx regulations. However, the stricter NOx regulations are not included in the MarPEM. Therefore, NOx regulations, with respect to the allowable NOx emissions based on the age of the vessel and the amount of power of the vessel's engine are included in EU-MarPEM. The enforcement of the regulations by means of fines and control percentage is present in MarPEM as a policy. In this study, these variables are treated as external factors. Besides, since bio methanol is the preferred fuel to be used by the shipping sector, the influence of a CO2 price and the willingness to pay for bio methanol are included as external factors of interest in EU-MarPEM. Both factors might influence the consumption of bio methanol by vessels.

5.3 Reusability of the source code of MarPEM

Based on the conceptualisation of the model, no major problems were expected to create EU-MarPEM. Thus, the conceptualisation of MarPEM is reused to a large extent. In addition, it was also possible to directly reuse some of the source code from the previous model. However, not all parts of the source code were equally reusable. This section reflects on the reusability of the source code and discusses the several steps that were taken to create EU-MarPEM, and the model to allow for experimentation.

5.3.1 Model behaviour

According to Valentin and Verbraeck (2002), the use of building blocks has benefits for the reusability and maintainability in simulation models. In such a way, models could be developed and maintained for a specific problem domain. However, these building blocks should be designed carefully to be able to modify them. For example, one option could be very fast, but not modular or user-friendly. Besides, the building blocks should allow for the scalability of the simulation model. Thus, well based decisions should be made for the selected modelling concepts (Valentin et al., 2002). The source code of the MarPEM can be perceived as building blocks, in a way that agent's behaviour could be separated in different behavioural blocks which can be connected to each other. The model consists of a go procedure in which the high-level procedures are defined. These procedures again consist of several procedures. For this reason, excluding agent behaviour from the models was in some case easy by excluding the behaviour on the highest level. An example of this is the exclusion of the LNG liquefaction plants and LNG bunker terminals.

Besides, agent behaviour not subjected to the scalability of the model could be reused easily. Therefore, one part of the source code that could be used directly was the procedure considering the market behaviour. Since only a small number of market agents is included in both models, including this procedure was not troublesome.

Moreover, an advantage of the model is that the characterises of the agents are loaded by means of separate text-files, which made it easy to adjust the number of agents by creating new input files. Also, new characteristics of agents could easily be added.

Further, more detailed behaviour is added to the model, such as vessel to be able to moor and bunker in the port of origin of the shipping assignment, and the selection process of shipping assignments. In addition. the risk aversion of liner vessels is calculated based on the line rotation, instead of assigning a value equal for each vessel. Besides, other behavioural changes were required to implement. Including the conceptualisation of the liner vessel's behaviour in the model depends on the additional characterises of line numbers which should be assigned to vessels, shipping assignments and shipping lanes. This characteristic is important for the behaviour related to the shipping traffic. Many procedures related to this behaviour had to be adjusted, especially the selection process of vessels to determine which shipping assignments to execute and shipping lanes to sail. Besides, for vessels to have the choice to bunker two types of fuels, additional variables had to be assigned to bunker terminals and propulsion technologies and selection procedures had to be adjusted.

In addition, the policies in MarPEM were implemented in such a way that it could be easily turned on and turned off. In this way, the control percentage and the fines for non-compliant vessels can be easily used as an external variable. The experimentation with the availability of methanol infrastructure in ports is represented in a similar manner as the LNG availability in ports in MarPEM.

Moreover, implementation of NOx regulations and the discount policies required changes through the sources code and profound knowledge of the source code was therefore needed. The implementation of discount required adjustments in the procedures to calculate the NPV of each technology, as well as when vessels deciding on the cheapest port to bunker. Furthermore, it required the shipping lanes to have additional characteristics, such as the number of the ECA lanes and non-ECA lanes present in the shipping lanes, in order to determine the number of fines. In addition, extra characteristic had to be added to ports to determine whether a port applies a discount on port dues.

5.3.2 Computational time

After implementing all behavioural changes in the source code and increasing the number of agents in the model, the model turned out to have extremely long computational times. The computational time of the model did not allow to run the required large set of computational experiments to explore many future scenarios. For this reason, MarPEM is found to be less suitable for the inclusion of more agents, and therefore for the change in geographical scale. Thus, the scalability of the model is perceived as the main issue when reusing MarPEM. To this end, many steps are taken to reduce the computational time. Trade-offs are be made between adding more detailed behaviour and the computational time of the model. To assess the parts of the source code which had a major influence on the total computational time of the model, the NetLogo profiler extension is used intensively. This section discusses the several steps that are taken to reduce the run time of the model.

5.3.2.1 Software

MarPEM was created in NetLogo 5.3. For this reason, EU-MarPEM was initially built in NetLogo 5.3. However, experiencing large computational times made it unavoidable to configure the model to the latest version NetLogo 6.0.4. NetLogo 6.0.4 has the advantage of faster internal processes which reduced the run time significantly.

5.3.2.2 Bunker-terminal price decisions

In MarPEM, bunker terminals make price decisions by means of a q-learning algorithm. For this purpose, bunker terminals make a simulation of the maritime fuel system. This means that the agents make a copy of the relevant system and simulate the operational behaviour of vessels. During this simulation, different prices are tested to determine the expected attractiveness of the price. However, due to these internal simulations, the computational time of the model increases significantly. For this reason, it is assessed if it is possible to capture these simulations in a regression model. Hereto, a sub-model of the simulated behaviour was created. The sub-model consists of the interactions between the vessels and bunker terminals. The interactions between the bunker terminals and fuel markets are not included in the sub-model, neither are the investment decisions of the vessels. 20.000 scenarios of this model were run to determine the price that was set by the bunker terminals, all with different input variables. The scenario space was created via the EMA workbench and experiments were run by using the workbench. The input variables which were altered during the runs are presented in table 3. The simulation time has been set to 90 ticks, meaning that every agent is simulating 90 days ahead to determine the best price.

First, the relation between each input variable and output variable was analysed. This analysis shows that there is a clear relation between the current price and simulated price, and that the simulated prices lay between the willingness to pay for the fuel by vessels and the minimum price the bunker terminal accepts. However, no other correlations were found and lack of pattern was missing (appendix B).
Afterwards, a linear regression model was fitted. A training set of 15.000 runs and a test set of 5.000 runs was created. The regression model was fitted over the training set. Subsequently, the fitted regression model was tested by using the test set. The regression model showed a very high mean square error and the fitted regression model could not be considered as reliable. It was tried to improve the regression model by neglecting parameters. However, this did not improve the reliability of the regression model. The mean squared error amounted 166.344 and the variance score was -0.09.
In addition, to investigate whether the model generated more complex behaviour, that could not be captured with a linear regression model, polynomial regression models with different degrees were fitted to determine if they would make better predictions. The opposite happened; the outcomes of the polynomial regression made the outcomes even less reliable.

Table 5.1: Regression input and output.

Input variable	**Input value**	**Coefficient**
Exploration rate decay bunker terminal	100000 - 14000	5.09883968e-05
Learning rate decay bunker terminal	10000 - 14000	-2.78072696e-05
Initial exploration rate bunker terminal	0.35 – 0.45	5.67356052e+00
Initial learning rate bunker terminal	0,35 – 0.45	-1.66406086e+00
Percentage of vessel with fuel of bunker terminal	0 - 100	5.14981997e-04
Willingness to pay vessels	100 - 120	3.69988228e-01
Willingness to accept bunker terminal	-	3.73111787e-01
Fuel	-	1.84571640e-01
Mean price of terminals with same fuel	-	4.26008641e-02
Percentage of bunker calls	-	-4.89318279e+01
Market price HFO, MGO, LNG, Methanol, Bio methanol	30 – 80, 35-90, 40-70, 50-80, 60-100	-2.49981090e-02
Price of simulated terminal	-	-2.49981090e-02

*Values that are not given, are determined by the model

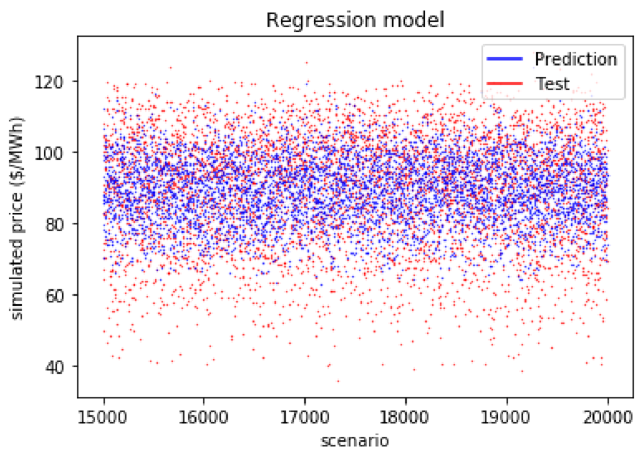

Figure 5.1: Predicted and test values of the regression model

Since the results of the regression analysis were not reliable it is decided not to apply the regression model to EU-MarPEM. The bunker terminal price decision procedure is replaced by another procedure to determine the price set by bunker terminals. This procedure is described in chapter 4.

5.3.2.3 Determine Net Present Value of propulsion technologies

As a consequence of including more agents in the model, the computational of calculating the Net Present Value (NPV) increased significantly. This procedure is called for each technology when vessels make investment decisions, which adds up to the total computational time of making investment decisions. Each time the NPV was calculated, the vessel determined which possible shipping assignments it could execute, which port is could call, which of these ports applied a discount, which shipping lanes could be sailed, the number of ECA and non-ECA lanes, and the mean distance of all possible shipping lanes. However, searching through all these long lists of agents was inefficient and time-consuming. To reduce the computational time, these variables are calculated for each vessel during the set-up of the model, avoiding that these calculations have to be made over and over again during the model run. During the implementation of these calculations in the setup, there was carefully assessed how the computational time could be kept to a minimum. Hereto, lists to search through first are divided into separate lists according to the type of cargo. Subsequently, the lists are assigned to the vessels.

5.3.2.4 Selection of shipping assignments and routes

Performance is not an issue with most of the basic operation present in the model, such as changes the status of agents. However, a bottleneck arises for selecting procedures. Shipping assignments and routes must be determined for each agent in the model to create a route from its current port to the destination ports. This is computationally expensive and has a big impact on the performance when considering a larger network with many ports and shipping lanes involved. The same problem has been identified by Mayrhofer (2015) for shortest path calculations in traffic models. Stating that the increase of number in vertices in a network might lead to memory issues on the computer which eventually could cause a java heap space overflow (meaning that the computer runs out of RAM). It is confirmed that the use of traffic models and networks are often not resistant to the scalability of the model and can be seen as a weakness for the reusability of agent-based models. For this reason, the routes of a shipping assignment are assigned in the setup of the model. In this way, vessels have to determine less frequently which shipping lanes to sail during the model run.

Besides, the selection of shipping assignments by vessels is a procedure which comprises searching through lists. The computational time of searching through these lists has been shortened by means of assigning the possible executable shipping assignment of a vessel in the set-up phase of the model. Furthermore, the order of asking in the procedure has been changed. For example, first checking if the bunker stock is enough, and then determine the executable assignments, reduces the computational time.

5.3.2.5 Loading files every tick

In MarPEM, the input file containing the shipping lanes was opened every model tick to update the allowable sulphur content of the shipping lanes. However, when including significant more shipping lanes in the model, reading the file will take more time. For this reason, the implementation of the sulphur regulations, as well as the NOx regulations are implemented in a different manner. In the EU-MarPEM, the files determine only whether a shipping lane is located in an ECA or non-ECA area. The allowable sulphur content is set as a global variable, whereas the allowable NOx emissions are determined per vessel dependent on the age of the vessel and the engine's power.

5.3.2.6 Port reservations by vessels

Due to the number of ports, vessels and ports calls, the reservation procedure was one of the procedures that caused a significant part of the computational time. However, since the procedure was not influential for the behaviour and validation of the model, the decision is made to exclude this procedure from the model.

5.3.2.7 Creating output variables

New procedures that would generate the output variables of interests are implemented since the outcomes of interest for this problem differ from the outcomes of interests included in MarPEM. However, creating model output can add significantly to the computational time of the model when many outcomes of interests are defined and many agents are included in the model. Therefore, it is necessary to define the output variables carefully. For this reason, the minimization computational time of creating model output is chosen above the minimization of source code. Therefore, instead of using reporters with "with" and "count" operators are tried to be avoided. Instead, counters in the format of variables increasing and decreasing are used, which led to significantly more source code to be produced.

Besides, the fact that the computational experiments are performed with the EMA workbench made that best way of saving the outcomes is in lists which are requested at the end of each model run by the EMA workbench. In this way, files do not have to be opened and written every time an outcome of interest is generated. Besides, several changes are made to be able to adjust the input variables with the EMA workbench.

In addition, while including more technologies and fuels in the model is not recognised as a problem for the computation time of a model run, it required to identify more performance metrics. Including more performance metrics made that more computer memory was needed when executing the experiments. As a result, the number of outputs of interests should be kept to a minimum.

5.4 Future use of MarPEM

For more successful implementation and use of the model, there are still some improvements that could be made to make the model more suitable for experimentation. However, these options are not implemented in the model, since they require large structural changes. In this research, due to time limitations, it was not possible to make these changes. The suggested adjustments are specific suggestions for the use of MarPEM at a more detailed level. However, some of the suggestion might impact the behavioural outcomes of the model and therefore could not be applied to every problem of interests.

The large number of model agents included caused large computational times of the model. For this problem, the physical presence of the shipping assignments is not per se from importance, since this research is not concerned about the cargo transported between ports, rather the sailed distances between ports is of interest to determine the fuel consumption and bunker behaviour of the vessels. To this end, shipping assignments, which in this model fulfil the role of determining to which ports vessels must sail, could be excluded. However, the model should still allow vessels to determine between which ports they have to sail. Hereto, it is suggested to include a procedure which determines the vessel's next port based on chances. The chances of each port to be called is then based on the number of port calls it receives per month compared to the total ports calls of all ports included in the model. Consequently, some characteristics belonging to shipping assignments must be assigned to the vessel, such as the time of arrival in the next port, and the route of the vessel. In addition, the parts of the source code referring to the shipping assignments must be replaced.

To create a model that allows for reuse, there is a need for an object-oriented modular approach. Besides, when reusing a model, the amount of re-coding could be reduced by using a hierarchical structure. Furthermore, the use of a hierarchical structure could reduce the risk of making errors (Manuel et al, 2017). A suggestion that could reduce the computational time of the model and increases the reusability of the model is to make use of several vessel agent types for the different cargo segments. Consequently, the shipping assignments must be separated according to the cargo segments as well. For the different segments of both vessels and shipping assignments, extra text files must be created as input files for the model. These changes imply a change in the hierarchical structure of the model.

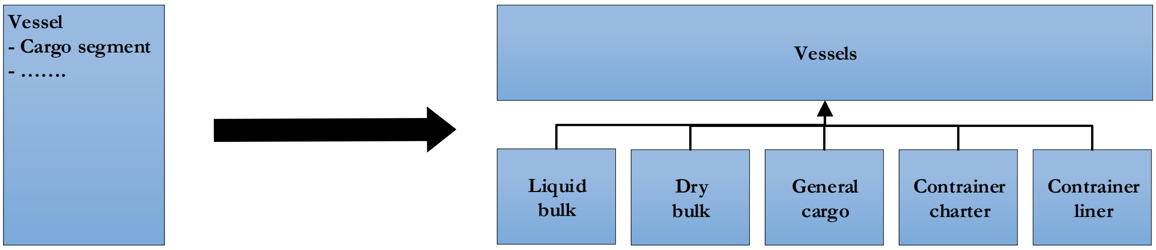

Figure 5.2: Hierarchical structure of vessels

Another suggested change is to assign the shipping lanes to ports. In MarPEM and EU-MarPEM, when vessels have to determine the route to their next port, vessels have to search through all possible shipping lanes. However, the search time can be reduced by assigning all route to a port, according to the port of origin. When a vessel has to decide which route it has to sail, it only has to search through a list with all shipping lanes with an origin in that particular port.

5.5 Conclusions

The conceptual model of MarPEM was reusable. It was easy to assess which components and procedures where of interest for the problem and in which order the behavioural procedures of the model should be implemented. This is expected to have saved a significant amount of time in the conceptualisation phase of the model creation. Thus, it is possible to use reuse the conceptualisation of the model, including components, the relation between these components, characteristics of these components and the flow of the model.

Aside, from the conceptual model, it was possible to include parts of the source code of the model. However, not all source code could be reused evenly well. It is found that procedures not subjected to the increase of the number of agents were relatively easy to reuse. More complications occurred when trying to reuse the parts of the source code which are subjected to significant more agents. Due to the fact that in MarPEM relatively little agents are included, it includes a large number of procedures which are not resistant to the use of many agents. Problems occurred when reusing procedures which make use of lists and "with" statements, these are often used in combination with each other and this was especially problematic for the operational behaviour of the vessels. In MarPEM, lists are used to search for a specific agent in combination with "with" statements in for selection procedure. However, making use of more agents in the model, made the lists significantly larger and therefore more time is needed to search through these lists. The total computational time increased extremely. For this reason, several attempts are made to decrease the computational time of the model. It is found, that the scalability is more of a concern when reusing agent-based models than the actual model behaviour. In addition, now that it is known that the model scalability is of big concern when reusing MarPEM, several suggestions are made to improve the performance of the model. A more hierarchical structure could benefit the computational time of the model.

However, an increase in computational time might not always be a problem and depends on the purpose of the model. In this case, the model is used to explore a large range of possible futures, requiring a large number of experiments to be performed. For this reason, a short computational time is required. Thus, when assessing the reusability, it is recommended to take into account the purpose of the study. Hereto, it is important to determine the number of experiments that are required, the output variables, and the scalability of the model. Besides, the fact that the model was well documented made that it was possible to reuse the model.

6. Model testing

Before executing the experiments, the model has been verified. Hereto, several steps were performed to verify the model. Further, the reliability of the model was tested by means of a stochasticity analysis. This chapter discusses the verification steps in section 6.1 and the results of the stochasticity analysis in section 6.2.

6.1 Verification

The model is verified to ensure that no mistakes were made during the model implementation. Several steps are undertaken to verify the model. Firstly, by means of tracking agent behaviour. During the implementation of the model, there is actively checked if mistakes were made by means of printing statements. Besides, a unit check is performed to make sure that all units of variables which are included in the model are consistent. Also, the model implementation was checked by means of single-agent testing, e.g. testing the behaviour and states of single-agents (for each type of agent). Another way of verifying the model that was applied is by interaction testing in a minimal model. Initially, the model has been built with only a small set of agents, which was scaled up later. Besides, the behaviour of charter and liner vessels has been tested separately. Finally, the model was verified with multi-agent testing, a variability test and sanity test were performed. By means of variability testing, the behaviour of the model was tested under extreme conditions. This allows for finding obvious mistakes and test the boundaries of the system. The outcomes of the tests were compared with the expectations. Performing these tests with extreme values testing allowed for finding divisions by 0, which caused errors. Hereto, extra checks have been added to the model to make sure that no divisions by 0 take place during the model executions. The outcomes of the model verification steps can be found in appendix C. After going through all these steps throughout the implementation process of EU-MarPEM, it is concluded that the model behaves in a way in which it is expected and wanted to behave.

6.2 Stochasticity analysis

A stochasticity analysis is performed to determine how sensitive the model is to stochasticity. The stochasticity present in the model comes from the order in which agents are asked to do things. 65 replications of one scenario are conducted to measure the stochasticity. These replications were executed with a fixed set of input values. By performing a set of replications, the mean values can be estimated using the sampled average across the replications. The figures below show the mean and the confidence interval of the 65 repetitions. It can be noticed that the model is sensitive to stochasticity. Meaning that the stochasticity of the model influences the outcomes of one single run. Therefore, we could not trust the outcomes of one single model run. To approach the real mean, several replications of a model run are needed. However, not all parameters were evenly subjected to stochasticity, the outcomes are shown in appendix D.

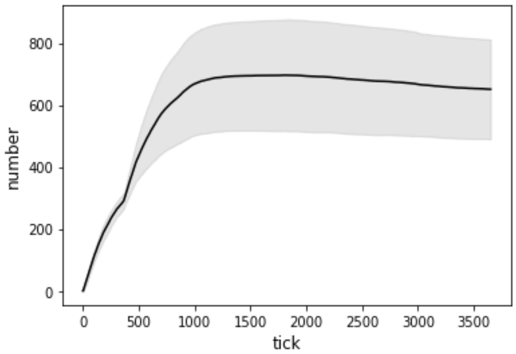

Figure 6.1: Stochasticity scrubber/SCR vessels

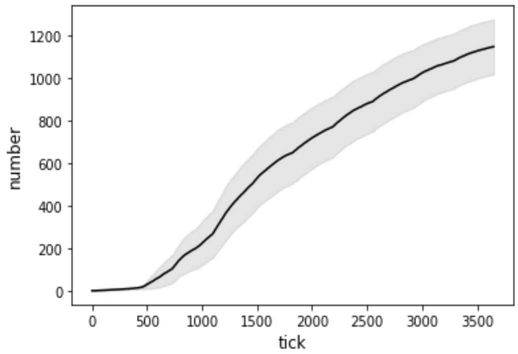

Figure 6.2: Stochasticity methanol vessels

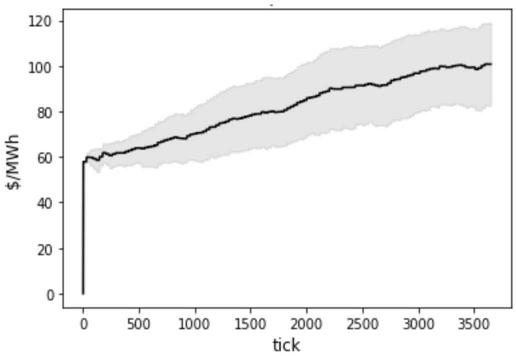

Figure 6.3: Stochasticity bunker terminal price HFO

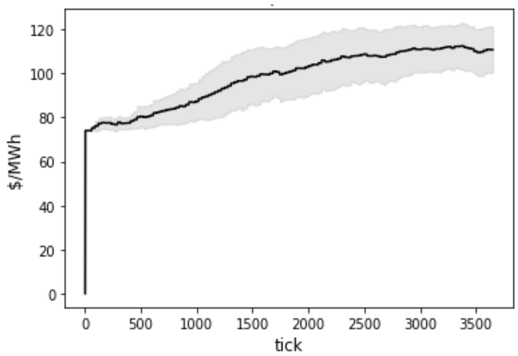

Figure 6.4: Stochasticity bunker terminal price MGO

To estimate the number of replications that is needed, from the 65 replication 4 different samples with different sizes, respectively 5, 10, 20 30, were taken. When increasing the number of replications, the estimated value becomes better. The outcomes of each sample group are analysed and compared. In appendix D, the results of this analysis are presented.

The figures below show that increasing the sample size, influences the estimated mean values. A significant difference can be noticed when increasing the samples size from 5 to 10 replications. Unfortunately, there is no specific rule about how to determine the required replications for a given simulation (Kelton, Smith. Sturrock & Verbraeck., 2010). A trade-off should be made between the computational run time and reducing the sampling error.

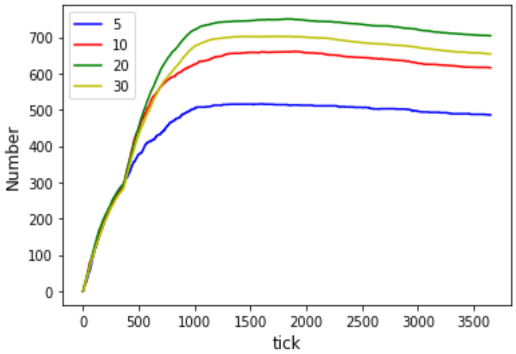

Figure 6.5: Samples scrubber/SCR vessels

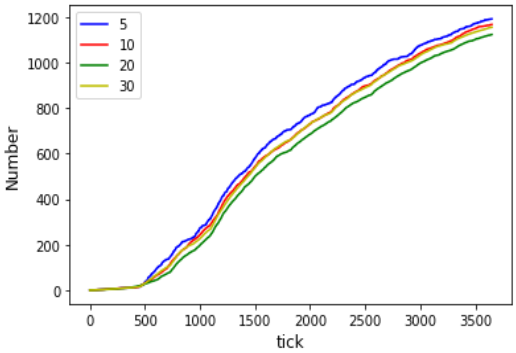

Figure 6.6: Samples methanol vessels

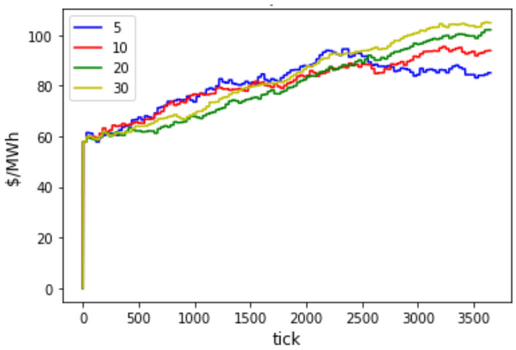

Figure 6.7: Samples bunker terminal price HFO

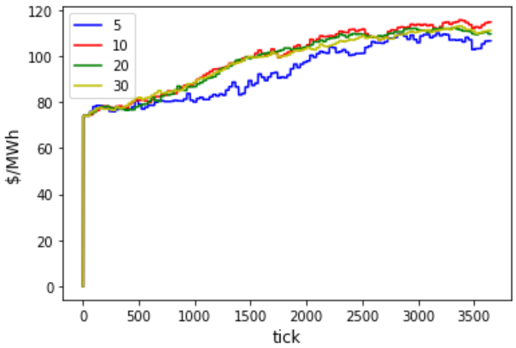

Figure 6.8: Samples bunker terminal price MGO

7. Model parameterization & validation

The next step in the development of the model is to set the parameters in the model according to real-world values. These values will be discussed in section 7.1. Section 7.2 comprises the validation of the model. The validation of the model determines whether the behaviour of the model, after the parameterization, gives valid outcomes which correspond with real-world observed behaviour.

7.1 Model parametrization

After software structures were implemented in the NetLogo model, real values are assigned to the variables. These values are obtained by means of desk research, data analysis and talking to experts. This section discusses the values that are taken as input values for the model.

7.1.1 Ports

Since the study focuses on the use of alternative fuels in ECAs, only shipping lines which are calling ECA ports are considered in the model. When analysing these lines, thirty ports (listed below) represent over 70% of the container liner port calls. For this reason, it is assumed that it represents significantly more than 70% of the bunkering of the vessels operating on these lines. The selected ports are located in ECAs, as well as in non-ECAs. In total there are 82 container lines, on which 173 vessels are operational. However, the liners including ports located in Greenland are left out of this study. The port of Rotterdam and the port of Moerdijk are modelled together as one port, assuming that the fuel is supplied to the vessels by the same fuel suppliers. Similarly, this is the case for the port of Antwerp and the port of Ghent, and the port of Immingham and Hull.

Ports included:
Rotterdam, Antwerp, Felixstowe, London, Dublin, Teesport, Le Havre, Immingham, Leixoes, Hamburg, Casablanca, Piraeus, Dunkerque, Cork, Setubal, Gdynia, Saint Petersburg, Vigo, Sines, Alexandria, Bremerhaven, Bilbao, Ashdod, Helsinki, Klaipeda, Ambarli, Algeciras, Liverpool, Belfast, Salerno

Another reason for the selection of 30 ports lies in the fact that including fewer ports leads to the exclusion of a large number of line rotations. Besides, including fewer ports in the model causes vessels to not be able to sail the distances between ports with a fuel bunker stock. However, the number of ports included is tried to be kept to a minimum since adding extra ports leads to larger computational times.

Port tariffs are assumed to be the same for each port and based on the port tariffs of the Port of Rotterdam. These tariffs consider only the part of port dues on which a discount is applied:

- Port tariffs charters: 0.33 $/dwt
- Port tariffs liners: 0.18 $/dwt

7.1.2 Shipping assignments

The number of port calls per port are retrieved from the Eurostat database. The data from 2017 is taken since this was the latest year of which the data was complete. Per cargo segment, the number of port calls of vessels with a maximum dwt of 20.000 are taken. The Eurostat database does not provide any data about the port of Saint Petersburg, Alexandria, Ashdod, and Casablanca. Therefore, for these ports, the values are estimates based on the port size and geographical location. The number of port calls per month for each port can be found in appendix E. In addition to the available data about port calls, the Eurostat database provides information about the short sea trade volumes between countries and regions. Based on this information assumptions are made about the transported volumes between ports. In this way, shipping assignments for charters are created. The shipping assignments executed by liner vessels are created based on the data of eeSea. eeSea provides data about the line rotations of container transport, the number of vessels on these lines, the capacity of these vessels and the duration of each line rotation. The rotation for each line has been modified in such a way that the ports not included in this research have been left out of the rotation schedule but includes the distances between these ports. A total number of 917 shipping assignments are included in the model of which 78 shipping assignments are assigned to liner vessels and 839 shipping assignments to charter vessels. The aggregation of the shipping assignments for liners corresponds to the number of vessels operating on the line. The aggregation of charter vessels is set to 5, meaning that each shipping assignment corresponds to five times the trade volume in the real world. An aggregation of the shipping assignments was made to reduce the run time of the model. However, choosing a higher aggregation level would lead to a significant exclusion of trade volumes between ports, since the trade volumes between ports are relatively low.

7.1.3 Shipping lanes

Two types of shipping lanes exist in the model. 1) Shipping lanes sailed by charters, and 2) shipping lanes sailed by liners. Shipping lanes belonging to charter vessels are all characterised by the same line number, while shipping lanes belonging to liner vessels are characterised by the line number of a specific line rotation. Port to port distances are obtained through marine-traffic.com. For the liner shipping lanes, the distances between ports not included in the model are summed and added to the shipping lane.

7.1.4 Vessels

Table 7.1 shows the initialisation of the vessels. Five classes are identified, which determine the cargo segment of the vessel and whether a vessel is a liner or a charter. 95% of short sea liner calls are container vessels (data PoR). For this reason, only liners carrying containers are included in the model. The other four classes represent the charter vessels. The number of vessels for each class of vessels is determined by the number of shipping assignments that need to be transported each month between the 30 ports. The vessels in class B, C and D have an aggregation of 5, e.g. each vessel represent 5 vessels. The vessels are all initialised which HFO as propulsion technology.

Table 7.1: Initialisation of vessels

Variable	Initialisation	Explanation
Class	Container liners: class A, Liquid bulk: class B, Dry bulk: class C, General cargo: class D, Container: class E	
Vessels (#)	Class A: 78, Class B: 125, Class C: 30, Class D: 256, Class E: 62	Based on the number of port calls of each cargo segment an estimation of the number of vessels needed to execute all the shipping assignments is made.
Aggregation of vessels (#)	Class A: depends on the line rotation Class B, C, D, E: 5	Data eeSea. Based on aggregation shipping assignments (see explanation 7.1.2)
Carrying capacity (dwt)	Class A depends on line Class B, C, D, E: Exponential distribution (mean=8.77921, sigma=0.5436955)	Data eeSea. Distribution is based on the distribution of the carrying capacity of container liner and distribution found in PoR data (F E)
Fuel capacity (MJ)	0,659 MWh/dwt	Based on the fuel capacity of 20 vessel of Damen Shipyards
Engine (kW)	dwt < 5000: 3000 kW 5000 < dwt > 8000: 4000 kW 8000 < dwt > 12000: 8000 kW dwt > 12000: 12000 kW	Groups identified by analysing fleet of Samskip
Propulsion technology	Non-compliant (HFO)	Based on data PoR
Age	Random integer 10950	Bas et al. (2017)
Economic lifetime (days)	1095	Bas et al. (2017)
Technical lifetime (days)	10950	Bas et al. (2017)
Speed (nm/day)	Class A varies per line rotation Class B, C, D, E: 210	Data eeSea. Mean speed of vessel Class A
Costs of lost cargo capacity (euro/%/mt)	100	Bas et al. (2017)
Discount rate (%)	10	Bas et al. (2017)
Willingness to pay fuel ($/MWh)	160	Bas et al. (2017)
Willingness to pay bio methanol ($/MWh)	0	-
Fuel consideration percentage (%)	50	-

7.1.5 Propulsion technology

Five different propulsion technologies are included in the model, each with its own specifications. Table 7.2 shows the values that are assigned to the propulsion technologies. The table does not only show the characteristics assigned to variables in the model but does also show the values used to obtain other values, such as the lower heating value and the density of the fuels.

Table 7.2: Characteristics of propulsion technologies

	Non-compliant	HFO + Scrubber / SCR	MGO + SCR	LNG	Methanol	Methanol (small)	Reference
Fuel	HFO	HFO	MGO	LNG	(bio) methanol	(bio) methanol	-
Lower Heating Value (MJ/ kg)	40	40	43	50	20	20	Ellis & Tanneberger, 2015
Density (kg/m3) *	989	989	Max 900	448	796	796	Ellis & Tanneberger, 2015
SOx emissions %	1	0.1	0.1	0.01	0	0	Brynolf, 2014; Brynolf, 2014
SOx emissions (g/MJ)	1,33	0,049	0,047	0,0001	0	0	Brynolf, 2014; Brynolf, 2014
NOx emissions (g/MJ)	1,6	0,28	0,28	0,12	0,28	0,28	Brynolf, 2014; Brynolf, 2014
CO2 emissions (g/MJ)	79	79	75	57	69	69	Brynolf, 2014; Brynolf, 2014
Replacement costs	-	926 $/kW	120000 + 542 $/kW	1275 $/kW	815 $/kW	815 $/kW	Ellis & Tanneberger, 2015
Retrofitting costs ($/kW)	-	489 $/kW	150000 + 63 $/kW	664 $/kW	392 $/kW	392 $/kW	Ellis & Tanneberger, 2015
Onboard space requirements (%)	-	0.06	0.03	0.04	0.04	0	Bas et al. 2017; Ellis & Tanneberger, 2015
Loss of bunker capacity (%)	-	0	0	0	0	2.5	-
Operational costs ($/MWh)	-	5	5	6	4	4	Ellis & Tanneberger, 2015
Fuel consumption (MWh/nm ton)	$2.607x 10^{-4}$	2.607×10^{-4}	2.669×10^{-4}	2.669×10^{-4}	2.669×10^{-4}	2.669×10^{-4}	Brynolf, 2014; Brynolf, 2014

7.1.6 Bunker terminals

A price difference exists between the different bunker supplier in Europe and this influences the bunker behaviour of vessels. Therefore, the model should allow for taking these price difference into account. For this reason, fixed bunker terminal costs are assigned to each bunker terminal. However, no data about these fixed costs is available. For this reason, the fixed costs of the HFO and MGO bunker terminals have been determined by analysing the fuel prices of the different ports in the period from 16 – 19 January 2019. For the fixed costs of HFO three groups are determined: 1) Ports that are relatively cheap because of the availability of refineries, 2) Ports with an average price, and 3) Ports that are relatively more expensive to bunker. MGO has been categorised in four groups. The fixed costs of the LNG terminals are determined by the availability of LNG in the Port. When LNG is available in the port the fixed costs of the terminal are set to 0. When there is no LNG available in the port, it is assumed that the LNG will be transported with a bunker barge to the port. The fixed costs are determined by the distance to the closest port with LNG available and the transport costs (0.0095 $/nm Bas et al., 2017). The fixed costs for methanol are determined by the availability of methanol plants in the country of the port. When methanol is produced, the fixed costs for methanol are assumed to be lower. For bio methanol such a distinction is not made, due to the fact that bio methanol is not well developed yet. When interpreting these costs, it should be taken into account that the bunker costs do not reflect the actual fixed costs of bunker terminals and that these costs only serve as a means to create a difference in fuel price between the different locations of bunker terminals. The representation of these fixed costs can be found in appendix E.

7.1.7 Fuel markets

Future fuel prices are highly uncertain. In this study, the prices during the parameterization of the model are set to the average prices of the scenarios represented in the study of Ellis & Tanneberger (2015) and Maritime Knowledge Centre et al. (2017).

Table 7.3: Initialisation of fuel market prices

Fuel	Value	Reference
HFO market price ($/MWh)	47.5	Ellis & Tanneberger, 2015 *
MGO market price ($/MWh)	87	Ellis & Tanneberger, 2015 *
LNG market price ($/MWh)	55.5	Ellis & Tanneberger, 2015 *
Methanol market price ($/MWh)	65	Ellis & Tanneberger, 2015 *
Bio methanol market price ($/MWh)	95	Maritime Knowledge Centre et al., 2017 *

*Values are corrected for the fixed costs of bunker terminals which are included in the model

7.1.8 External variables

Several external variables could influence the behaviour of the actors represented in the European Maritime fuel system. Three external factors are identified that might influence the behaviour of these actors and are therefore included in the model. These external factors represent the uncertainty in the enforcement of regulation by the IMO and the EU.

- Control percentage: the control percentage represents the strictness of enforcement of the regulations. It presents the percentage of a vessel being controlled when calling a port.
- Fines: these are penalties given to ship operators when they are getting caught with no compliant propulsion technology. How much the fines will amount in the future is not yet known and could differ from country to country. For this reason, experiments are performed with fines between the 10.000 and 100.000 per port call.
- CO2 taxes could influence the uptake of biofuels. For this reason, a CO2 price is included in the model as an external factor. ECN (2017), made a prognosis of future CO2 prices. This prognosis is included in the model, ranging from only increasing to 11 euro per tonne CO2 to an increase up to 50 euro per tonne CO2 in 2028.

7.2 Validation

To validate the model outcomes, the output generated by the model is compared with historical data. The total number of ports calls each month is compared with the expected amount of port calls. In addition, the port calls of each separate port are compared with the expected port calls. Figure 7.1 shows the total port calls in the model and the expected port calls. The total port calls observed in the model are slightly higher than the expected port calls. This is due to the fact that the number of vessels that selects an assignment with its origin the current port is slightly lower than expected. The observed difference is not expected to have a noticeable impact on the total performance of the model and the results. Subsequently, the number of port calls of each port are analysed. Here, the observed number of port calls does differ to a slightly higher extent. Most of the deviations in port calls are not worrisome. However, it is worth mentioning that the observed port calls of Gdynia and Felixstowe deviate significantly from the expected values (figure 7.3 and 7.4). This is caused by the relatively high number of vessels that sail to these ports to pick-up a shipping assignment. The rest of the port call validation plots are depicted in appendix F.

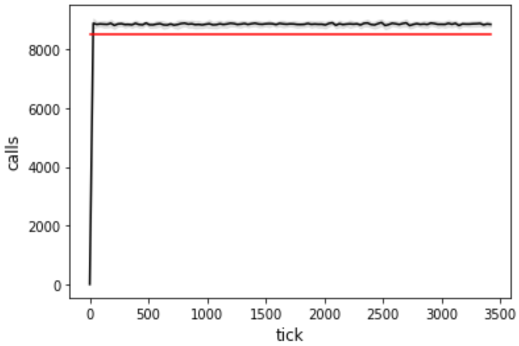

Figure 7.1: Validation total port calls

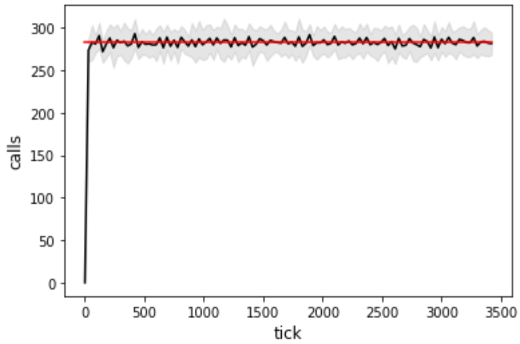

Figure 7.2: Validation port calls London

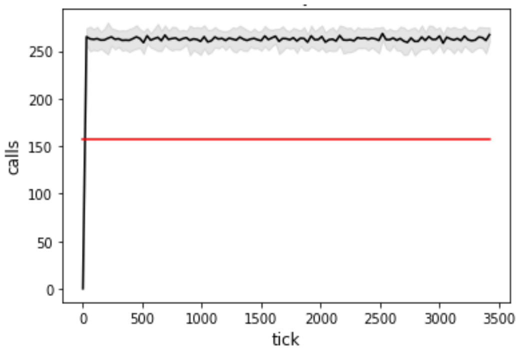

Figure 7.3: Validation port calls Gdynia

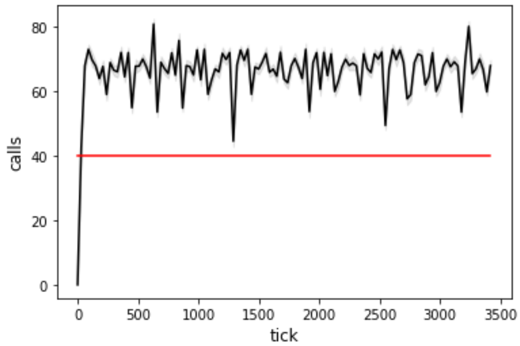

Figure 7.4: Validation port calls Felixstowe

8. Experiments

Computational experiments have the role of providing insight into different uncertainties and the effects of different policy measures. The experiments examine the ranges of possible outcomes. They gave insight into how the stakeholders in the maritime fuel systems behave under different circumstances. Besides, EMA is used to identify which policies are most robust subjected to different scenarios. These scenarios are created by changing the input values of uncertain parameters in the NetLogo model. In this chapter, in section 8.1, the different uncertainties examined during the experiments are identified. Subsequently, in section 8.2, the policies tested during the experimentation are discussed. Further, other settings used during the experiments are discussed in section 8.3. Section 8.4 presents an overview of the experimental design which is used the execute the computational experiments.

8.1 Uncertainties in the maritime fuel system

The future is subjected to various types of uncertainties in different stages and activities in the supply chain of maritime fuels. These uncertainties can vary in degree and to which extent they influence the outcomes of the system. Scenario analysis is a straightforward way to address these uncertainties. Both technological as regulatory uncertainties are identified as key uncertainties which caused the absence of investment decisions by ship operators.

8.1.1 Regulatory uncertainties

Regulatory incentives, such as government incentives and policies, are uncertainties which influence the behaviour of the stakeholder in the system. A significant uncertainty in the biofuel market is the government support. Governments can give incentives to stimulate the production and consumption of biofuel, so they become more competitive with conventional fuels. Examples of incentives are tax reduction or subsidies. In this research, the uncertainty around regulation towards the support of biofuels on the one hand and on the other hand, the disapproval of conventional fuels is modelled by means of a CO2 price. A higher CO2 price will support the use of bio methanol and discourage the use CO2 emitting fuels. The uncertainty around the enforcement of emission regulations is explored by means of applying fines and controlling vessels for non-compliance. Moreover, uncertainties related to fuel prices can play a substantial role in the emergence of alternative fuels for the shipping sector. Future fuel prices are highly uncertain and therefore explored during the experiments.

8.1.2 Technological uncertainties

Further, technological uncertainties might play a role in the adoption of certain technologies. Technological innovation might influence the investment costs and space requirements of technologies. Besides the investment costs and space requirements differ from vessel to vessel and are therefore an uncertain factor.

8.1.3 Parameter setting uncertainties

To trace down which variables have an impact on the outcomes, the uncertain variables to include should be carefully chosen. Including too many uncertain variables could make it hard to assign the outcomes of the model to certain input values of the model when not enough experiments are performed. Therefore, a selection of uncertain factors is made. The included uncertainties are those which are expected to influence the outcomes of interests the most or are identified as uncertainties of interests.

Table 8.1: Uncertain parameters

Uncertainty	Default value	Lower-bound	Upper-bound	Comment
HFO market price ($/MWh)	47.5	31	64	Ellis & Tanneberger, 2015 *
MGO market price ($/MWh)	87	56	118	Ellis & Tanneberger, 2015 *
LNG market price ($/MWh)	55.5	46	65	Ellis & Tanneberger, 2015 *
Methanol market price ($/MWh)	65	50	80	Ellis & Tanneberger, 2015 *
Bio methanol market price ($/MWh)	95	80	110	Maritime Knowledge Centre, 2017 *
Onboard space scrubber (%)	1	0.80	1.20	-
Onboard space SCR (%)	1	0.80	1.20	-
Onboard space (%)	1	0.80	1.20	-
Onboard space (%)	1	0.80	1.20	-
Investment costs scrubber (%)	1	0.80	1.20	-
Investment costs SCR (%)	1	0.80	1.20	-
Investment costs LNG (%)	1	0.80	1.20	-
Investment costs methanol (%)	1	0.80	1.20	-
Costs of lost cargo capacity (euro/%/dwt)	70	40	100	Upper-bound: Bas et al. (2017) Lower-bound: back on the envelope calculations
Control percentage (%)	0.50	0	1	-
Fine ($)	50.000	10000	100000	-
CO2-price rate	1.0005	1.0005	1.0009	ECN, 2017
Willingness to pay bio methanol (%)	0	0	0.10	-

*Values are corrected for the fixed costs of bunker terminals which are included in the model.

8.2 Policies

In total, 4 different policy levers are identified. The first policy lever contains the ports collaborating with each other. Table 8.2 shows the 5 groups which are defined as collaborative ports for a discount on port dues. The amount of discount is represented by the second policy lever, varied with no discount, 10% discount and a 20% discount. Policy lever 3 comprises the discount on bunkering bio methanol, varied with 5% or 10 %. Policy lever four covers the collaboration between ports with respect to the availability of methanol infrastructure available in the port. The same groups as for the first policy lever are used for this policy lever (table 8.2).

Table 8.2: Scenarios of port collaboration

Scenario	Ports	# Ports
1	Rotterdam	1
2	Rotterdam, Piraeus, Antwerp, Immingham, Algeciras	5
3	Rotterdam, Piraeus, Antwerp, Immingham, Algeciras, Liverpool, Dublin, London, Teesport, Hamburg	10
4	Rotterdam, Piraeus, Antwerp, Immingham, Algeciras, Liverpool, Dublin, London, Teesport, Hamburg, Casablanca, Klaipeda, Saint Petersburg, Bremerhaven, Ambarli, Ashdod, Belfast, Helsinki, Leixoes, Bilbao	20
5	Rotterdam, Piraeus, Antwerp, Immingham, Algeciras, Liverpool, Dublin, London, Teesport, Hamburg, Casablanca, Klaipeda, Saint Petersburg, Bremerhaven, Ambarli, Ashod, Belfast, Helsinki, Leixoes, Bilbao, Le Havre, Gdynia, Salerno, Dunkerque, Vigo, Setubal, Sines, Alexandria, Cork, Felixstowe	30

8.3 Experimental settings

This section entails the experimental settings which are used to explore the behaviour of the model under different parameter settings. These settings are used when executing the experiments via the EMA workbench.

8.3.1 Number of experiments

Policies and scenarios are identified through the design of experiments in the EMA workbench. When the number of uncertain parameters is too large to execute a full factorial experiment within a reasonable amount of time, one can opt for using a fractional- factorial design. Latin Hypercube Sampling is a technique to obtain a fractional- factorial design (LHS). It allows for selecting a preferred number of experiments which uniformly distributes the parameters over the parameter space (Chappin, 2008). In total 500 scenarios and 35 policies are randomly generated by sampling over the uncertainties and policy levers using LHS. Given these policies and the generated scenarios, the experiments can be performed. The total set of experiments consist of each possible combination between scenarios and policies. A total of 17.500 experiments are performed.

8.3.2 Number of replications

The stochasticity analysis presented in chapter 6 provides information about the number of replications that are needed to deal with the stochasticity of the model. Increasing the model from 5 to 10 replication showed significant improvement in the estimated mean values. Whereas increasing the number of replications from 10 to 20 had a significantly smaller effect. Since a trade-off must be made between the number of scenarios, the number of policies and the number of replications, it has been decided to execute 10 replications of each experiment.

8.3.3 Warm-up period

The model is initialised with vessels having a full bunker stock and with the market price not yet cleared. For this reason, the data generated in this initial transient period of the model will give biased statistics. The number of bunker calls, the fuel bunkered in ports, and the total fuel supply are significant less in the first period of a model run. Therefore, a warm-up period is applied when executing experiments. A warm-up period of 180 ticks is sufficient in order to deal with the initial transient period of the model.

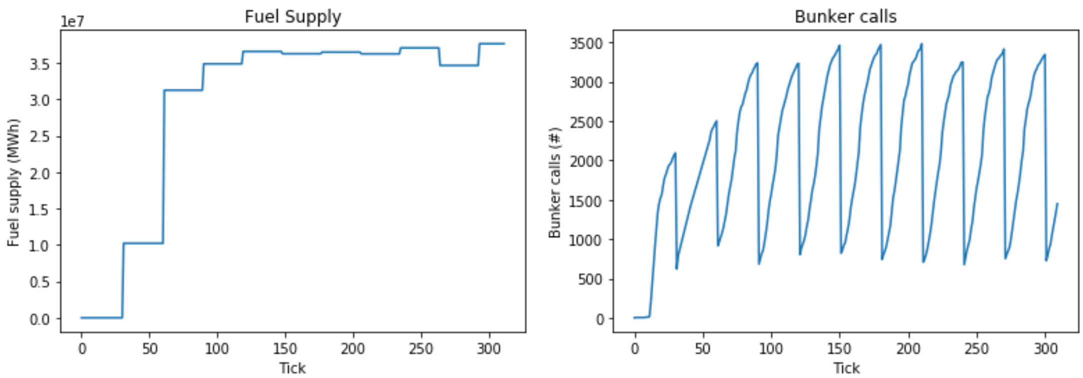

Figure 8.1: Initial transient period of model

8.3.4 Run length

The model run length is set to 3465 ticks including the warm-up time of the model. One tick represents 1 day in real life, so in total the data of 9 years will be gathered, representing 2019-2028.

8.3.5 Performance metrics

The model can provide data about many variables included in the model. However, not all these variables are of interest for this study. Besides, including more outcomes of interest adds up to the total memory needed to save the outcomes of the experiments and leads to higher computational times. This makes that the outcomes of interests are chosen wisely and are kept to a minimum. The answers to sub-question 2, 3, 4 could be provided by means of the experimental outcomes. Per sub-question, there is assessed which performance metrics are required to answer the sub-question. In total 23 outputs of interest were identified. For each experiment, the mean value of the 10 replication every 30 ticks is saved.

Table 8.3: Performance metrics

Performance Metric	Unit
Number of charter vessels with technology	#
Number of liner vessels with technology	#
Mean bunker terminal price of each bunker terminal	$/MWh
Percentage bunker calls of Port of Rotterdam	%
Total supply of fuel of each fuel	MWh/month

8.3.6 Overview of experimental design

The previous sections discussed the settings of the experimental design. Figure 8.2 depicts an overview of the experimental designs by using the XLRM framework. This experimental design is used to perform the computation experiments with the created NetLogo model; EU-MarPEM. These experiments are run via the EMA workbench.

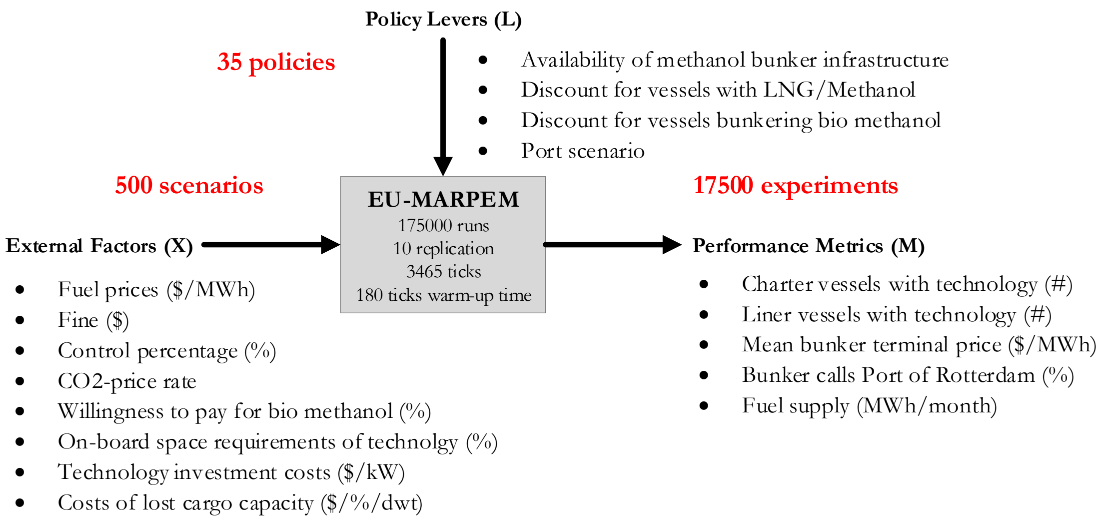

Figure 8.2: XLRM framework of experimental design

9. Data analysis

Data is obtained by means of executing computational experiments with EU-MarPEM. This chapter entails the various steps concerned with the analysis of these experimental outcomes. These steps provide insight into how the model behaves subjected to several uncertainties and policies. First, a short overview of the data analysis methods is given in section 9.1. Afterwards, in section 9.2, 9.3, and 9.4 the outcomes for each variable of interest, and the relation between these outcomes are discussed.

9.1 Data analysis methods

This section provides a brief description of each of the data analysis methods that are applied to analyse the outcomes of the 17.500 experiments. First, by means of scatterplots, the relations between the outcomes of interests are explored. The plots show a quick visualisation of the correlations between the end values of each model run. The plots show the relations between all types of fuels, the relations between all types of emission abatement technologies for charters and liners, and the relations between the fuel supply and the deployment of the associate emission abatement technologies. These plots are depicted in appendix H. Subsequently, feature scoring is used to identify the most influential uncertain parameters on the system behaviour (appendix I). The higher the score and the darket the cel is, the more influential the variable is on the outcome of interest. Next, for each outcome of interest, line plots are created. These plots show the behaviour of the model overtime. The shaded envelopes show the minimum and maximum values for each outcome over time, the coloured lines show the behaviour of 30 random experiments. The kernel density estimator (KDE), shown on the right-hand-side of the line plots, shows the distribution of the outcomes at the end of the simulation. From this analysis, the set of experiments of interest is determined. In addition, the KDE of each variable at several time steps are depicted in appendix G. Further, the set of experiments of interests is analysed more in depth by means of scenario discover. In this way, combinations of uncertain parameters and policies which results in regions of interests in the outcome space are identified. A method that enables to easily find these scenarios is dimensional stacking. The parameters related to the uncertainties, as well as parameters related to the policies are included in this analysis. An example of a dimensional stack plot is figure 9.4. The outcomes on the x-axis and y-axis show the most influential variables. The darkness of each cell relates to the region in which most outcomes of interest can be found. The dimensional stack plots are depicted in appendix J.

The above-mentioned data analysis methods are applied. In the successive sections, the results of these analyses are presented. First, the outcomes related to the deployment of emission abatement technologies are discussed in section 9.2. This section reflects on the outcomes related to sub-question 1. Second, the outcomes related to the bunker behaviour of vessels are discussed in section 9.3. By doing so, it is aimed to provide an answer to sub-question 2. Finally, in section 9.4, the influence of the policies is analysed. In this way, an answer to sub-question 3 can be provided.

9.2 Emission abatement technologies

In the model, the majority of the vessels are charters, meaning that these vessels deliver shipping assignments according to the demand. These vessels are thus not operating in fixed rotation schedules. When these vessels are making decisions towards the investments in emission abatement technologies, they take into account the variety of ports they are able to call. Adopting a certain emission abatement technology can influence the number of shipping assignment they can execute in the future due to: 1) the availability of the bunker fuel in ports, and 2) due to the fact that some technologies influence the distance that can be sailed with a full fuel tank. Liner vessels take into account their rotation schedules when making decisions towards emission abatement technologies. When investing in a certain technology, it is important for them to assess whether it is possible to bunker the fuel in the ports of their rotation schedule because they must be able to execute the full rotation without running out of fuel. The upcoming sections elaborate on the investment decision of ship operators towards emission abatement technologies and the dynamics and factors behind these decisions. In section 9.2.1, the relations between the adoption of the deployment of each emission abatement technology is discussed. Afterwards, in section 9.2.2, the most influential uncertainties towards these developments are identified. In addition, the deployment of each emission abatement technology is discussed in more detail in section 9.2.3.

9.2.1 Relations between the deployment of emission abatement technologies

This section reflects on the deployment of emissions abatement technologies by ship operators. For each emission abatement technology scatterplots that show the relation between charter vessels and liner vessels with a certain emission abatement technology, as well as the relation with the supply of each fuel, are made (appendix H). These plots show that the deployment of a certain technology by charters and liners is positively correlated, as well as the deployment of the technology and the supply of the associated fuel. These results are rather logical. However, the relation between the amount of bio methanol supplied and the number of vessels operating with methanol propulsion technology is not that obvious since bio methanol in not often chosen to operate with. Besides, the relations between the number of vessels with methanol propulsion technology in combination with a large fuel tank are not clear since the decision to invest in a large methanol fuel tank were not often made. Besides, the relation between the deployment of each emission abatement technology for charters and liners is identified by means of scatter plots. These plots are depicted in appendix H. The plots show that the relation between the deployment of each emission abatement technology is negative.

9.2.2 Uncertainties influencing the deployment of emission abatement technologies

After analysing the relation between the outcome variables related to the abatement technologies adopted by vessels, the most influential uncertainties are identified by means of feature scoring. Figure 9.1 depicts the outcomes of the feature scoring analysis. The colour and number in each cell indicated the importance of the feature. The variables on the y-axis relate to the uncertainties and the variables on the x-axis relate to the outcomes of interests. This figure indicates that for the deployment of non-compliant vessels and vessels with a scrubber/SCR system, the control percentage and the fine were highly influential uncertainties. The adoption of an SCR system in combination with MGO, LNG propulsion technology, and methanol propulsion technology was mostly influenced by the HFO market prices and the price of the associate fuel that comes with the implementation of the abatement technology.

Further, technological uncertainties appear to play a minor role in the deployment of emission abatement technologies. The investment costs and costs of lost cargo capacity have a relatively low influence in comparison to the fuel costs, control percentage and fines. For this reason, they did not have an effect on the investment decisions in emission abatement technology.

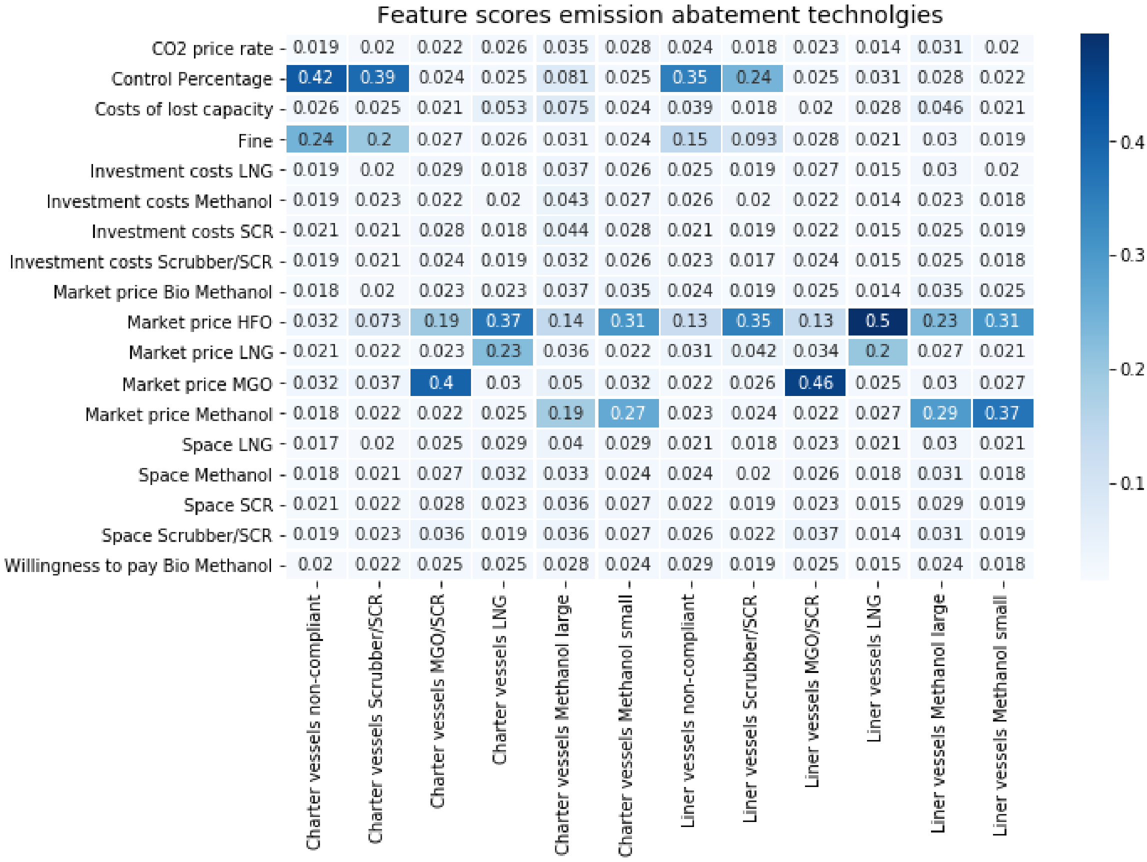

Figure 9.1: Feature score emission abatement technology

9.2.3 Reflection on the deployment of each emission abatement technology

In the next sections, the outcomes of the deployment of each emission abatement technology is discussed in more detail. For each abatement technology, the results for charters and liners are discussed by means of reflecting on the line plots and the outcomes of the dimensional stacking analysis.

9.2.3.1 Non-compliant vessels

When analysing the development of non-compliant charter vessels, in all experiments the total number of non-compliant charter vessels decreased. By 2028, a maximum of 85% non-compliant vessel is found. Further, two areas are addressed in which a significant part of all experiments end up. These areas are depicted on the right-hand side of figure 9.2, and show the distribution of outcomes at the last time step of each model run. The first area, involving 43% of the experiments, concerns the experiments in which the percentage of non-compliant vessels was smaller than 15%. These outcomes are favourable and therefor of interest. Nevertheless, another area, concerning over 33% of experiments, results in a percentage of non-compliant charters between 60-85%. Although the outcomes of these experiments are unfavourable, obtaining insight into the influential parameters can help to understand the behaviour of the overall system. These two areas are further investigated by means of dimensional stacking (appendix J). Dimensional stacking shows that with a low fine or control percentage ship operators were not stimulated enough to invest in emission abatement technologies. Consequently, the experiments with a final percentage of non-compliant charter vessels below 15% are characterized by a high fine and control percentage (figure 9.4).

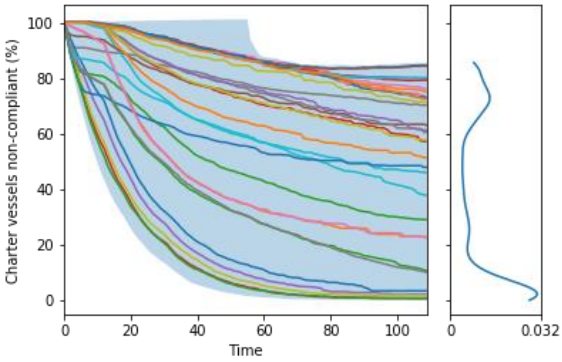

Figure 9.2: Line plot charters non-compliant

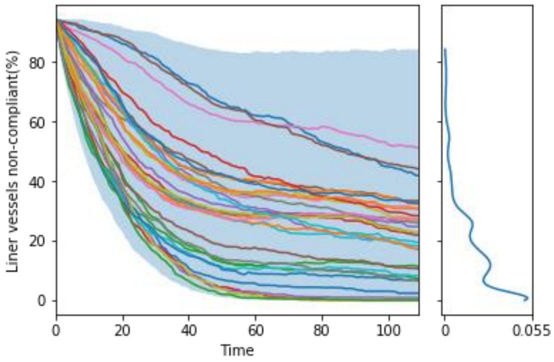

Figure 9.3: Line plot liners non-compliant

Figure 9.3 shows the decrease of the non-compliant liner vessels over time. The KDE plot on the right side shows that the percentage of liner vessels decreased significantly in most of the scenarios. In 46% of all experiments, the percentage of liner vessels that was not compliant at the end of the model run was less than 10%. In contrast to charter vessels, only a relatively small number of experiments exist in which the number of non-compliant vessel remained high. Like charters, dimensional stacking shows that the control percentage and the fine are important uncertainties which influence the investments in emission abatement technologies.

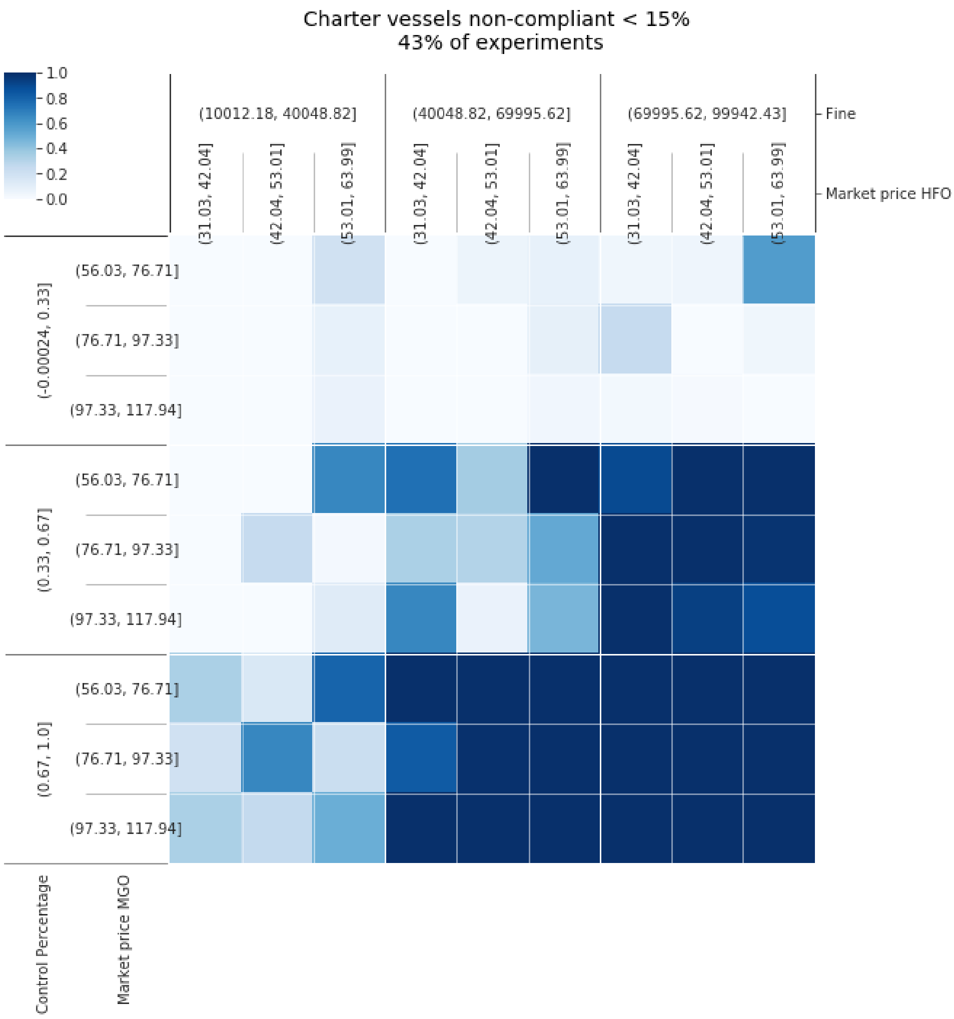

Figure 9.4: Dimensional stacking non-compliant charter vessels

9.2.3.2 Scrubber/SCR vessels

The development of charter vessels with a scrubber/SCR is depicted in figure 9.5. The plot shows that in 33% of the experiments the final percentage of scrubber/SCR charter vessels was above the 80%. On the contrary, a significant number of experiments resulted in a percentage of less than 40% installed scrubbers/SCR systems on charter vessels as well. When considering the experiments with a percentage above the 80% scrubber/SCR charters, it is observed that those cases were influenced by a high fine or control percentage in combination with either a high or medium control/percentage. In addition, in these cases, the HFO market price was not high. When the HFO market price was medium-high, the availability of methanol infrastructure in ports had an influence on the investments in scrubbers/SCR systems. Analysing the cases with a percentage of scrubber charters smaller than 20%, a high HFO market price was required, as well as the availability of methanol bunker infrastructure in each port.

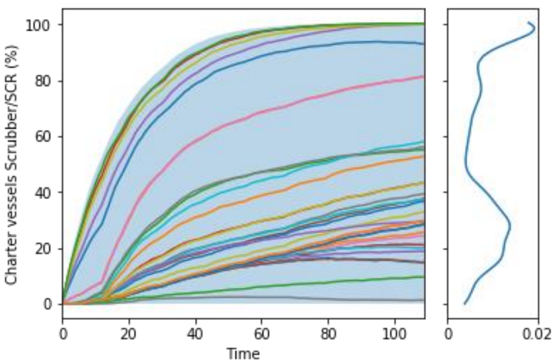

Figure 9.5: Line plot scrubber/SCR charters

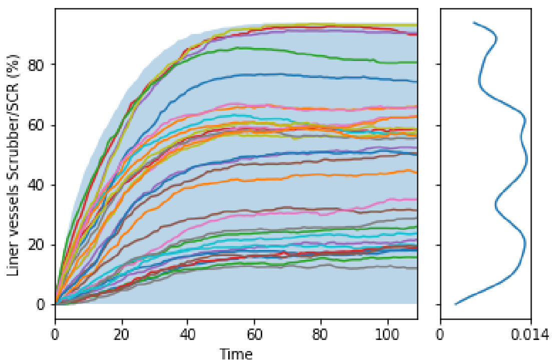

Figure 9.6: Line plot scrubber/SCR liners

The range in percentages of liner vessels with a scrubber/SCR was more distributed. A maximum value of more than 80% was achieved in 13% of the experiments. The behaviour of the adoption of scrubber/SCR systems by vessels is observed to be stagnating over time. This implies that most of the scrubbers were installed on operating vessels instead of on new build vessels. In contrary to charter vessels, dimensional stacking shows that the HFO market price was the principle feature relating to investments in scrubbers/SCR systems by liner vessels. The lower the HFO market price was, the more scrubber/SCR systems were installed. Still, the control percentage and fine were the consecutive most important features which influenced this adoption. The higher these values were, the more investments in scrubber/SCR system took place.

9.2.3.3 MGO/SCR vessels

In most of the experiments, the adoption of an SCR system in combination with MGO as fuel remained low. In 86% of the experiments, the percentage of charter vessels stayed below 10%. The investment decisions in SCR systems by ship operators were mainly driven by the MGO market price and the HFO market price. Addressing the scenarios belonging to the experiments with more than 60% charter vessels (3% of total experiments), these were subjected to a high market price for HFO and a low MGO market price. In contrary, the experiments with a percentage of MGO/SCR vessels less than 10% were subjected to a high MGO market prices and a low HFO market price.

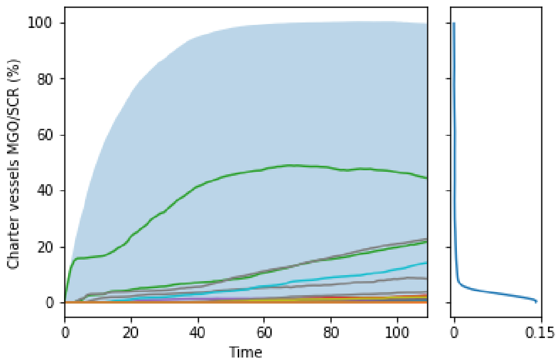

Figure 9.7: Line plot MGO/SCR charters

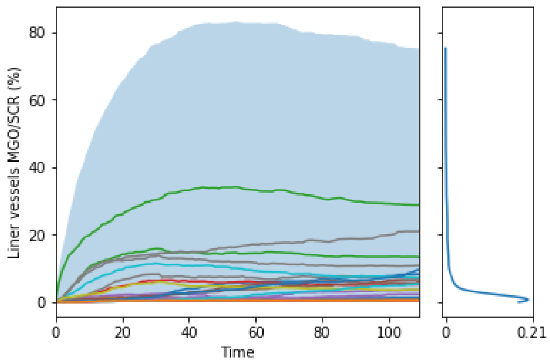

Figure 9.8: Line plot MGO/SCR liners

The observed behaviour for MGO/SCR liner vessels is almost similar to the behaviour observed for MGO charter vessels (figure 9.8). Although, the maximum percentage of MGO/SCR liner vessel is less. When identifying the scenarios with a percentage of MGO/SCR liner vessels of more than 10%, which contains only 14% of all experiments, it is shown that next to the HFO and MGO market price, the control percentage and the space for a scrubber/SCR system influenced this development. The positive effect on the space of a scrubber/SCR system (applied in combination with HFO) is rather unexpected. Further, the lower the control percentage, the more MGO/SCR liner vessels did exist.

9.2.3.4 LNG vessels

The line plots corresponding to the development of LNG charter vessels show that in most of the experiments the number of LNG charter vessels was less than 5% (figure 9.9). The maximum percentage of LNG charter vessels did not exceed 50%. The experiments of interests with a percentage of more than 40% LNG charter vessels (15% percent of the experiments) showed that, next to the HFO and LNG market price, the market price of methanol and the control percentage were influential uncertainties as well. A high methanol market price influenced the development of LNG positively, meaning that some of the vessels make a trade-off between methanol and LNG based on the fuel market price.

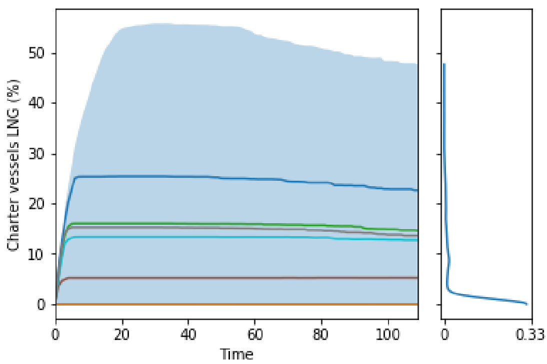

Figure 9.9: Line plot LNG charters

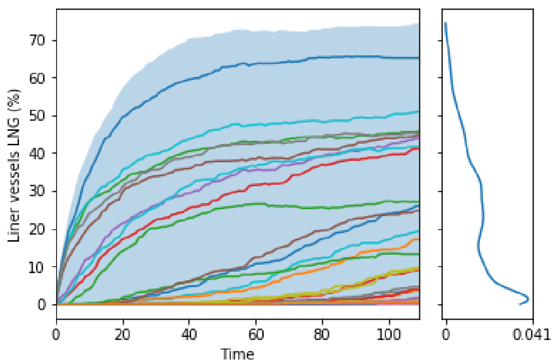

Figure 9.10: Line plot LNG liners

LNG propulsion technology was more adopted by liner vessels than by charter vessels. The percentage of liner vessels with LNG propulsion technology reached a value of over 70%. Despites this, in a substantial number of experiments the percentage of LNG liner vessels remained smaller than 10%. The HFO market price was again the most dominant uncertainty influencing the development of LNG liner vessels, followed by the LNG market price. Nevertheless, considering the outcomes with an LNG liner percentage over the 40% (15% of the experiments), the control percentage and the availability of methanol bunker infrastructure in ports are recognised as the influential factors as well. A lower control percentage and less available methanol infrastructure influenced the deployment of LNG among liner vessels positively.

9.2.3.5 Methanol vessels

The uptake of charter vessels with a methanol propulsion technology and a large methanol fuel tank barley took place and, in most cases, no investments took place at all. In contrast, the use of small methanol tanks was more common for charter vessels, with outcomes ranging from 0 to almost 100% adoption. Nevertheless, in most scenarios, the percentage of charter vessels with a small methanol fuel tank did not exceed 10%. When considering the experiments for which the percentage of methanol charters with a small fuel tank was higher than 20% (approximately 5% of the experiments), it is observed that the HFO market price and methanol market price were the two key uncertainties which influenced the decisions of ship operators to invest in a small methanol fuel tank. A high HFO price in combination with a low methanol price influenced the development of methanol positively. Besides, the availability of methanol bunker infrastructure in ports was an important factor that influenced the investment decisions in methanol propulsion technology.

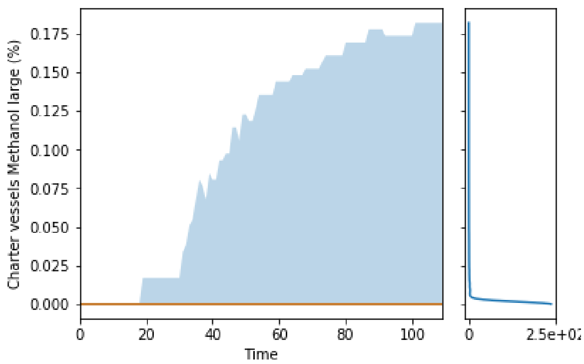

Figure 9.11: Line plot charters methanol large fuel tank

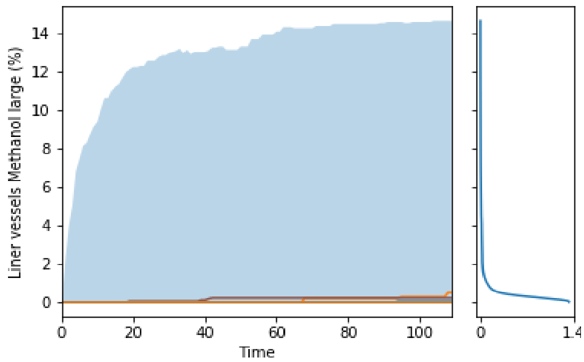

Figure 9.12: Line plot liners methanol large fuel tank

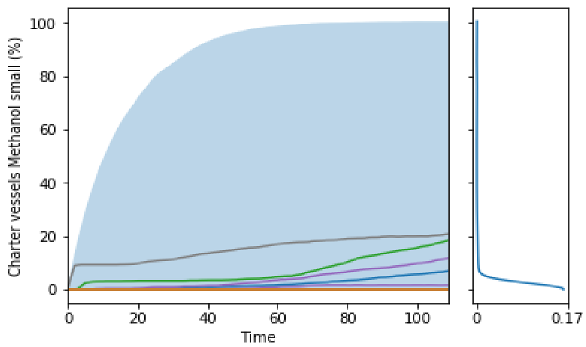

Figure 9.13: Line plot charters methanol small fuel tank

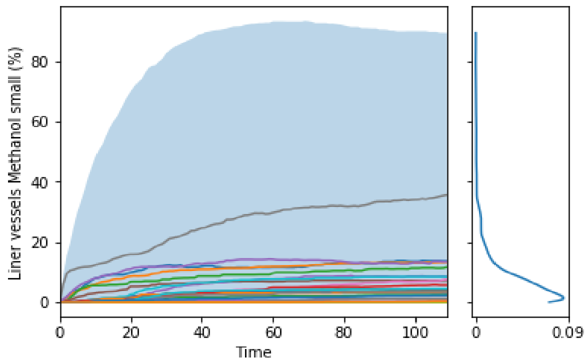

Figure 9.14: Line plot liners methanol small fuel tank

The adoption of methanol propulsion technology in combination with a large fuel tank occurred more often among liner vessels than charter vessels. Nevertheless, in most of the cases, the percentage remained smaller than 2% and a maximum of about 14% is observed. The methanol technology in combination with a small fuel tank was more favourable among liner vessels. Although the maximum percentage of liner vessels with the technology was less than the maximum percentage of the charters.

Significant more experiments with outcomes achieving a percentage between 10 to 40% did exist. For both small and large methanol tanks, the methanol and HFO market price were the principal uncertain factors. When analysing the 10% of the experiments achieving a percentage of more than 20% methanol vessels operating with a small tank, it is examined that the availability of methanol bunker infrastructure in ports was an important factor that influenced the deployment of this propulsion technology. At least 20-30 ports should have the methanol bunker infrastructure available. Noteworthy, when comparing the number of methanol vessels with a large fuel tank and with a small fuel tank with respect to the availability of methanol infrastructure in ports, liner vessels did not make investments in methanol technology in combination with a large fuel tank when the methanol bunker infrastructure was widely available. Instead, vessels were investing in methanol propulsion technology in combination with a small fuel tank. With an increase in the availability of methanol, it became possible for liner vessels to bridge the distances between bunker ports (see figure 9.24).

9.2.4 Regulation

The regulatory uncertainties concerning the amount of fine and the control percentage, are identified as important uncertainties that influenced the investment decisions of ship operators in emission abatement technology. Because these two variables are highly related, they are combined in a new variable "Enforcement" by multiplying the two variables. In this way, better insight is obtained into the effects of regulation enforcement on the behaviour of the model. The new variable determines the amount of fine needed when the control percentage is 100%. It is found that a threshold should be passed before investments in emission abatement technologies took place. Thus, when there is no regulation enforcement, investments in abatement technology did not take place. Figure 9.15 shows the relations between the amount of regulation enforcement and the number of liner vessels being non-compliant, with scrubber/SCR, and with methanol propulsion technology in combination with a small fuel tank. The scatterplots on the left-hand side show for each experiment the percentage of vessels and the amount of regulation enforcement. The plots on the right-hand-side visualise the density of the number of experiments in the gird. The plots for the other emission abatement technologies are depicted in appendix H.

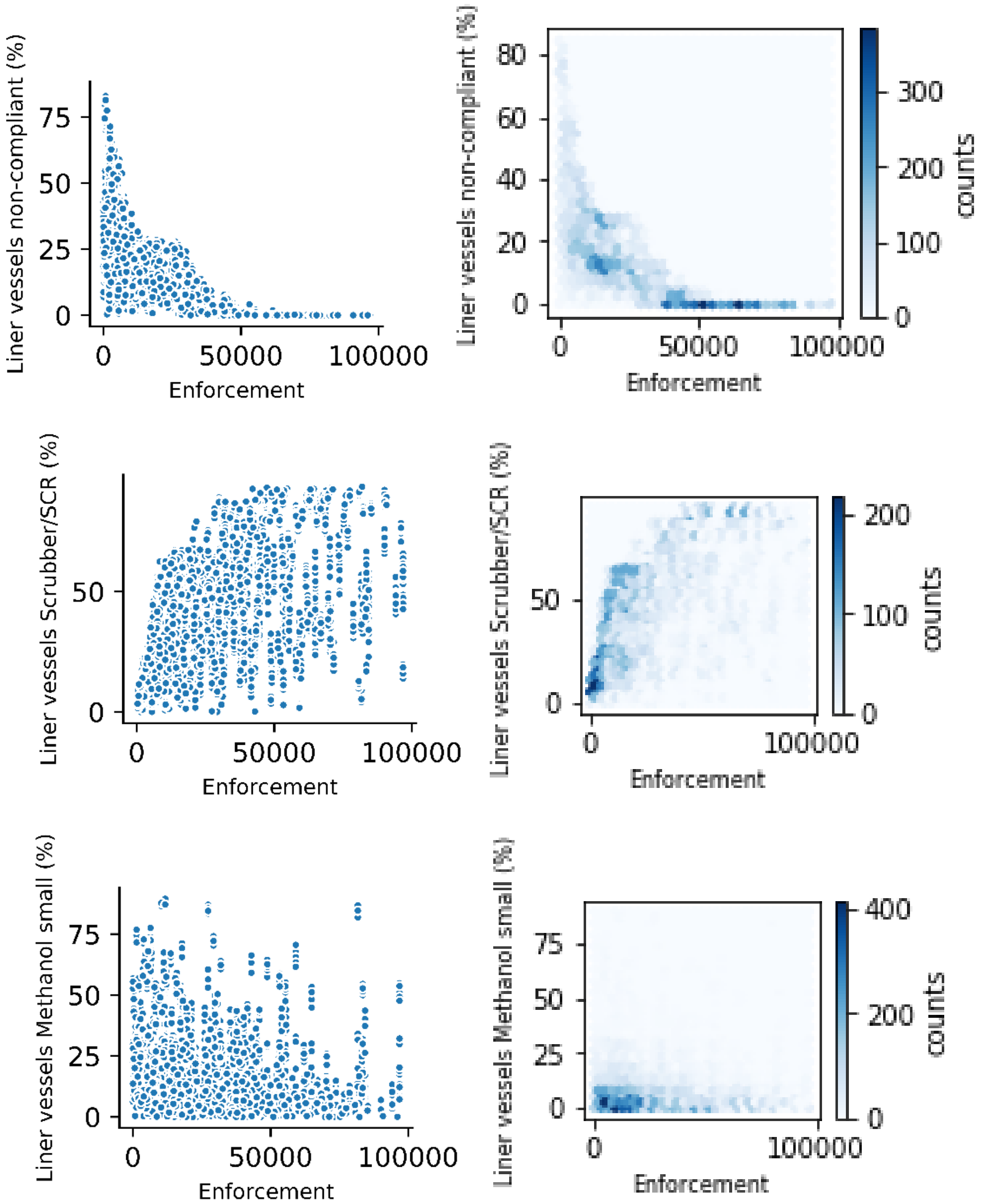

Figure 9.15: Scatter plots enforcement vs propulsion technology

The plots show that the higher the regulation enforcement is, the fewer vessels remained to operate without emission abatement technology. Besides, a clear relation is indicated between the regulation enforcement and the percentage of vessels operating with a scrubber, namely, the higher the regulation enforcement was, the more vessels installed a scrubber in combination with an SCR system. Additionally, it is noticeable that the higher the regulation enforcement was, the less investments took place in MGO/SCR, LNG, and methanol vessels, especially when considering the liner vessels. This indicates that when a transition to alternative fuels is wished, the timing of regulation enforcement should be determined carefully. On the one hand, when no enforcement takes place, no investments in abatement technology will be made. On the other hand, when the regulation enforcement is implemented to quickly, a transition of compliant vessels with a scrubber and SCR system is likely to emerge, instead of the transition to a maritime fuel system depending on the consumption of alternative fuels.

9.3 Bunker behaviour of vessels

When vessels are investing in emissions abatement technologies, it is in some cases required to switch to another type of fuel. When vessels are investing in scrubbers and SCR systems, HFO can still be consumed by the vessel while being compliant with the regulations. When vessels are only investing in an SCR system, vessels must switch to MGO to be compliant with regulations. Operating with LNG propulsion technology is only possible by using LNG as a fuel. Methanol propulsion technology offers the possibility to use conventional methanol, as wells as bio methanol. Whilst the previous section is concerned with the deployment of emission abatement technologies, this section aims to investigate what the effects of the change in propulsion technology are on the fuel supply and consumption. Hereto, in section 9.3.1, an overview is given of the relations between different outcomes of interests. Afterwards, the main uncertainties influencing the supply of the fuels are identified in section 9.3.2. Subsequently, in section 9.3.3, the supply of each fuel over time is discussed. Finally, the influence on the bunker calls of the Port of Rotterdam is discussed in 9.3.4.

9.3.1 Relations between the fuel supply of each fuel

Figure 9.16, shows the relation between the outcomes related to the supply of fuels. The points in the plots represented the values of the variables in the last time step of each morel run. The plots shown on the diagonal show the KDE, which gives insight into the distribution of the points in each plot.

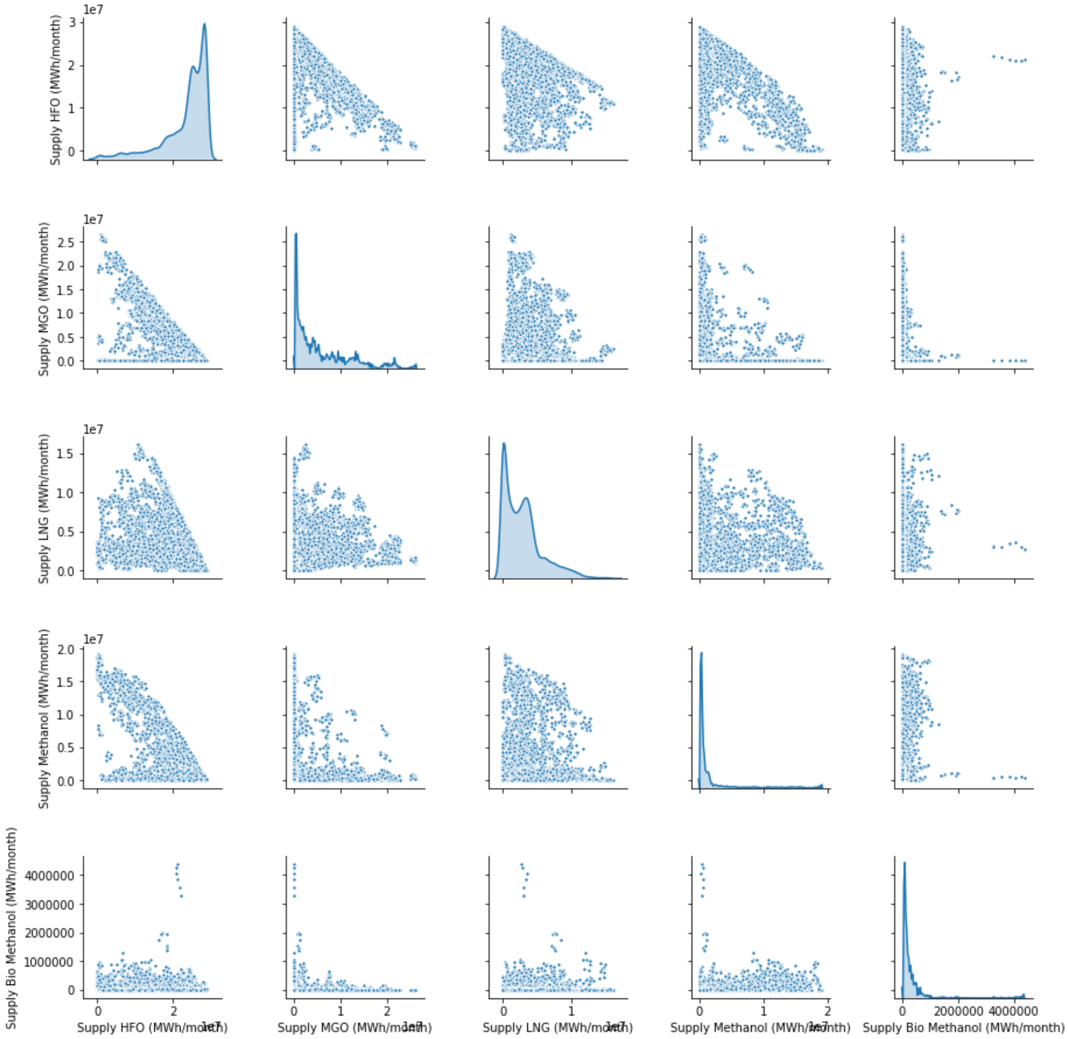

Figure 9.16: Pairs scatter plots of fuel supply

At first sight, it is noticed that for most fuels the supply is correlated negatively. However, for the bio methanol, no clear correlations can be observed, since bio methanol is not supplied at all in many of the experiments, or is only consumed is small quantities. Besides, the plots indicate that to a certain extent, an increase in HFO supply comes with an increase in LNG supply.

9.3.2 Uncertainties influencing the fuel supply

Figure 9.17 depicts how the uncertain factors influenced the fuel supply. The variables on the x-axis relate to the outcome variables, the values on the y-axis related to the uncertainties. The colours and values in each cell indicated the importance of each uncertainty on the outcome variable. The higher the score or the darker a cell is, the more influential the uncertainty was on the associate outcome variable. Similarly, to the deployment of MGO/SCR, LNG, and methanol emission abatement technologies, the supply of MGO, LNG and methanol were also highly influenced by the HFO market price and the market price of the associate fuel. This was also the case for the supply of bio methanol, however less obvious due to the fact that bio methanol was not supplied in many of the experiments. However, in contrary to the use of HFO and the use of scrubber/SCR systems, for which the control percentage and the fine were indicated as the most influential factors, the supply of HFO was mainly influenced by the HFO and MGO market price.

However, figure 9.17 indicates that the CO2 price did not have a significant contribution to the use of alternative fuels. The CO2 prices included in the scenarios were not high enough to stimulate ship operators to consume less CO2 emitting fuels. Further, the willingness to pay for bio methanol did not give ship operators incentives to invest in methanol propulsion technology or to bunker bio methanol.

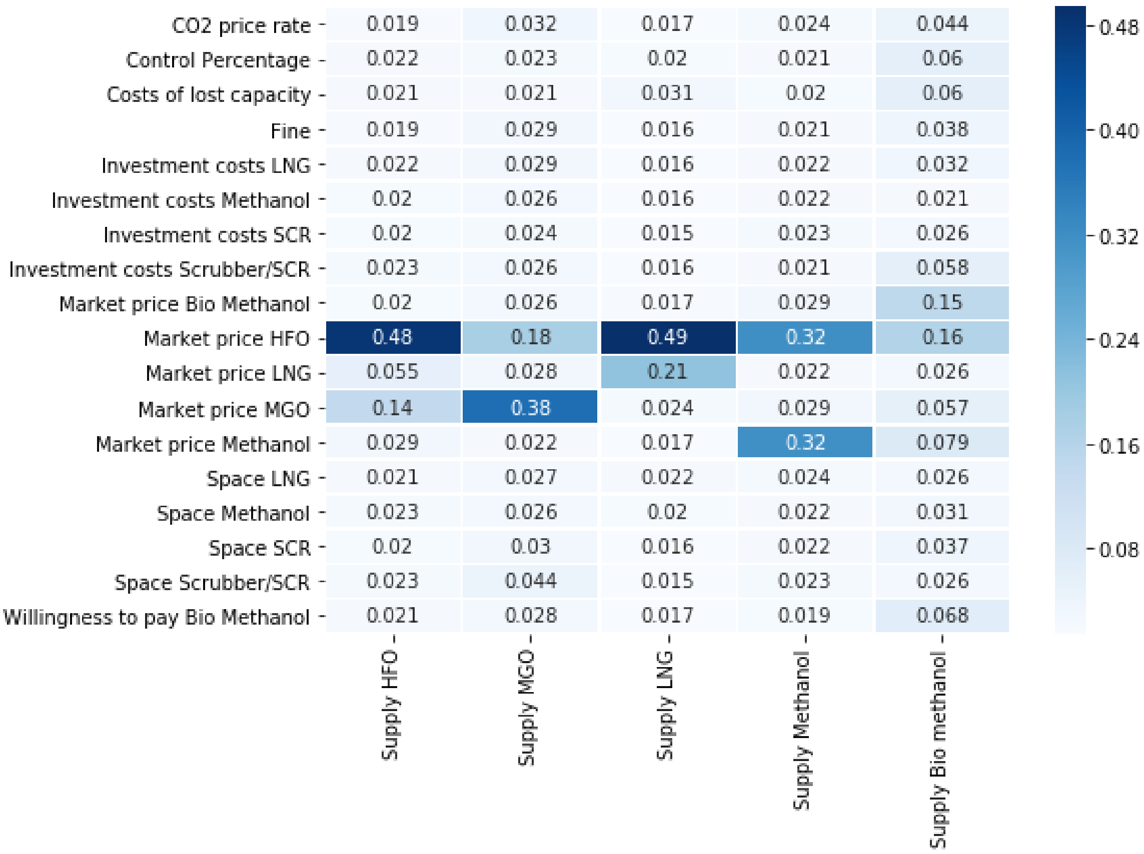

Figure 9.17: Feature scores of fuel supply

9.3.3 Reflection on the supply of each bunker fuel

This section discusses the outcomes of the fuel supply of each bunker fuel in more detail. Line plots are used to identify how the fuel supply developed in the experiments. Furthermore, by means of dimensional stacking, scenarios are discovered which lead to specific outcomes of interests.

9.3.3.1 HFO supply

The supply of HFO had a large range of possible outcomes, ranging from supplying the total fuel demand to not being supplied at all at the end of each simulation run. Nonetheless, the KDE plot on the right-hand-side of figure 9.18 shows that most experiments ended up with a significant part of the fuel demand supplied by HFO bunker terminals. The explanation can be found in the fact that in a large number of experiments the number of vessels operating with either no emission abatement technology (consuming HFO) or vessels operating with scrubber/SCR systems (consuming HFO) ended up high. The dimensional stack plot, containing 9% of the experiments ending up below 15 million MWh/month HFO supply, shows that besides the HFO and MGO market price, the methanol market price and the availability of methanol bunker infrastructure in ports were influential uncertainties. Meaning that when the variables related to the methanol deployment and methanol supply are favourable towards the deployment of methanol, the less vessels continued to operate with HFO.

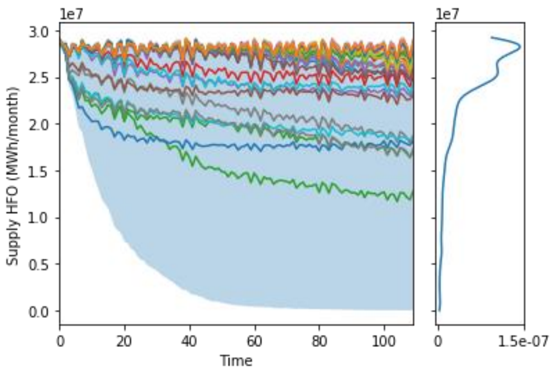

Figure 9.18: Line plot HFO supply

9.3.3.2 MGO supply

The MGO supply per month is depicted in figure 9.19. In most experiments, the total supply of MGO stayed rather low. Still, there are several experiments that showed that a significant part of the fuel demand to be supplied by the MGO bunker terminals, with a maximum of approximately 85% of the total fuel demand. The dimensional stack, concerning experiments with an MGO supply less than 300.000 MWh/month and representing 77% of the scenarios, shows that the outcomes were highly influenced by the HFO and MGO market price. Either a low HFO market or a high MGO market price resulted in a low MGO supply. Besides, the space of a scrubber/SCR combination (applied in combination with the use of HFO) affected the use of MGO. Contrary, when the HFO price is high and the MGO price is low, the supply of MGO increased. In these cases, the availability of methanol bunker infrastructure in ports had a small influence. When methanol was supplied in each port, the consumption of MGO by ship operators was less.

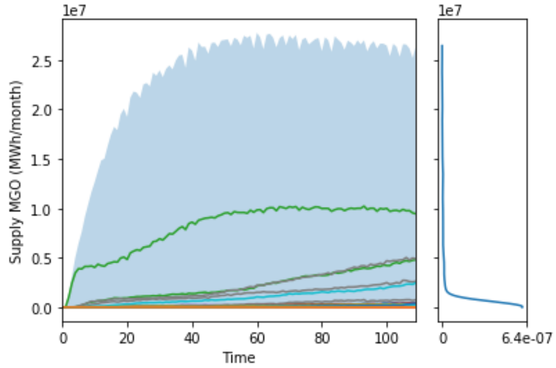

Figure 9.19: Line plot MGO supply

9.3.3.3 LNG supply

The uptake of LNG as a fuel for the European short sea sector is rather rare. In most cases, the total supply of LGN remained low. However, in a small number of experiments the total supply of LGN achieved a significant part of the total fuel supply. In the most beneficial scenarios, the LNG supply covered more than half of the energy demand. The underling mechanisms of the experiments with a supply of more than 10 million MWh/month and a supply of less than 1 million MWh/month are further analysed by means of dimensional stacking. The dimensional stacking analysis for the experiments with an outcome of more than 10 million MWh of LNG supply (3% of all experiments), shows that a high HFO and MGO market price in combination with a low LNG market price influenced the supply of LNG positively. Besides, the availability of methanol bunker infrastructure in ports had an impact as well. The more availability of methanol infrastructure, the lesser the LGN supply was. The experiments resulting in an LNG supply of less than 1 million MWh/month, again are highly influenced by the LNG market price and the HFO market price. Besides, the costs of lost cargo capacity had an effect on the total supply of LNG. When the costs of lost cargo capacity were high, the supply of LNG was less, since LNG requires more space on board than some of the other technologies.

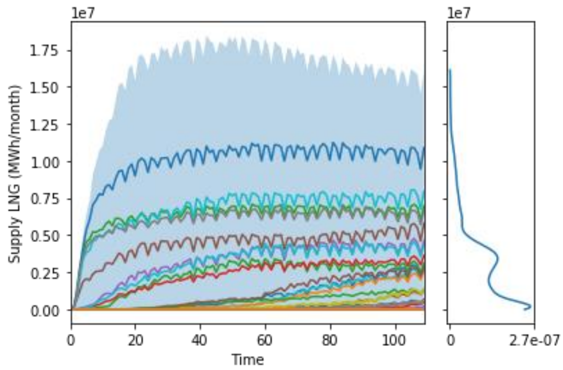

Figure 9.20: Line plot supply LNG

9.3.3.4 Methanol supply

Figure 9.21 shows a large range of possible outcomes for the supply of methanol, up to a maximum of almost 20 million MWh/month (representing almost 2/3 of the total fuel demand). Nevertheless, the KDE on the right side of the line plot shows that in most cases the supply of methanol remained smaller than 2,5 million MWh/month. When looking at the 5% of the experiments with a methanol supply of over the 5 million MWh/month, it is noticed that the market price of HFO and methanol were important features for this development. Besides, the availability of methanol bunker infrastructure was an important variable that stimulated the use of methanol, the experiments for which the outcomes of the methanol supply is higher than 5 million MWh/month, were all subjected to the availability of methanol in each port.

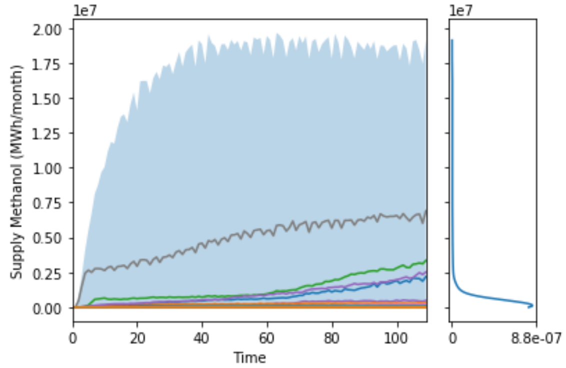

Figure 9.21: Line plot supply methanol

9.3.3.5 Bio methanol supply

The line plots of the bio methanol supply and KDE on the right-hand-side of figure 9.22, show that the bio methanol supply remained in most scenarios extremely low. In 50% of the experiments, there was no bio methanol supplied at all. Mostly caused by a low HFO market price and an underdeveloped availability of methanol bunker infrastructure in ports. However, by analysing the remainder of the experiments, valuable insights are obtained. There were very few cases in which the total supply achieved a total amount between the 3 and 4 million MWh/month. Looking at the 5% of the experiments with a final supply of bio methanol above the 100.000 MWh/month, it is noticed that these experiments were subjected to a high HFO market price in combination with a low bio methanol market prices and the methanol bunker infrastructure was available in all ports. Besides, the methanol market price was in these experiments low as well, since this stimulates and initiates the deployment of the methanol propulsion technology.

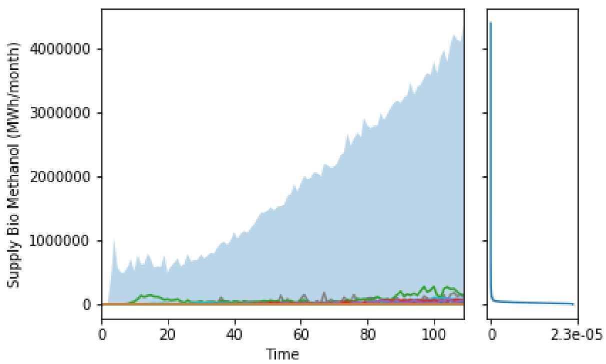

Figure 9.22: Line plot supply bio methanol

9.3.4 Bunker calls of vessels

The percentage bunker calls of the port of Rotterdam is analysed to identify the impact of uncertainties and policies on the bunker behaviour of vessels. As is observed, when more vessels operated with methanol propulsion technology in combination with a small fuel tank, vessels had to bunker more often. However, insight should be obtained whether certain collaborative port strategies are of more advantage with respect to the percentage of bunker calls. Line plots show that most commonly the percentage of bunker calls was between 30 and 45%. However, some of the experiments show a significant higher outcome for the percentage of bunker calls of the port of Rotterdam. The underlying behaviour of these outcomes is investigated. Feature scores shows that the most influential uncertainties on the percentage of bunker calls were the methanol market price, HFO market price and MGO market price (appendix I). Dimensional stacking shows that a percentage over the 45% bunker calls was highly influenced by the availability of methanol infrastructure in ports and to a lesser extent the HFO market price and the methanol market price. Remarkable is that all these experiments were subjected to scenarios in which each port had methanol infrastructure available. Hence, it can be assumed that an increase in the availability of methanol bunker infrastructure has a positive effect on the percentage of bunker calls of the Port of Rotterdam. In this analysis, the tipping point, at which more availability of methanol infrastructure leads to a smaller percentage of bunker calls is not found. It might be that this tipping point does exist, but lays above the 30 ports with methanol infrastructure available. Since not all ports were included in the research, no conclusions can be drawn.

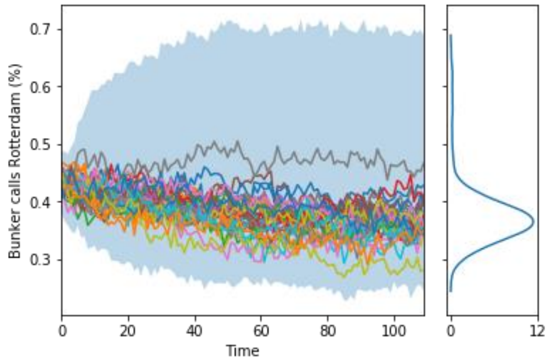

Figure 9.23: Line plot bunker calls Rotterdam

9.4 Collaborative port policies

The influence of 35 policies on the deployment of each emission abatement technology and the supply of each fuel is assessed. It is observed that some of the policies were significantly more effective than other policies.

Firstly, it is observed that the discounts given on port dues for vessels with an LNG or methanol propulsion technology did not stimulate investments in these propulsion technologies. The cost savings of the discounts did not add up to the total investment costs of LNG or methanol and the higher fuel prices. Similarly, the discounts on the port dues for bunkering bio methanol did not contribute to the number of vessels with a methanol propulsion technology, neither did it have an influence on the amount of bio methanol bunkered.

Nevertheless, the availability of methanol bunker infrastructure in the ports had a significant effect on the adoption of methanol propulsion technology. It is observed that when more ports provided the methanol infrastructure, the more investments took place in methanol propulsion technology. The experiments in which all ports provide the methanol bunker infrastructure was therefore the most beneficial scenarios for the deployment of methanol propulsion technology. When looking at the liner vessels, a percentage of more than 80% vessels operating with methanol propulsion technology was achieved. In addition, it is noticed that the availability of methanol infrastructure highly influened the decisions of ship operators to either invest in a large methanol fuel tank or a small methanol fuel tank, especially liner vessels were influenced by this (figure 9.24). Furthermore, the availability of methanol infrastructure is also perceived as beneficial for the number of bunker calls of the Port of Rotterdam. Due to the fact that more vessels operate with a small methanol fuel tank when more infrastructure was available, vessels had to bunker more often. This could be beneficial for ports and for fuel suppliers.

Nevertheless, the availability of methanol infrastructure influenced the deployment of LNG negatively (appendix H).

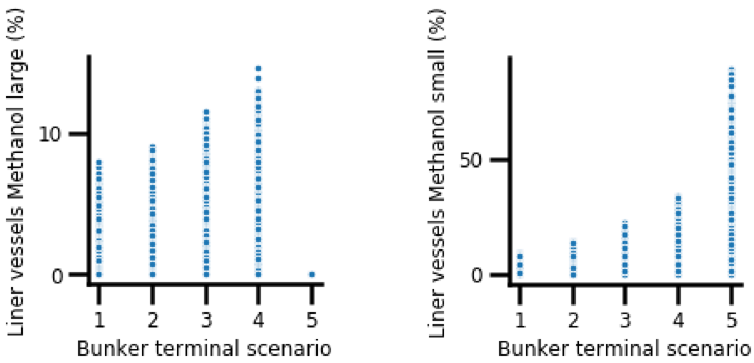

Figure 9.24: Scatter plots availability of methanol infrastructure

10. Discussion

This research is concerned with the emission reduction of the short sea shipping sector of Europe. Several stakeholders have raised concern. However, an understanding of how certain stakeholders react to policies and uncertainties is missing. The aim of this study is to explore future scenarios and to provide insight into the influence of uncertainties and policies. In this way, more insight can be obtained into how this problem can be tackled. This chapter entails a comprehensive reflection on the research approach and model outcomes, as well as the scientific and social relevance of this research.

10.1 Reflecting on the research approach

In this research, it is argued that an agent-based approach is a suitable approach to get insight into how the European short sea fuel system might evolve and react to uncertainties and policies. The principal choice made during this research was to reuse an already existing agent-based model: MarPEM. In fact, reusing this model was the most suitable option to capture the complexity of the system in a model given the time of this project. Consequently, the first objective of this study was to assess the reusability of this model. The study illustrated how MarPEM could be reused to study the effects of policies on the transition towards the deployment of alternative fuels for the European short sea sector. The reuse of MarPEM enabled to quickly obtain an understanding of the behaviour in the system and create a conceptual model of the European short sea fuel system. However, trying to understand somebody's else's understanding of the system can result in a narrow perspective of the system, since the model constructed originally is at the same time a first abstraction of the reality, what in turn makes the second model an abstraction of the abstraction with the risk of losing understanding of what the actual outcomes of the model mean. For this reason, the behaviour of the model was discussed and validated with several experts of the Port of Rotterdam. Furthermore, by reusing MarPEM, there had to be dealt with already existing structures and procedures, which were sometimes hard or even impossible to change. Since EU-MarPEM was subjected to a different scale, some of these structures turned out not to be resistant to this difference in scale. Hereto, several simplifications had to be made in the behaviour and a high level of aggregation was needed. In addition, suggestions for more efficient use of MarPEM in the future are given. However, these suggestions and might not be applicable to each problem of interest.

In this research, an ABM approach in combination with an EMA approach was applied. This is perceived as a useful combination because the various uncertainties to which this system is subjected can be addressed when analysing a wide range of scenarios. Exploring future scenarios by means of the EMA workbench was complex but useful. EU-MarPEM allows for creating a wide range of scenarios since it includes plentiful variables that could be changed. By including a large number of scenarios and policies in this exploration, a large range of plausible futures could be discovered. However, the complexity and scale of the agent-based model led to long computational times. This was challenging when aiming to explore a large number of scenarios and policies. Hereto, simplifications were made, such pricing decisions of bunker terminals. Besides, the structure of the model was modified. In addition, it encouraged to choose the chose the uncertainties included in the scenarios and the policies carefully. In total, 17.500 experiments were successfully executed.

10.2 Reflecting on experimental execution

During the experimentation phase, a large number of scenarios was created by varying parameters between runs. For example, a different value for the market price of a fuel was given in each run, which falls within a specific range. In this case, the need for data was limited and only the minimum and maximum values were needed for each parameter to reflect the uncertainty. Nevertheless, in reality, these parameters and uncertainties are more complex. More realistic scenarios could be developed by including trends. However, this is more difficult and data intensive. It requires the implementation of representations of price trends of each fuel. However, methanol and bio methanol are not yet extensively used in the shipping sector and no market is developed yet. Also, the application of bio methanol is uncertain and it is not known for which kind of industries it will be used and therefore not known how this market will develop in the future.

Besides, policies are modelled as a fixed system parameter. This implies that agents base their decisions on the initial policy setting and are assumed to be stable during a model run. Modelling policy as an endogenous system parameter could establish better policy implementation. This implies that ports make their decisions to apply a certain policy during a simulation run based on their own state, the state of their environment, and rules (Chappin et al, 2008). The model does not take into account the adaptiveness of ports to the deployment of fuels and the effect that other's port strategies have on a port's policy. However, it might be that with an increase of vessels using a certain fuel, more ports start considering to offer a fuel. This effect has been described by Adams et al. (2009) for the development of the Environmental Ship Index (ESI). The implementation of the ESI was initiated by the port of Rotterdam, after which other ports followed with applying the ESI. Therefore, it might be that staring collaborations with fewer ports, might end up in an evolving availability of methanol infrastructure across Europe. Besides the policies were created by means of Latin Hypercube Sampling, which randomly combined the policy levers with each other. However, next time it might be more sophisticated to create the combination of policy levers by hand to obtain more relevant combinations of policies.

To track down which variables have an impact on the results, only a limited number of uncertain factors were included in the model. Several of these uncertainties were observed to highly influential on the model outcomes. Besides, some technological uncertainties included did not seem to have an impact on the model behaviour. However, this can still give valuable insights to policy makers and ship operators. Furthermore, there were uncertain factors, which were not varied during the execution of the experiment which might influence the model outcomes, but due to limited time, it was not possible to perform the experiments in an incremental way and include these variables in another round of experiments. Besides, the upper value of the CO2 price rate did not seem the have a noticeable influence on the model outcomes. Therefore, it is hard to make concrete conclusions about the effects of CO2 pricing on the development of alternative fuels. A higher CO2 price might lead to the use of more sustainable fuels

Finally, the fact that a large amount of computer memory was needed to execute the experiments, only a limited number of outcomes variables were defined. This limited the insights that could be obtained by the experiments. For example, it made it impossible to assess whether a propulsion technology was more adopted among retrofit vessels or new build vessels, or which liner vessels were the least hesitated in investing in methanol propulsion technology.

10.3 Reflecting on model findings

This section reflects on the model findings. First, a comparison of the model outcomes and general findings in literature is presented. In this way, outcomes are validated and additional insights are obtained. Subsequently, a reflection on the influences of the modelling assumptions on the model outcomes is given.

10.3.1 Comparing findings with the literature

The model outcomes showed that in most experiments, the number of non-compliant vessels decreases significantly and vessels thus make investment decisions towards compliant technologies. However, it also showed that when regulations are not enforced, ship operators are hesitated or have a lack of incentives to invest in abatement technology. Although the market prices of each fuel turned out to be the paramount uncertainty towards the development of alternative fuels, it is shown that the enforcement of regulations is also one of the key influencers. These findings are in accordance with what was expected and due to the findings in literature and due to the insights obtained during several meetings with professionals of the Ports of Rotterdam. Alpha Tanker (2018) predicts the compliance of vessels at over 90% in 2020. This study shows that in a significant number of scenarios the percentage of non-compliant vessels in 2028 is less than 10%, with a significant decrease in non-compliant vessels in the first few years.

Under current conditions, the findings of this research show that the instalment of scrubbers in combinations with an SCR system is most likely to emerge. This is in line with the study conducted by Alpha Tanker (2018), which shows that the number of installed scrubbers is expected to increase rapidly in the upcoming years. It is the least radical emission abatement solution for ship operators since they are able the continue to operate with cheap HFO which is available in all ports.

The observed behaviour by the model shows that the development of LNG vessels in the upcoming years will stay rather low. This is similar to the findings of other studies. According to Aronietis, Hassen & Vanelslander (2016) the predicted growth in LNG bunker calls in Antwerp will not exceed a maximum of 2% of the total bunker calls in 2025. Alpha Tanker (2018) estimated that globally the share of LNG vessels is expected to increase to 7% in 2022. Nevertheless, a percentage of less than 7% is expected in a significant number of experiments performed in this study. An explanation can be found in the fact that LNG requires significant space onboard, which could cause a loss of cargo capacity. Therefore, the use of LNG is more likely to take place among deep sea vessels than among short sea vessels. Moreover, as expected and observed, this study shows that investments in LNG propulsion technology are more likely to take place among liner vessels, which is also stated by Alpha Tanker (2018).

Besides, according to Alpha Tanker (2018), the development of alternative fuels is a policy and financing problem, and commercialisation of alternative fuels is dependent on adequate policy. These findings are confirmed by this research, since the regulation enforcement and fuel markets were the principal uncertain factors towards the deployment of LNG and methanol propulsion technology.

Moreover, this study indicated that an increase to 3% - 14% of bio methanol supplied by 2028 is extremely rare. Tyrovola et al. (2017), argued that driven by both regulatory and market factors, biofuels could make up 5- 10% of the total global marine fuel mix by 2030. Although this study was considered with the fuel mix of the short sea shipping sector, the observed behaviour of the model is not unlikely. However, the factors driving this development should be more favourable than were explored in this study in order to be more sure about the emergence of a 5-10% share of biofuels.

Further, it is confirmed that the availability of methanol bunker infrastructure in the ports is one of the key reasons why investments are not taken place. It is shown that with an increase in availability of the infrastructure, ship operators are less hesitated to invest in methanol.

10.3.2 Model assumptions

Although the findings are in accordance with the general findings is literature, this study has some limitations. During this study, numerous assumptions had to be made, since it is difficult or even impossible to capture the full complexity of a system in a model. The main modelling assumptions are discussed in chapter 4. These assumptions could affect the representativeness of the model and influence the findings of this study. Nevertheless, by keeping the conceptual model narrow, it could help to pinpoint the most relevant emerged patterns and reveal the very few properties that matter. For this reason, we reflect on the limitations of these assumptions.

The first assumption that was made is that liner vessels operate in fixed routes that do not change over time. By making this assumption, the model does not take into account the fact that vessels might change their line schedules according to the availability of methanol infrastructure or fuel prices in ports. This might have caused that in this study vessels might have been more hesitated to invest in methanol propulsion technology than actually is the case. In addition, it is assumed that vessels bunker full capacity. However, in reality, vessels make more rational and strategic decisions. This assumption might in particular have influenced the conclusions drawn up on the bunker behaviour of vessels. However, it is not expected that this assumption influences the investments decisions of ship operators.

Another reservation of the results is that the experiments do not take into account the scarcity of fuels or technologies. This implies that bunker terminals are always able to supply the demand of the shipping sector. Especially for bio methanol this is an unrealistic assumption since the availability of bio methanol Europe in the near future is not likely to exceed 300.000 MWh/y. For this reason, findings should be interpreted as what- if scenarios. Further, a limitation of this research is the fact that is it does not take into account the influence of the deployment of a propulsion technology on the investment costs over time. Generally, when a technology is more applied, innovation and scaling benefits might cause a decrease in investment costs. This again might lead to more investments in the propulsion technology. Contrary, it is not sure if the market could supply the demand for certain technologies, this might induce an increase in investment costs or shortage, which force vessels to invest in other abatement technologies.

Finally, the level of model abstraction might influence the model outcomes. When more ports would be included in the model, the risk aversion of charter vessels towards investments in technology could have influenced the outcomes of the model.

10.4 Boundaries of the research

This research was concerned with the exploration of scenarios and the analysis of policy strategies. Because of the exploratory nature of this study, no optimal outcomes are identified. The availability of methanol infrastructure has shown to be effective towards the developments of methanol as a fuel for the shipping industry. However, these findings make it hard to translate them in direct policy requirements. This study shows the effects of collaboration associated with the availability of methanol in the ports. However, it did not make any suggestion about how collaboration should take place and this might be a complex process as well. Whereas large ports might have more resource available to enable the facilitation of the infrastructure in the ports smaller ports are more likely not be able to fund the infrastructure. Besides, the risk for smaller ports is also more obvious. Moreover, the availability of methanol in larger ports might threaten the position and competitiveness of small ports (Gritsenko et al., 2012). In addition, it is indicated how well the methanol infrastructure must be developed but does not make any suggestions for specific locations to provide methanol bunkering facilities.

10.5 Societal relevance

By means of this study, insight into possible future scenarios for the European short sea fuel system is obtained. Uncertain factors and policies are explored which might steer this system to a more sustainable future. In this way, more robust strategies can be developed to contribute to local and regional problems, such as environmental pollution. Moreover, these policies could contribute to the mitigation of climate change effects and therefore support the global goals to reduce climate change.

Furthermore, uncertainties as a result of regulation and fuel prices make it hard to predict what favourable strategies for ports and ship operators are. By the combination of an ABM and an EMA approach, the influence of these uncertainties is addressed, which enables to obtain a better understanding of the behaviour of the actors involved in the system. In this way, ports could timely react and prepare themselves for future scenarios. Furthermore, the study provides ship owners, shipbuilders, and fuel suppliers insights into the most important decision variables. In this way, it could support the decisions making process and risk of stakeholders, such as ports, fuel suppliers, and ship operators. Besides, it could support the decision-making process of the IMO, EU, and national authorities towards the enforcement of emission regulations.

10.6 Scientific relevance

More and more organisations like the Port of Rotterdam are using complex simulation models in order to develop strategies. However, these models are time intensive and costly to create. Nevertheless, similar questions for these organisations rise and this asks for the reusability of models. However, simulation models are often hard to understand and adjusted by others. This study gave insight into the applicability of domain models to similar problems of interest and therefore the reusability of agent-based models. For example, MarPEM was previously used for the exploration of policies towards LNG infrastructure on a global scale, whereas in this study the model was used for the exploration of policies towards fuels for the short sea sector in Europe. Although the research approach and methods turned out to be difficult to apply, this research contributed to knowledge about the reusability of complex simulation models by reusing MarPEM. It is proved to be possible to reuse these kinds of models for similar kind of questions. However, the process of reusing the model was rather complex and time-consuming. Furthermore, it was found that profound knowledge about the model was needed, as well as programming skills. It revealed the advantages and disadvantages of the reusing the conceptual model. Moreover, it gave insight into the reusability of different concepts of source code. Where currently literature is limited by the creation of reusable models, this research extends the current state of knowledge by reflecting on the assessment of the reusability of a model. First, it is found that documentation is key for the reusability of the model. Besides, conceptualization has been stated to be a better fit rather than the reusability of source code. Further, the scalability of the model rather than the agent's behaviour included in the model is an important factor that determines the reusability. By means of reusing the model, suggestions are made to improve the performance of MarPEM. In this way, the model can be used more efficiently in the future. The suggestions are aimed to reduce the complexity and computational time of the model. In this way, the model will allow for better integration of ABM and EMA. Besides. EU-MarPEM can be used in the future as well, for example to for more specific parts of the short sea network.

In addition, this research contributed to scientific knowledge about the combination of ABM and EMA. It showed that a trade-off should be made in the computational time and the number of experiments aimed to be executed. By using a complex agent-based model, this research has found and pushed the boundaries of using NetLogo in combination with the EMA workbench. Reflecting on this allows for improving the EMA workbench, which might be beneficial for future use of the EMA workbench by scholars.

Finally, the study provides complementary knowledge to the existing literature. Whereas current literature is mostly concerned with providing static analyses about the environmental, technical, and economic performance of emission abatement technologies, this approach is fundamentally different and therefore provided new insights. The combination of an ABM and EMA approach proved to be useful to actually analyse the problem because it captures the mutual influence of the technical and social systems. A model that represents the European short sea network was created, which was not only validated by means of general expectation in literature and experts. The model also confirms that the finding in these studies and expectations are reasonable and reveals the underling mechanisms of these expectations. In this way, more confidence into the expectations of the development of the European short sea fuel system is obtained.

11. Conclusions and recommendations

In this final section of the master thesis, conclusions are drawn in order to answer the research questions. Besides, recommendations for further research are provided.

11.1 Conclusions

Increasing ship emission are of big concern because they contribute to the effect of climate change and have an impact on the local and regional environment. Due to these concerns, striker regulations are enforced upon the shipping sector by the IMO and EU. However, since new regulations are enforced, stakeholders have been slow to react. Therefore, the research presented in this thesis had the objective to explore port polices that might stimulate the use of alternative fuels for the European short sea shipping sector. The following research question was formulated:

"What are the effects of port strategies on the deployment of alternative fuels for short sea shipping in Europe?"

In an attempt to answer this research question, an agent-based modelling approach was applied in combination with the exploratory modelling and analysis approach. It was aimed to reuse the agent-based model MarPEM. However, the process of reusing the model was rather complex and time-consuming, but gave valuable insights into the reuse of agent-based models. It revealed the advantages and disadvantages of the reusability of the conceptual model. Moreover, it gave insight into the reusability of different concepts of source code. Besides, it is found that documentation is key for the reusability of a model. Further, the conceptualization of the model was perceived to be more suitable to reuse than the reusability of source code. It was found that the scalability of the model is the paramount factor that determines the reusability of the model rather than the agent's behaviour included in the model. By means of reusing the model, suggestions are made to improve the performance of MarPEM. The suggestions are aimed to reduce the complexity and computational time of the model. In this way, the model will allow for better integration of ABM and EMA. Besides. EU-MarPEM can be used in the future as well, for example to for more specific parts of the short sea network.

Nevertheless, a model representing the European short sea shipping sector was successfully created and considered to be a valid representation. In total 35 policies and 500 scenarios were created which resulted in the execution of 17.500 computational experiments. By analysing the outcomes of the model in combination with the system analysis, the research questions can be answered. In this section, the conclusions of the research are presented. However, conclusions drawn should be considered within the research limitations discussed in chapter 10.

Overall, this study provided insight into the dynamics of the adoption of propulsion technologies by short sea vessels in Europe. The outcomes of the model provide insight into the most influential uncertainties towards the deployment of propulsion technology and the effects of port strategies, which enables to better understand where the system might go in the future. The outcomes show that the uncertainties in fuel prices are the most important uncertainties towards the deployment of emission abatement technologies. The technological uncertainties explored in this study, such as space requirements and investments costs are not expected to have a significant impact on the adoption of emission abatement technologies. The study shows that being compliant is highly dependent on the HFO fuel price. Besides, the regulation enforcement is a prominent uncertainty affecting the behaviour of ship operators. Nevertheless, the outcomes show that it is most likely that a transition away from non-compliant vessels will take place when regulations are enforced. However, the outcomes also indicate that when HFO prices remain low with respect to other fuel prices, scrubbers in combination with SCR systems are the most costs-effective option for ship operators apply. However, whilst vessels are compliant with emission regulations when operating with scrubbers and SCR systems, it does not influence the amount of HFO fuel bunkered, since vessels continue to consume HFO, and thus CO2 emissions remain high.

In addition, key uncertainties influencing the deployment of the other emission abatement technologies are the HFO price and the associate fuel price of the technology. Further, regulation enforcement is recognised as an important factor that can steer the transition to LNG or methanol propulsion technologies. It is indicated that enforcement is needed to initiate the uptake of emission abatement technologies. However, when ship operators experience the pressure of emission regulation to early, ship operators are likely to make their investment decisions towards the technologies with the least radical implications. Scrubbers and SCR systems are often considered then, since vessel can continue to operate with cheap HFO and besides the fuel is available in all the ports. For this reason, it might be more beneficial to give vessels more time to make well considered decisions towards emission abatement technology.

Besides, when a transition to alternative fuels is more favourable than a transition to the compliance of vessels, it is concluded that governing the fuel prices might be more effective than the enforcement of regulations. It is recognised that when the fuel prices for methanol or LNG are favourable and the HFO price is relatively high, the uptake of methanol or LNG propulsion is likely to take place. Besides, when HFO prices are high, it will be less attractive to invest in scrubbers and SCR systems. Hereto, subsidies could be awarded to the use of alternative fuels or a CO2 price can be applied. Further, it is not expected that vessels operating with a methanol propulsion technology will make a shift to the consumption of bio methanol under current circumstances. It is expected that even when ship operators are willing to pay a little more for being more sustainable, the incentives are insufficient. In addition, the CO2 price considered in this study showed not to be effective. Therefore, a CO2 price of at least 50 $/ton should be applied.

Furthermore, this study has identified several ports strategies that could influence the use of alternative fuel by short sea operators in Europe. However, it is expected that only the Port of Rotterdam applying a strategy is not likely to initiate the uptake of alternative fuels. Therefore, collaborative port strategies are tested. The strategies explored in this study are: ports providing a discount on port dues for vessels with LNG or methanol propulsion technology, ports providing a discount on port dues for vessels bunkering bio methanol in the associated port, and ports providing the methanol bunker infrastructure. Distance-related emission charges was identified as policy option as well, although not included in the model and experiments. The influence of 35 policies is assessed on the development of the supply of each fuel, as well as on the number of vessels operating with a certain propulsion technology. From this analysis, it could be observed that some of the policies were significant more effective than others.

Firstly, it is expected that the discount given on port dues for vessels with an LNG or methanol propulsion certain technology does not influence the investment decisions of ship operators. The cost savings of the discount will not add up to the total investment costs of LNG or methanol and the higher fuel prices. Similarly, the discount for bunkering bio methanol is not likely to contribute to the number of vessels operating with a methanol propulsion technology, neither is it expected to have an influence on the amount bio methanol bunkered.

Nevertheless, the availability of methanol infrastructure in ports is likely to have a significant effect on the deployment of methanol propulsion technology. It is expected that when more ports provide the methanol infrastructure, the more ship operators apply the emission abatement technology. The availability of methanol infrastructure directly lowers the risk of not being able to bunker and the number of shipping assignments that could be executed by a vessel, which makes the technology more attractive. The experiments in which all ports provided the methanol infrastructure showed to be significantly more effective for the uptake of methanol propulsion technology. Methanol propulsion technology is more attractive for ship operators in combination with a small fuel tank, since the loss of cargo capacity can be kept to a minimum. Therefore, methanol becomes economically attractive when the bunker fuel is supplied in all ports. This is especially observed for liner vessels due to the fact that more vessels are than able to bridge the distances in their rotation schedules without running out of fuel. Besides, the risk for charter vessels of not be able to bunkers and the number of shipping assignments able to execute, will be kept to a minimum. Under favourable fuel price,s the uptake of methanol propulsion technology among liner vessels will already emerge when 2/3 of the ports have the bunker fuel available.

The uptake of methanol prolusion technology in most cases came in combination with a small fuel tank. This causes vessels to bunker more often, which could be beneficial for ports and fuel suppliers. This study has made an attempt to find the trade-off between the availability of bunker infrastructure and the percentage of bunker calls for the Port of Rotterdam. However, this trade-off is not found. This indicates that the Port of Rotterdam does not have to be afraid of losing its competitiveness when methanol bunker infrastructure is available in many ports.

The conclusions of this research underpin the multi-actor complexity of the problem. Collaboration between different ports is needed, when the emergence of methanol as a maritime fuel is whished. Aside from the availability of bunker infrastructure, this transition is highly dependent on how the regulations are enforced and how policy towards CO2 emissions will be developed, and thus on governmental bodies. It shows that it is impossible to formulate robust strategies by the Port of Rotterdam themselves and therefore requires collaboration between ports and governmental authorities.

11.2 Recommendations

Though the deployment of methanol as a maritime fuel across Europe is not likely to emerge in the upcoming years, it might be possible to establish such a transition on a smaller geographical scale. For this reason, it is advised to conduct further research and look for collaborations with ports serving similar line rotations that operating in a small geographical area, since the study showed that the uptake of methanol is more likely to take place among liner vessels, and a percentage of more than 20% of the liners operating with methanol propulsion technology is possible when 2/3 of the ports did have methanol bunker infrastructure available. It is recommended to look for liner schedules which are able to execute the rotation with a small methanol fuel tank and a minimum number of ports having the methanol bunker infrastructure available. Liner schedules with small distances between ports are thus more favourable. An optimization approach will allow for this. Afterwards, the implementation should be further developed with both ports and ship operators to keep the risks for both parties to a minimum. In this way, the transition to methanol as maritime fuel might speed up. Nevertheless, ports should asses the number of bunker calls they need in order to benefit from supplying the fuel infrastructure. It might be that on a small scale the supply of methanol is not profitable.

Moreover, the central issue concerning the results is the sustainability of certain path ways. Bio methanol has the potential to mitigate the effects of maritime shipping on climate change. However, it is not yet widely available and therefore in order to start this transition, the use of conventional methanol is required. Nonetheless, the use of conventional methanol is less sustainable than the use of LNG. Hence, the transition to the deployment of methanol propulsion might be less desirable. Especially, if other alternatives to reduce CO2 emissions, such as hydrogen or batteries, will be better developed in the future. Nevertheless, with the development of more renewable electricity, it might be possible to produce methanol in a sustainable way by converting the electricity in methanol. For this reason, it is important to look beyond 2028 and see what futures might arise and are desired. Not taking into account long-term developments and goals might lead to a less sustainable transition. Thereby coming that decisions made at present will influence the options available in the future, since the long lifetime of assets present in the system.

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Appendix A: Model Inventory

This appendix contains the inventory of the relevant elements of the systems. For each agent in the model, the variables belonging to the agents are determined, as well as the units and the software structure present in the model.

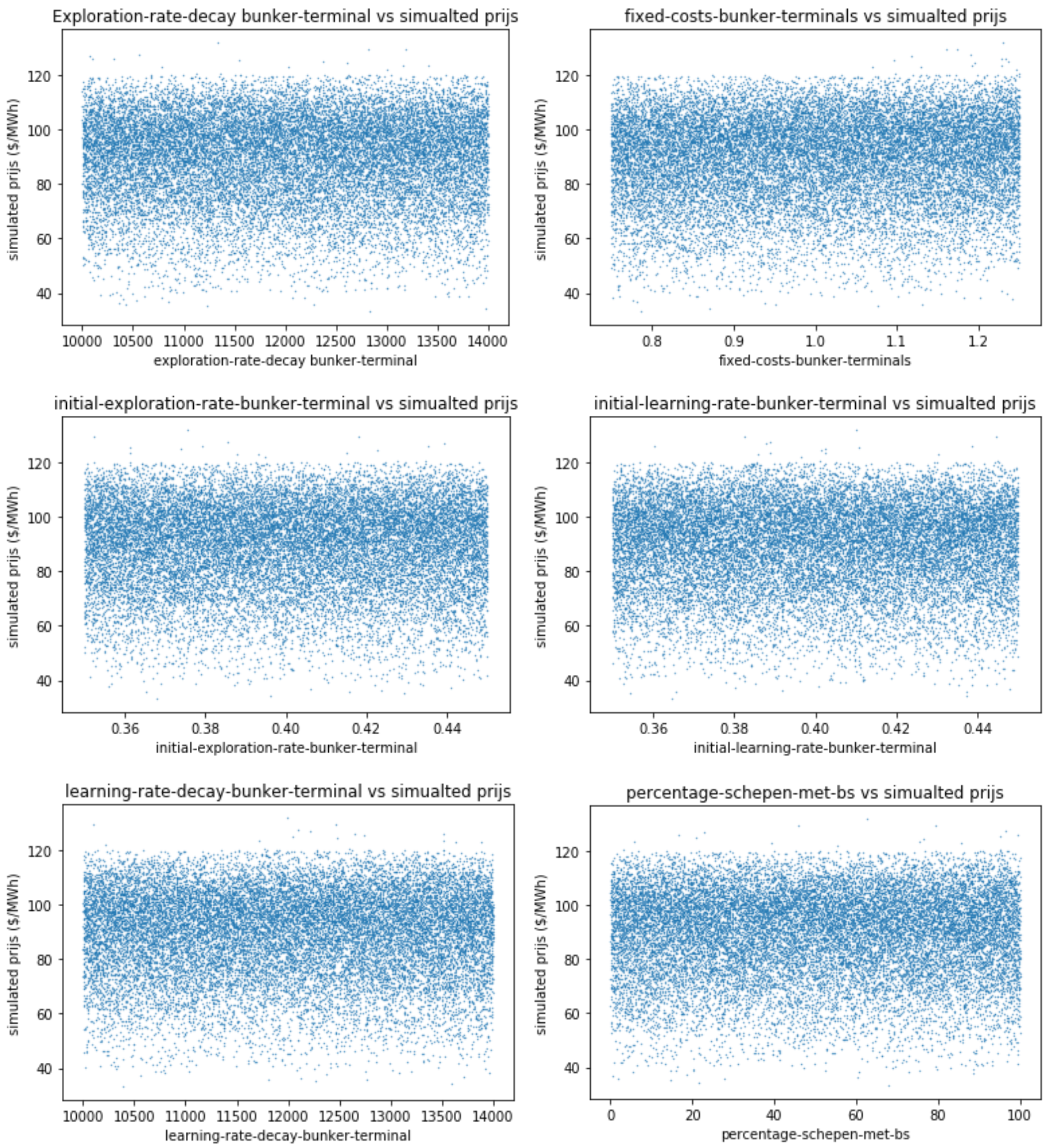
Table A1. Model Inventory

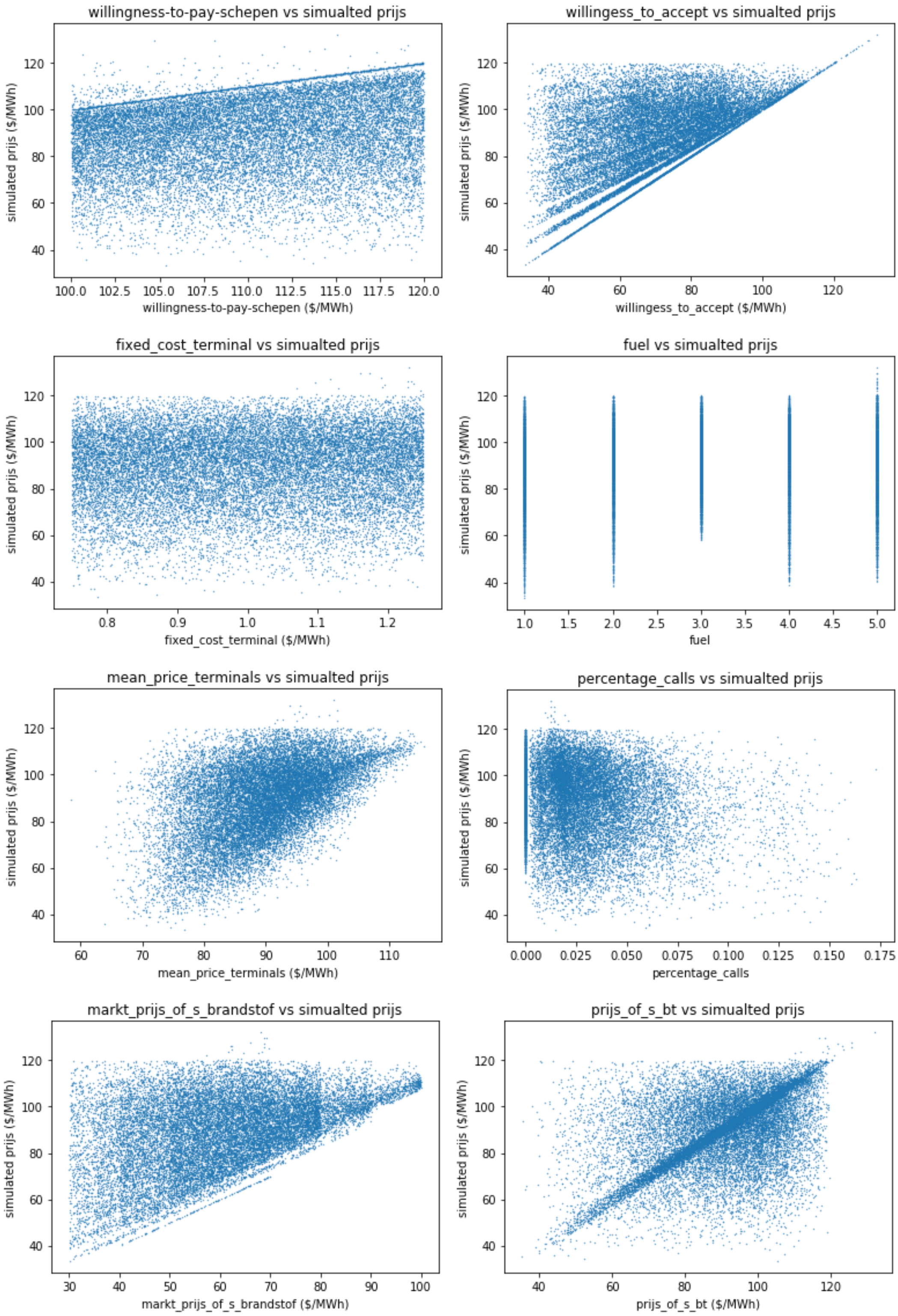
Agent	Variable	Unit	Software structure
Ports	Location	-	Xy-coordinate
	Fuels suppliers	-	List
	Port calls	#/month	Integer
	Discount	-	Boolean
	Port tariffs	$/dwt	Double
Vessels	Cargo segment	-	String
	Capacity	dwt	Float
	Engine	kW	Integer
	Age	days	Tick
	Economic-lifetime	days	Tick
	Propulsion technology	-	String
	Bunker capacity	MWh	Float
	Bunker stock	MWh	Float
	Costs of lost cargo capacity	$/%/ton	Float
	Yearly distance	nm	Float
	Discount rate	%	Float
	Risk-aversion	%	Double
	Aggregation	#	Integer
	Speed	nm/day	Float
	Willingness to pay	$/MWh	Integer
	Willingness to pay bio methanol	%	Double
Propulsion Technology	Name	-	String
	Fuel	-	String
	Vessel-type	-	String
	Fuel consumption	MWh/nm ton	Float
	SOx emission	%	Double
	NOx emission	g / MWh	Float
	On-board space	%	Double
	Investment costs retrofit	$/kW	Integer
	Investment costs new	$/kW	Integer
	Operational costs	$/MWh	Integer
	Loss of bunker capacity	%	Double
Shipping assignments	Port of origin	-	String
	Port of destination	-	List
	Cargo segment	-	String
	Route	-	List
	Delivery time	day	Tick
	Pick up time	day	Tick
	Line number	-	Integer
	Maximum distance	nm	Integer
Shipping lanes	Port of origin	-	String
	Port of destination	-	String
	Distance	nm	Integer
	Non-ECA	#	Integer

	ECA	#	Integer
	Line number	-	Integer
Bunker terminals	Port	-	Sting
	Fuel	-	String
	Type of fuel	-	String
	Fixed costs	$/MWh	Integer
	Price	$/MWh	Float
	CO2 emissions	ton / MWh	Double
	Willingness to pay	$/MWh	Double
	Willingness to accept	$/MWh	Double
	Fuel demand	MWh	Float
	Expenses	$	Float
	Revenues	$	Float
	Fuel orders	List	Agent set
	Last price	$/MWh	Float
Fuel markets	Fuel	-	String
	Supply curve	-	List
	Market price	$/MWh	Float
	Orders	#	Agent set
Orders	Buyer	-	Agent
	Supplier	-	Agent
	Gross price	$/MWh	Float
	Mean gross price	$/Mwh	Float
	Net price		Float
	Quantity	MWh	Float
Global	CO2 price	$/ton	Float
	CO2 price rate	-	Float

Appendix B: Regression model

To reduce the computational time of the model, attempts are made to capture the complex behaviour of the bunker terminals in a regression model. The price decisions made by bunker terminals were made by means of testing attractiveness of several prices by means of simulating the behaviour of vessels subjected to different prices. This simulation is tried to be captured within a regression model. In this appendix, the outcomes of the relations between the input variables and the simulated prices are shown. The figures show the relation of each variable with the simulated price. The input of each variable is shown on the x-axis and the simulated price is shown on the y-axis. The figures indicated that there is a clear correlation between the current price of the bunker terminal. However, the spread around the current price seems to be lagging of pattern.




willingness-to-pay-schepen vs simualted prijs
simulated prijs ($/MWh)
willingness-to-pay-schepen ($/MWh)
willingess_to_accept vs simualted prijs
simulated prijs ($/MWh)
willingess_to_accept ($/MWh)
fixed_cost_terminal vs simualted prijs
simulated prijs ($/MWh)
fixed_cost_terminal ($/MWh)
fuel vs simualted prijs
simulated prijs ($/MWh)
fuel
mean_price_terminals vs simualted prijs
simulated prijs ($/MWh)
mean_price_terminals ($/MWh)
percentage_calls vs simualted prijs
simulated prijs ($/MWh)
percentage_calls
markt_prijs_of_s_brandstof vs simualted prijs
simulated prijs ($/MWh)
markt_prijs_of_s_brandstof ($/MWh)
prijs_of_s_bt vs simualted prijs
simulated prijs ($/MWh)
prijs_of_s_bt ($/MWh)

Appendix C: Model Verification

This appendix shows the result of the verification steps that have been undertaken in order the verify the model. Verification is done by means of single agents testing, e.g. tracking the states of a single-agent by means of printing statements. Besides, the model is verified by means of multiple agent testing.

The following statements have been verified in order to check whether changes were implemented correctly. These statements are verified by means of printing statements and by looking and the state value of single agents.

- Loading files: each variable corresponds to the right item. **Confirmed**
- Determine the risk aversion of liners: liners determine if it is possible to invest in methanol technology in current scenario, e.g. determine whether it is possible to sail between the ports in rotation without running out of fuel based on the availability of with methanol infrastructure. **Confirmed**
- Liner vessels determine the shipping lanes of their route according to their schedule. **Confirmed**
- Vessels, shipping assignments and shipping lanes are assigned to each other according to their line number. **Confirmed**
- CatA are assigned as liners, catB, catC, catD, catE are assigned as charters. **Confirmed**
- During the set-up of the model, each vessel gets possible shipping assignments, shipping lanes, ECA-lanes, non-ECA lanes, ports, ports and mean distance assigned. **Confirmed**
- Discount of ports is assigned according to the scenario. **Confirmed**
- Availability of methanol is according to the scenario. **Confirmed**
- CO2 price is updated. **Confirmed**
- Allowable sulphur emission is updated and lanes have assigned a number of SOx lanes. For every shipping lane, it is defined whether it is located in an ECA. **Confirmed**
- Every thirty ticks, shipping assignments are made available to be executed. **Confirmed**
- Vessel sail via assigned rotations of the shipping assignments. **Confirmed**
- Adding pickup and delivery time to vessels, vessels moor when they pick up a shipping assignment. **Confirmed**
- Update route of liner vessel. After a vessel has arrived in a port it determines the next port in the schedule. **Confirmed**
- The fuel consumption is calculated according to the travelled distance and the fuel consumption of the vessel. **Confirmed**
- Vessels select a shipping assignment according to their cargo segment. **Confirmed**
- Vessels select a shipping assignment that has not been executed yet. **Confirmed**
- Vessels select, if possible, a shipping assignment with an origin in the port of origin. **Confirmed**
- Vessels select, a shipping assignment with a minimum distance from its current position. **Confirmed**
- Vessels determine bunker terminals in port, both bio methanol and methanol for vessels with methanol technology. **Confirmed**
- Bunker terminals determine price based on price, discount, willingness to pay for bio methanol and CO2 price. **Confirmed**

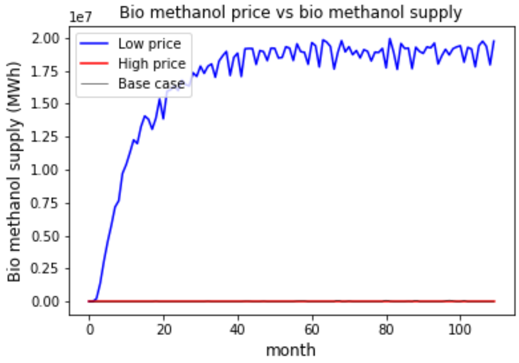
- Vessels order fuel from the right bunker terminals, allow for methanol and bio methanol. **Confirmed**
- Vessels take into account the willingness to pay bio methanol when bunkering fuel. **Confirmed**
- Vessels selected the cheapest bunker terminal. **Confirmed**
- Liners decide if they can make the fuel rotation without bunkering. **Confirmed**
- Bunker terminals order fuel from the right bunker market. **Confirmed**
- Age of vessels is set to zero after investment in a new vessel. **Confirmed**
- Bunker capacity of vessel is altered after investing in small methanol technology. **Confirmed**
- Checking if vessels invest in technologies with the lowest NPV value. **Confirmed**
- Determine possible technologies based on the max distance and bunker capacity. **Confirmed**
- Discount is taken into account when calculating NPV. **Confirmed**
- NOx regulations are implemented conform to the Tier requirements. **Confirmed**
- Discount is taken into account when taking bunker decisions. **Confirmed**
- Take into account CO2 price in NPV calculation. **Confirmed**
- Take into account the willingness to pay bio methanol in NPV calculations. **Confirmed**
- Bunker terminals decide upon their pricing decisions. **Confirmed**
- Bunker market clears market price. **Confirmed**
- Orders bunker terminals are removed when receiving the fuel from the market. **Confirmed**
- Check if updated every 30 ticks output variables. **Confirmed**
- New shipping assignment every 30 ticks. **Confirmed**

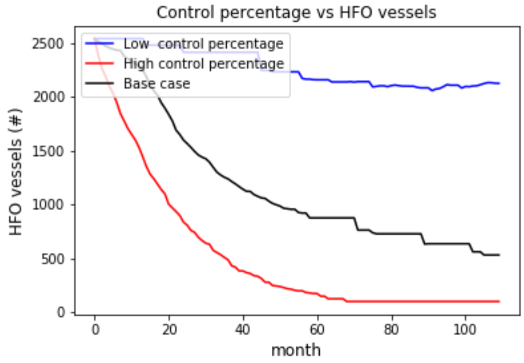
Multi-agent testing

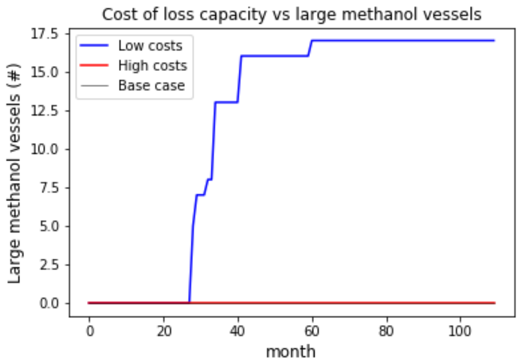
In addition, verification of the interactions between multiple agents discussed. A variability test, as well as timeline sanity test, are performed.

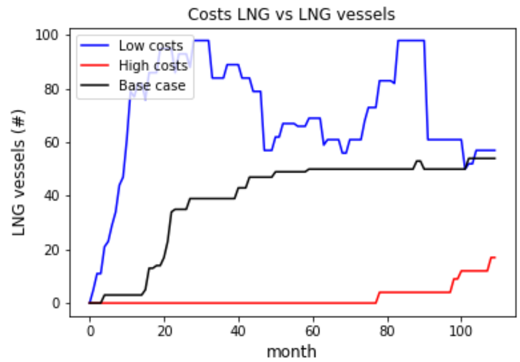
Variability testing

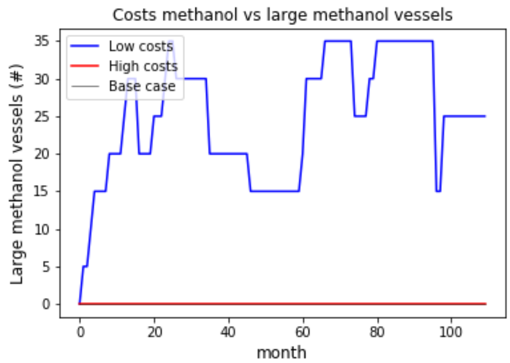
The plots depicted in this section show the outcomes of the variability tests. Input variables have been changed and with the base case scenarios. There has been checked whether the observed values meet the expectations. During the variability test, no unexpected behaviour was observed.

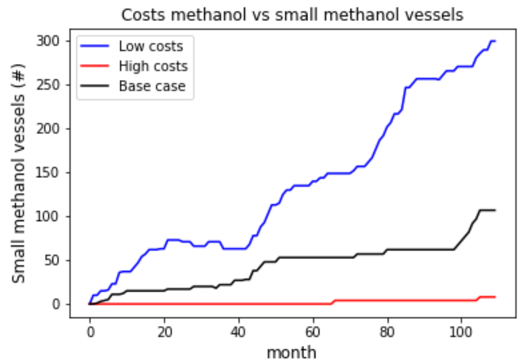

Bio methanol price vs bio methanol supply
1e7
Bio methanol supply (MWh)
month
Low price
High price
Base case

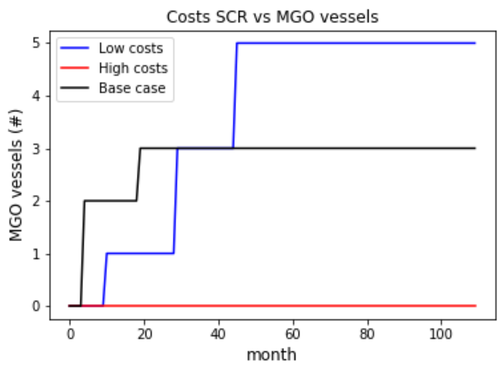

Control percentage vs HFO vessels
HFO vessels (#)
month
Low control percentage
High control percentage
Base case

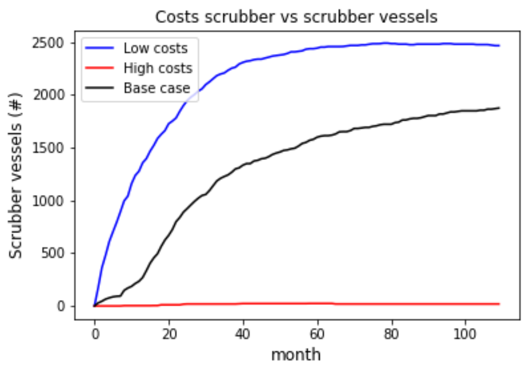

Cost of loss capacity vs large methanol vessels
Large methanol vessels (#)
month
Low costs
High costs
Base case

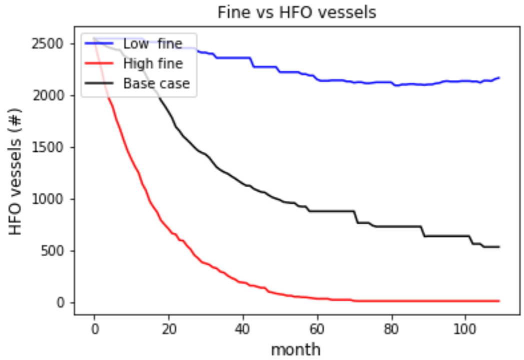

Costs LNG vs LNG vessels
LNG vessels (#)
month
Low costs
High costs
Base case

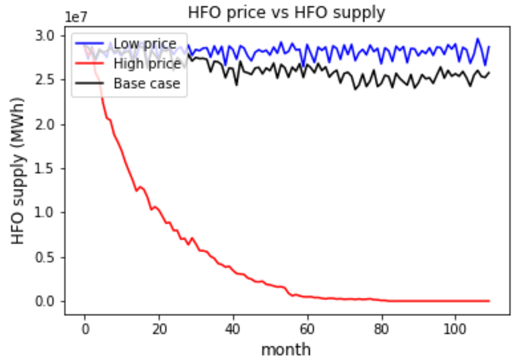

Costs methanol vs large methanol vessels
Large methanol vessels (#)
month
Low costs
High costs
Base case

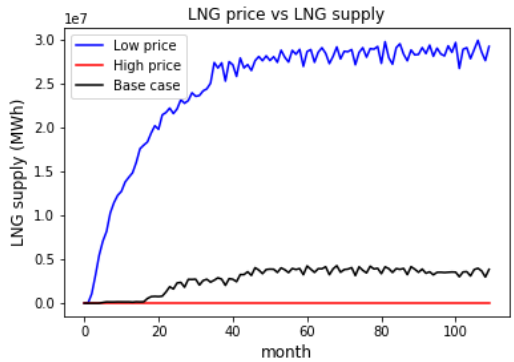

Costs methanol vs small methanol vessels
Small methanol vessels (#)
month
Low costs
High costs
Base case

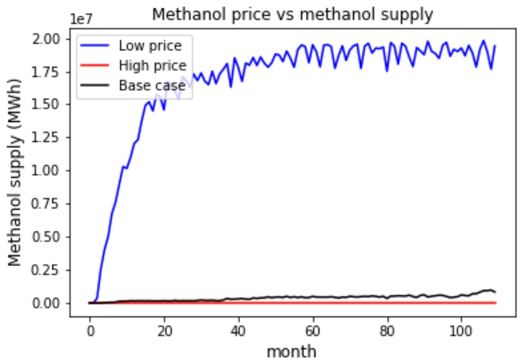

Costs SCR vs MGO vessels
MGO vessels (#)
month
Low costs
High costs
Base case


Costs scrubber vs scrubber vessels
Scrubber vessels (#)
month
Low costs
High costs
Base case

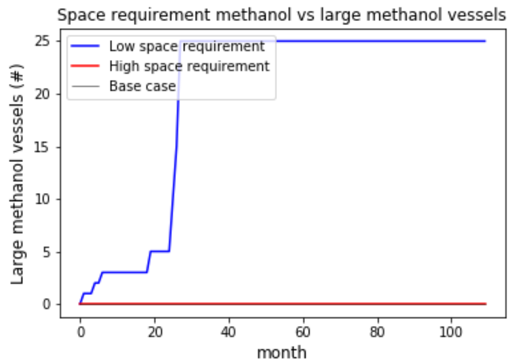

Fine vs HFO vessels
HFO vessels (#)
month
Low fine
High fine
Base case

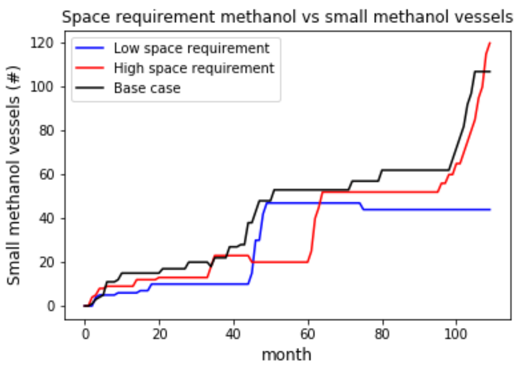

HFO price vs HFO supply
1e7
HFO supply (MWh)
month
Low price
High price
Base case

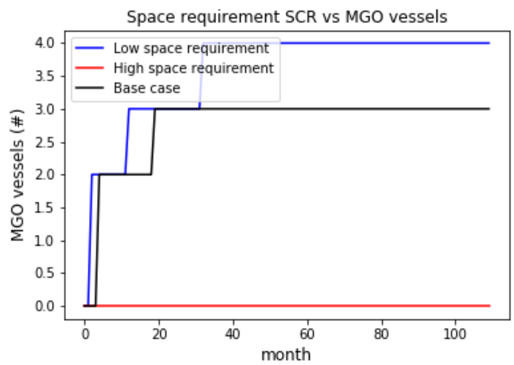

LNG price vs LNG supply
1e7
LNG supply (MWh)
month
Low price
High price
Base case

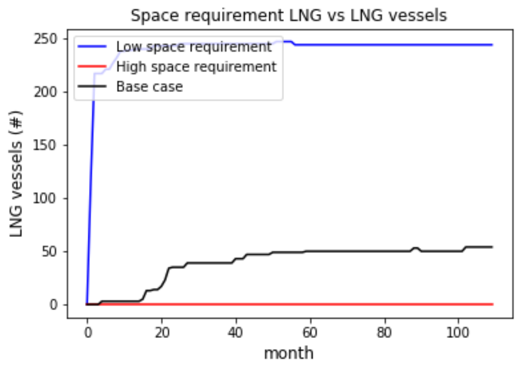

Methanol price vs methanol supply
1e7
Methanol supply (MWh)
month
Low price
High price
Base case

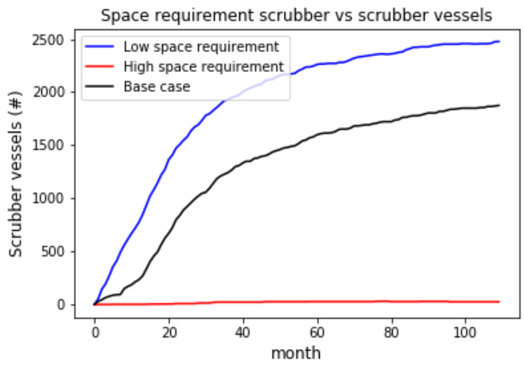

MGO price vs MGO supply
1e7
MGO supply (MWh)
month
Low price
High price
Base case

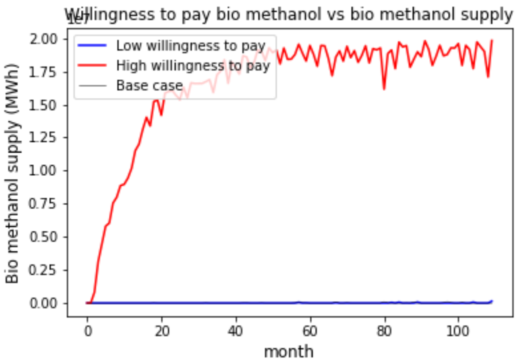

Space requirement methanol vs large methanol vessels
Large methanol vessels (#)
month
Low space requirement
High space requirement
Base case


Space requirement methanol vs small methanol vessels
Small methanol vessels (#)
month
Low space requirement
High space requirement
Base case


Space requirement SCR vs MGO vessels
MGO vessels (#)
month
Low space requirement
High space requirement
Base case

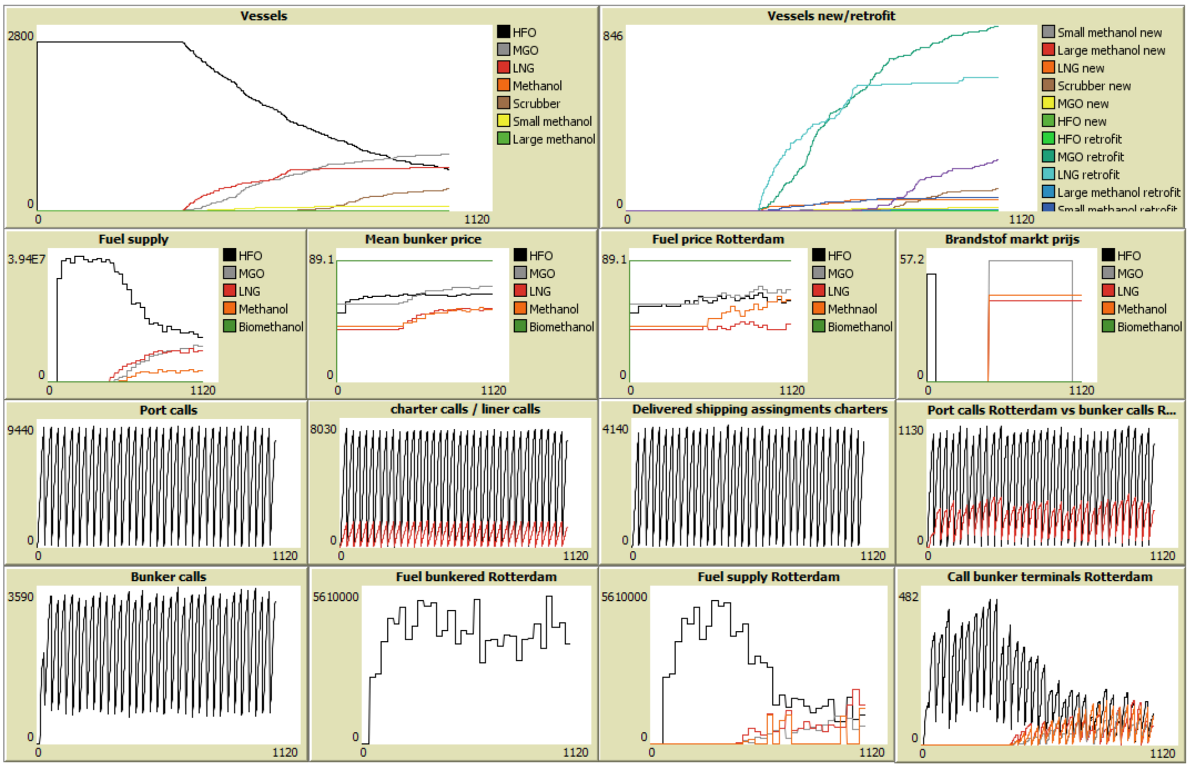

Space requirement LNG vs LNG vessels
Low space requirement
High space requirement
Base case
LNG vessels (#)
month


Space requirement scrubber vs scrubber vessels
Low space requirement
High space requirement
Base case
Scrubber vessels (#)
month


Willingness to pay bio methanol vs bio methanol supply
1e7
Low willingness to pay
High willingness to pay
Base case
Bio methanol supply (MWh)
month

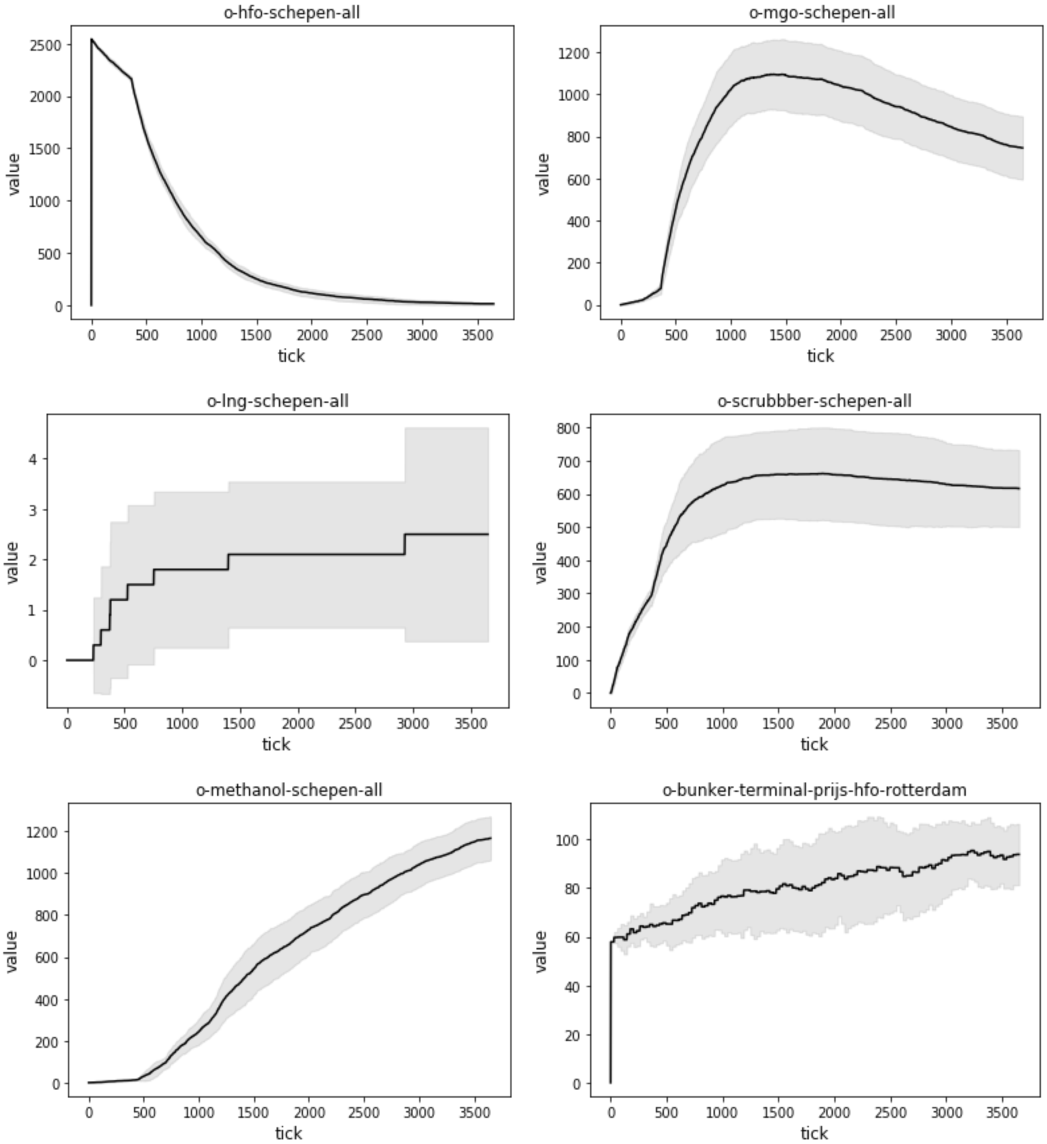
Timeline sanity test

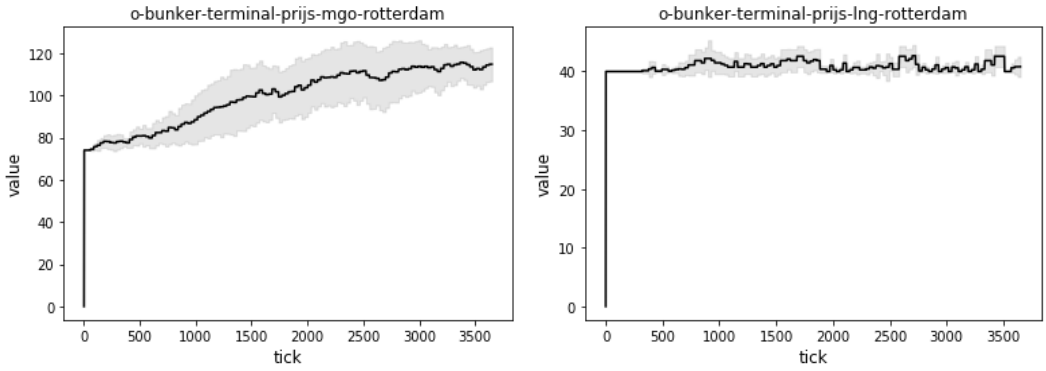
During the creation of EU-MarPEM, the behaviour of the model was constantly check by means of monitoring the output. A print screen of the variables that were monitored is depicted below. In this way, it could be checked whether the model behaved as expected when changes to the model were made.



Appendix D: Stochasticity Analysis

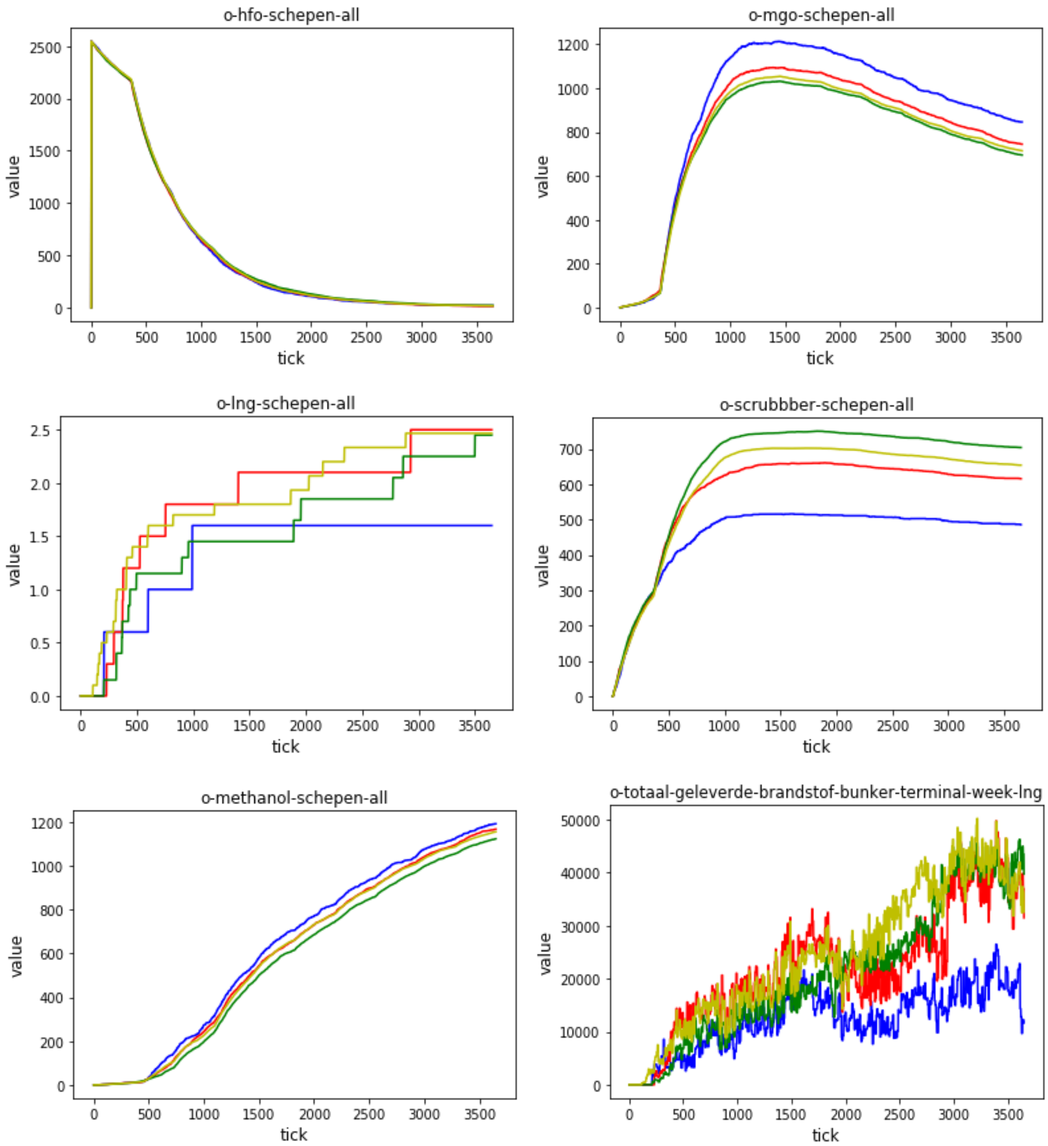
This figures in this appendix depict the results of the stochasticity analysis. The black line corresponds to the mean value of the outcomes of 65 replications. The grey area represents the confidence interval. When analysing the plots, it can be noticed that the model is subjected to stochasticity. However, not every outcome of interest is subjected to stochasticity equally.

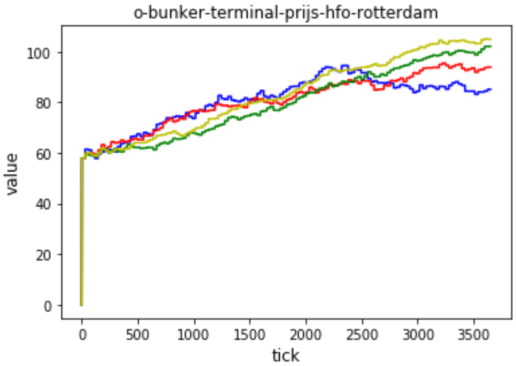


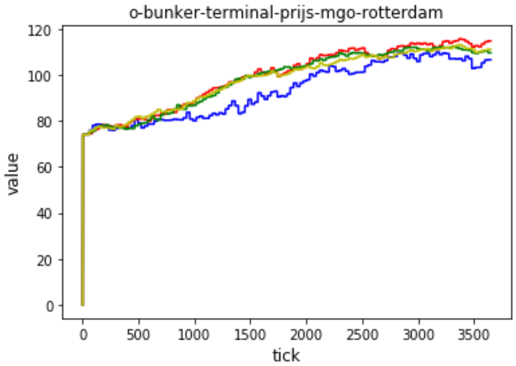


Sample sizes

To estimate the number of replications that are needed, from the 65 replication 4 different samples with different sizes, respectively 5, 10, 20 30 3, were taken. When increasing the number of replications, the estimated value becomes better. The outcomes of each sample group are analysed and compared. In this section the results of this analysis are presented.




o-bunker-terminal-prijs-hfo-rotterdam
value
tick
0
20
40
60
80
100
500
1000
1500
2000
2500
3000
3500


o-bunker-terminal-prijs-mgo-rotterdam
value
tick
0
20
40
60
80
100
120
500
1000
1500
2000
2500
3000
3500

Appendix E: Model Parameterization

This appendix comprises information about the model parameterization. The tables contain data which is used for the parameterization of the model. Shipping assignments are created based on the number of port calls of the included ports and the percentage of the transport between the country of the ports and regions. This data is derived from the Eurostat database.

Table E1: Port calls per month

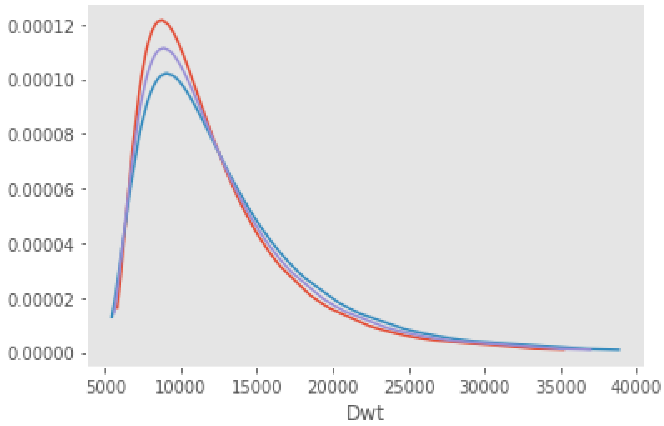
Port	Liquid bulk	Dry bulk	General cargo	Container	Container Liner	Total
Piraeus	29	9	767	91	36	932
Rotterdam	374	14	357	44	280	1068
Antwerp	363	17	259	0	134	818
Liverpool	86	6	267	34	16	409
Dublin	36	3	234	2	68	342
Immingham	165	5	234	25	56	484
London	67	15	132	0	68	283
Teesport	144	1	58	0	64	268
Hamburg	29	23	42	121	36	252
Klaipeda	27	18	157	24	20	246
Bremerhaven	21	1	19	159	24	225
Ambarli	7	84	38	73	20	221
Belfast	28	5	168	3	16	219
Helsinki	5	4	132	35	20	196
Leixoes	31	4	64	35	40	174
Bilbao	37	40	46	25	24	171
LeHavre	102	1	0	0	60	157
Gdynia	26	12	81	11	28	157
Salerno	0	0	128	0	16	144
Dunkerque	36	44	14	0	32	126
Vigo	2	4	52	9	24	91
Setubal	8	3	42	0	32	85
Sines	50	1	8	1	24	83
Cork	23	19	0	0	32	72
Felixstowe	1	0	0	0	72	40
Casablanca	29	23	42	121	36	252
Saint Petersburg	27	18	157	16	28	246
Alexandria	50	1	8	1	24	83
Ashdod	7	84	38	73	20	221
Algeciras	124	11	229	71	20	455

Table E2: Percentage of transport between ports and regions

Port	North Sea	Balti Sea	Black Sea	Mediterranean Sea	Atlantic Ocean
Piraeus	6	0,70	16	76	1
Rotterdam	32	35	5	12	10
Antwerp	31	17	2	32	16
Liverpool	53	9	1	8	31
Dublin	40	3	1	2	54
Immingham	53	9	1	8	31
London	53	9	1	8	31
Teesport	53	9	1	8	31
Hamburg	31	54	1	7	7
Klaipeda	7	62	0	6	24
Bremerhaven	31	54	1	7	7
Ambarli	8	3	27	57	4
Belfast	53	9	1	8	31
Helsinki	3	56	0	4	35
Leixoes	20	7	8	32	31
Bilbao	14	5	5	50	23
LeHavre	20	10	10	30	30
Gdynia	5	45	1	13	35
Salerno	3	3	14	77	1
Dunkerque	20	10	10	30	30
Vigo	14	5	5	50	23
Setubal	20	7	8	32	31
Sines	20	7	8	32	31
Cork	40	3	1	2	54
Felixstowe	53	9	1	8	31
Casablanca	20	7	8	32	31
Saint Petersburg	7	62	0	6	24
Alexandria	8	3	27	57	4
Ashdod	8	3	27	57	4
Algeciras	7	62	0	6	24

Capacity of vessels

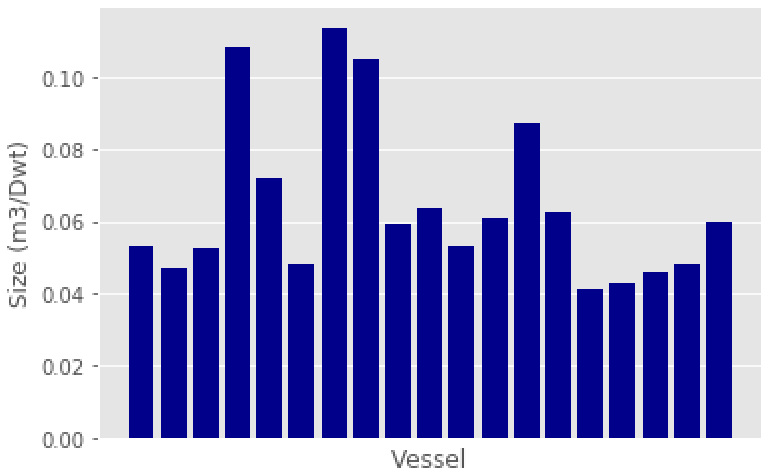
A data set of the PoR and eeSea have been compared to determine the capacity of a vessel. The figure below represents the distribution of the capacity of the vessels. Both data sets have a distribution that does not seem to be very different. The average of these two distributions is taken as distribution for the capacity of charters (purple line)



Distribution of capacity vessels

Fuel tank capacities

Based on 19 vessels of the fleet of Damen Shipyards an average of 0,659 MWh/dwt has been taken as the fuel tank capacity of vessels.



Fuel tank capacities

Fixed costs bunker terminals

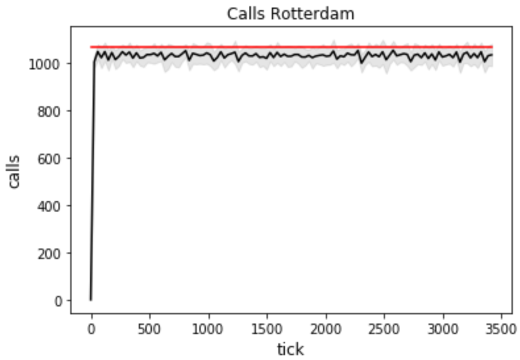
The fixed costs of the HFO and MGO bunker terminals have been determined by analysing the fuel prices of the different ports in the period from 16 – 19 January 2019. For HFO three different groups are determined: 1) Ports that are relatively cheap because of the availability of refineries, 2) Ports with an average bunker price, and 3) Ports that are relatively more expensive to bunker. MGO has been categorised in four different groups. The fixed costs of the LNG terminals are determined by the availability of LNG in the Port. When LNG is available in the port the fixed costs of the terminal are 0. When there is no LNG available in the port, assumed is that the LNG will be transported with a bunker barge to the port. The fixed costs are determined by the distance to the closest port with LNG available and the transport costs (0.0095 $/nm; Bas et al., 2017). The fixed costs for methanol are determined by the availability of methanol plants in the country of the port. When methanol is produced, the fixed costs for methanol are assumed to be lower. For bio methanol such a distinction is not made, due to the fact that bio methanol is not well developed yet.

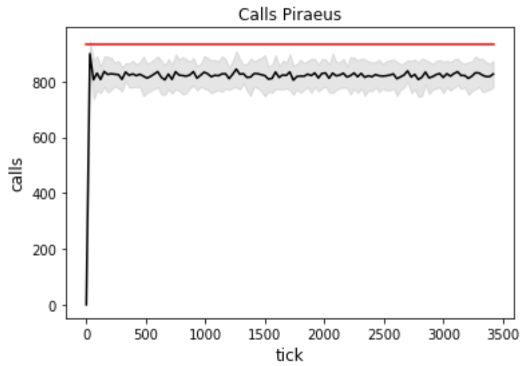
Table E3: Fixed costs bunker terminals ($/MWh)

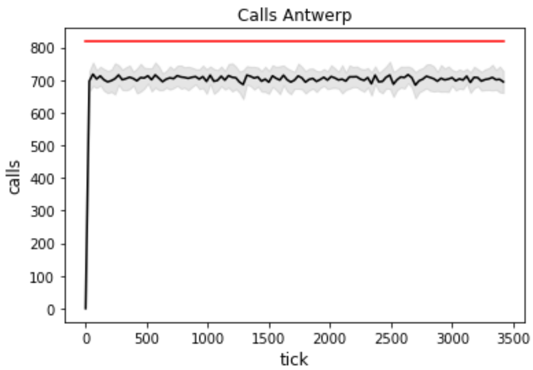
Port	HFO	MGO	LNG	Methanol	Bio methanol
Alexandria	9	16	23	5	10
Algeciras	4	8	0	10	10
Ambarli	4	8	11	10	10
Antwerp	4	4	0	10	10
Ashdod	4	8	11	10	10
Belfast	14	11	0	10	10
Bilbao	4	8	29	10	10
Bremerhaven	9	4	52	5	10
Casablanca	14	16	0	10	10
Cork	14	11	9	10	10
Dublin	14	11	17	10	10
Dunkerque	9	4	41	10	10
Felixstowe	14	11	45	10	10
Gdynia	9	8	0	10	10
Hamburg	9	4	6	5	10
Helsinki	4	4	9	10	10
Immingham	14	11	0	10	10
Klaipeda	4	4	5	5	10
Le Havre	9	4	17	10	10
Leixoes	4	8	0	10	10
Liverpool	14	11	12	10	10
London	14	11	18	10	10
Piraeus	4	8	0	10	10
Rotterdam	4	4	0	5	10
Saint Petersburg	4	4	0	5	10
Salerno	4	8	32	10	10
Setubal	4	8	3	10	10
Sines	4	8	0	10	10
Teesport	14	11	23	10	10
Vigo	4	8	8	10	10

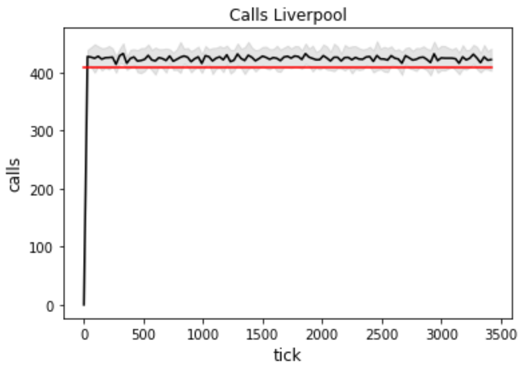
Appendix F: Model Validation

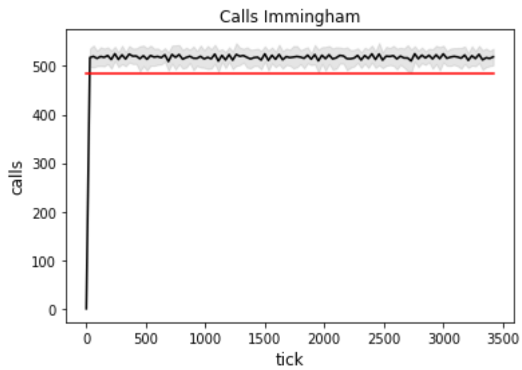
This appendix contains the validation of port calls. The figures show the observed port calls of 20 independent random sampled scenarios. The red lines indicate the expected value, the black line the observed mean value. The grey area shows the confidence interval.

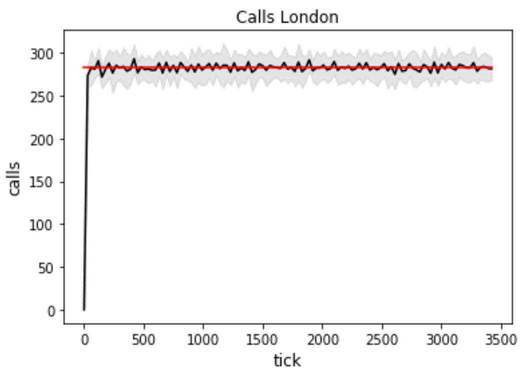


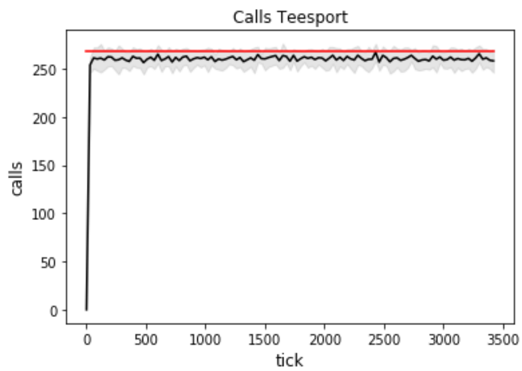


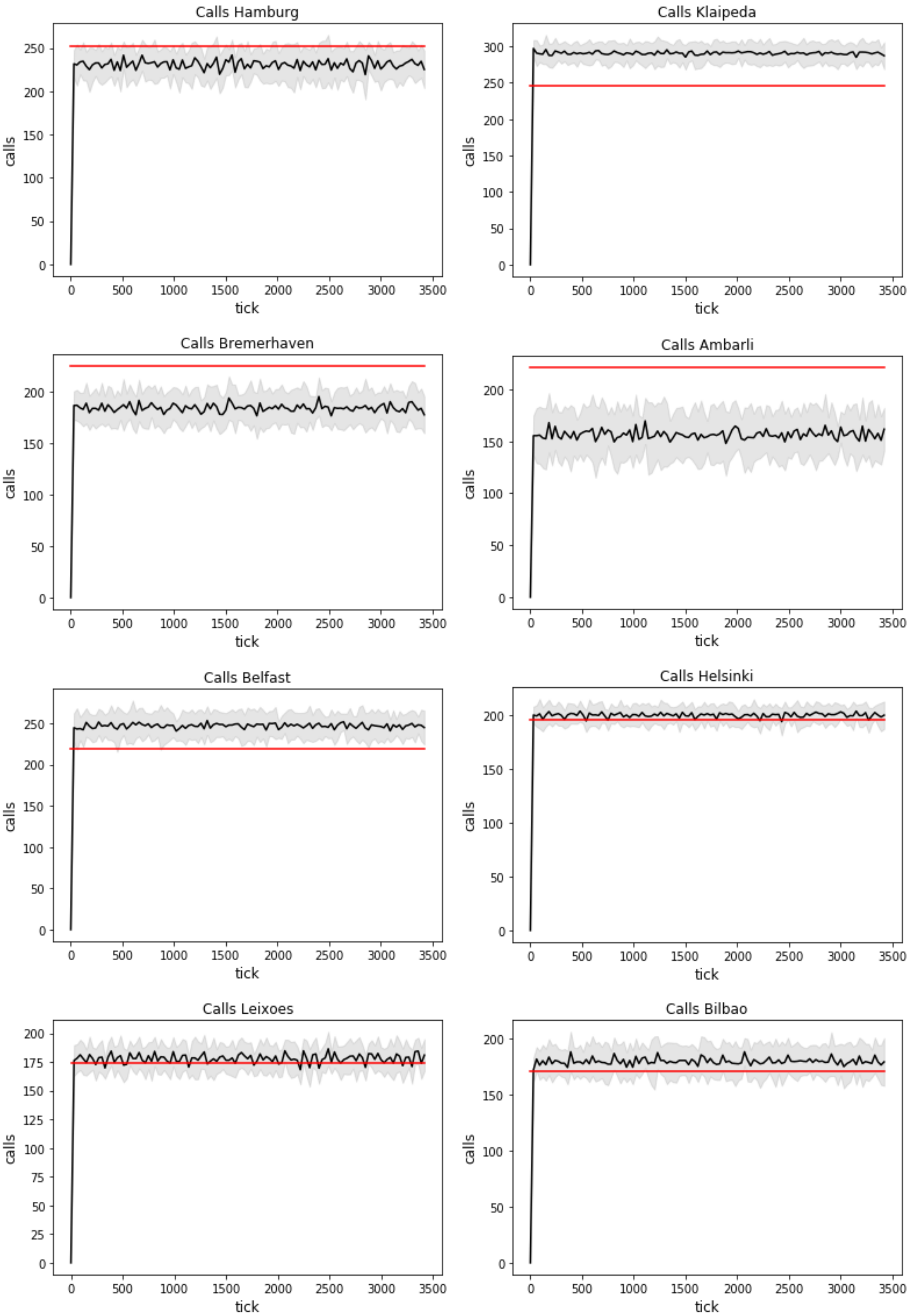


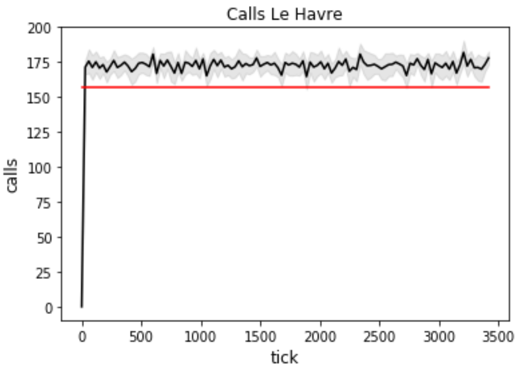


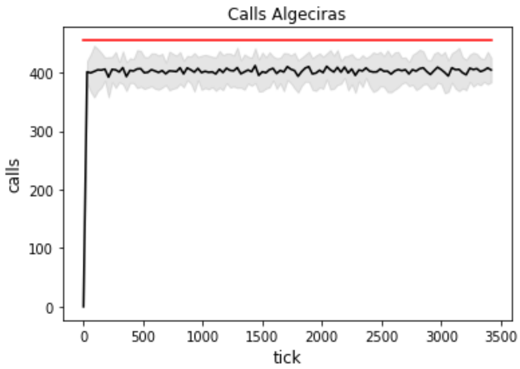


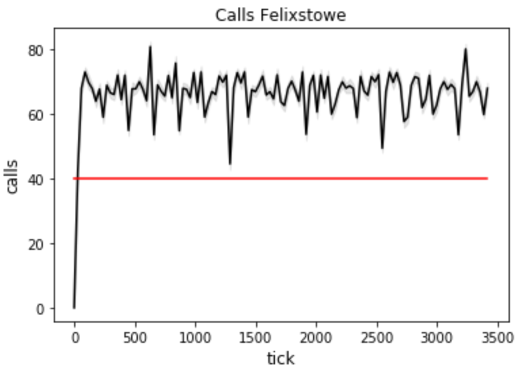


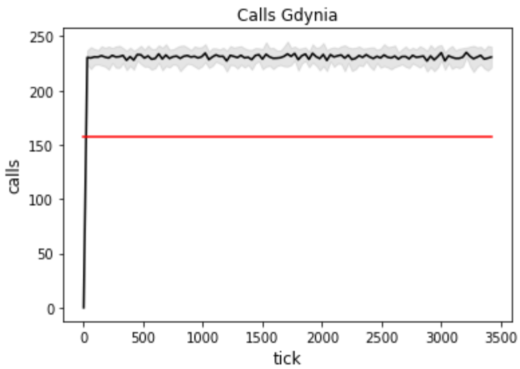


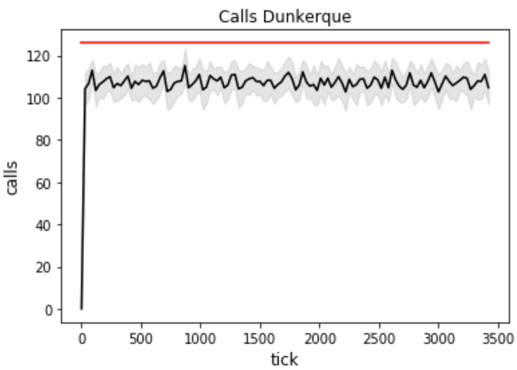

Calls Hamburg
Calls Klaipeda
Calls Bremerhaven
Calls Ambarli
Calls Belfast
Calls Helsinki
Calls Leixoes
Calls Bilbao
calls
tick

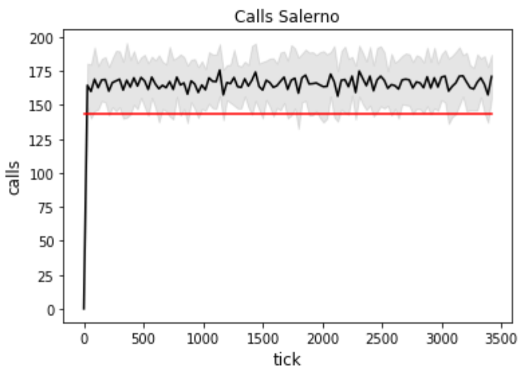

Calls Le Havre
calls
200 175 150 125 100 75 50 25 0
0 500 1000 1500 2000 2500 3000 3500
tick

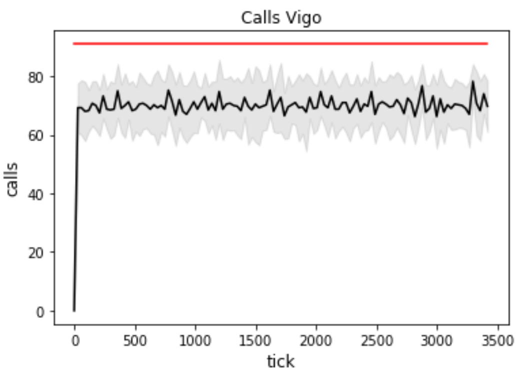

Calls Algeciras
calls
400 300 200 100 0
0 500 1000 1500 2000 2500 3000 3500
tick

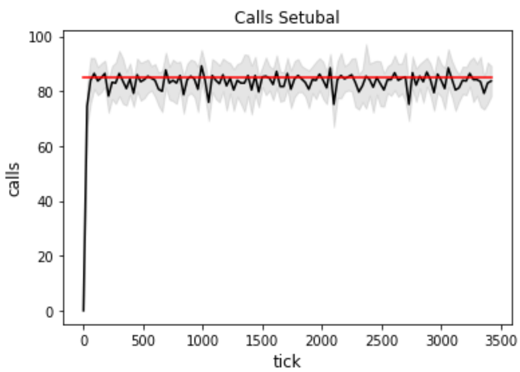

Calls Felixstowe
calls
80 60 40 20 0
0 500 1000 1500 2000 2500 3000 3500
tick

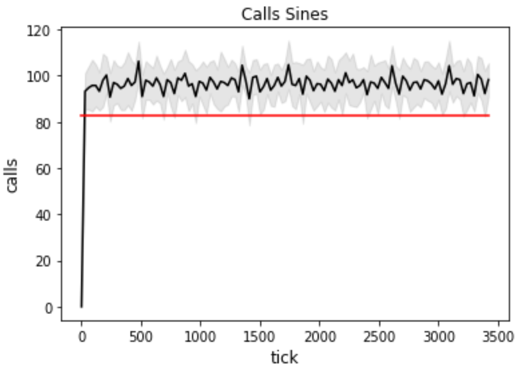

Calls Gdynia
calls
250 200 150 100 50 0
0 500 1000 1500 2000 2500 3000 3500
tick

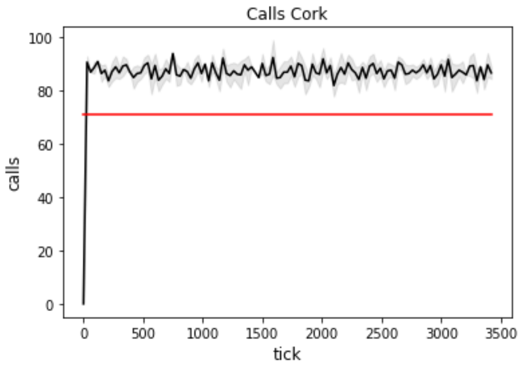

Calls Dunkerque
calls
120 100 80 60 40 20 0
0 500 1000 1500 2000 2500 3000 3500
tick

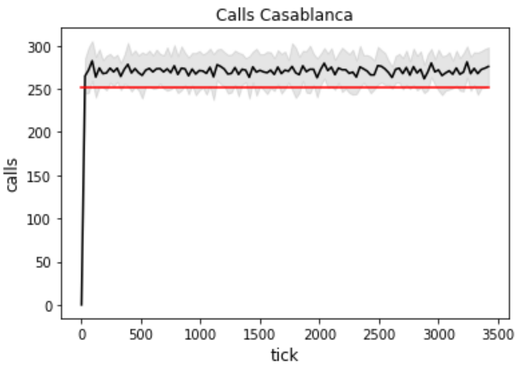

Calls Salerno
calls
200 175 150 125 100 75 50 25 0
0 500 1000 1500 2000 2500 3000 3500
tick

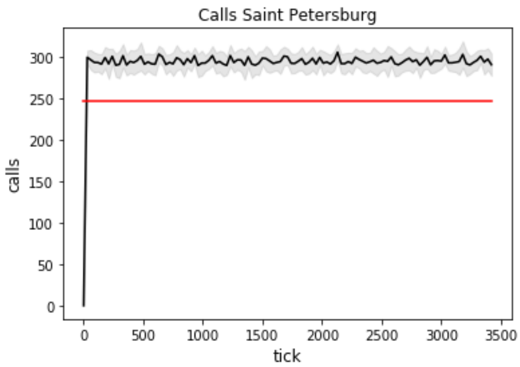

Calls Vigo
calls
80 60 40 20 0
0 500 1000 1500 2000 2500 3000 3500
tick

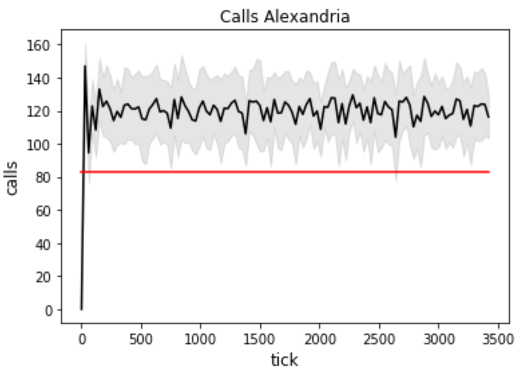

Calls Setubal
calls
100 80 60 40 20 0
0 500 1000 1500 2000 2500 3000 3500
tick

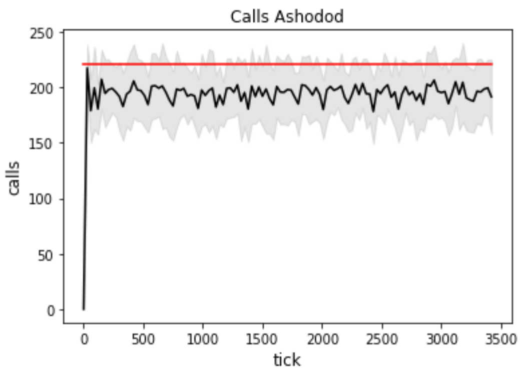

Calls Sines
calls
0
20
40
60
80
100
120
0
500
1000
1500
2000
2500
3000
3500
tick


Calls Cork
calls
0
20
40
60
80
100
0
500
1000
1500
2000
2500
3000
3500
tick


Calls Casablanca
calls
0
50
100
150
200
250
300
0
500
1000
1500
2000
2500
3000
3500
tick

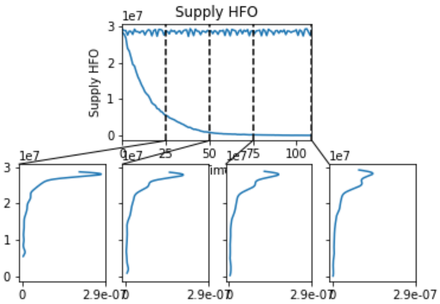

Calls Saint Petersburg
calls
0
50
100
150
200
250
300
0
500
1000
1500
2000
2500
3000
3500
tick

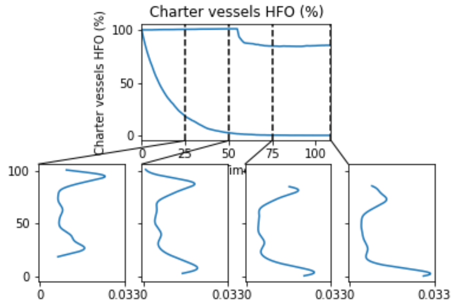

Calls Alexandria
calls
0
20
40
60
80
100
120
140
160
0
500
1000
1500
2000
2500
3000
3500
tick

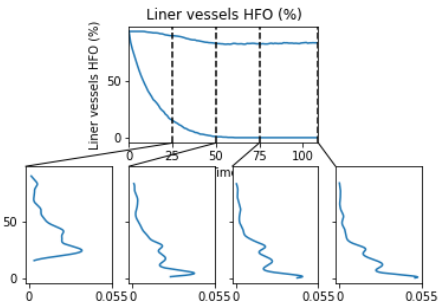

Calls Ashodod
calls
0
50
100
150
200
250
0
500
1000
1500
2000
2500
3000
3500
tick

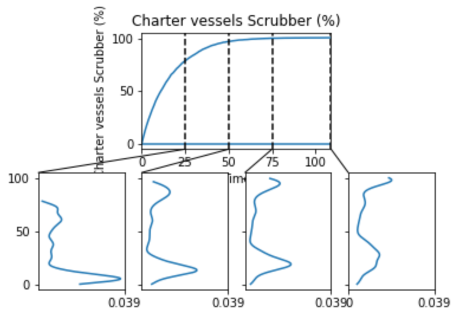
Appendix G: Multiple Densities

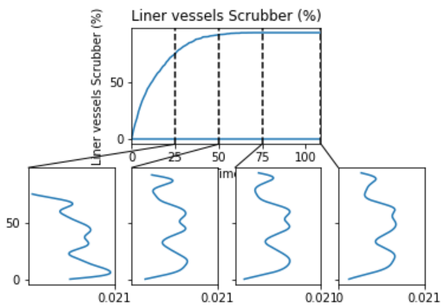
The graphs shown in this appendix show the minimum and maximum value of each model outcome over time. The four graphs beneath each model outcome, show the KDE at different time steps during the simulation run, respectively 25, 50, 75 and 110 months.

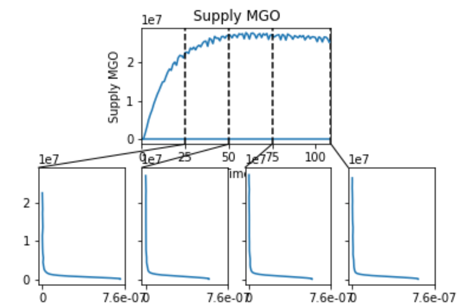


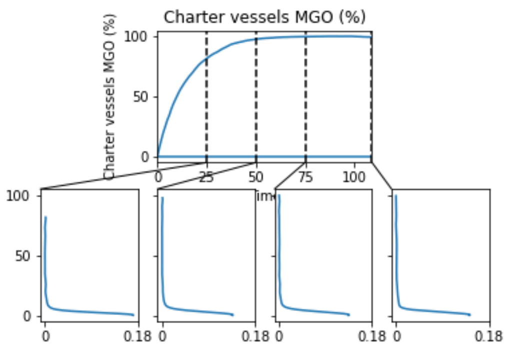


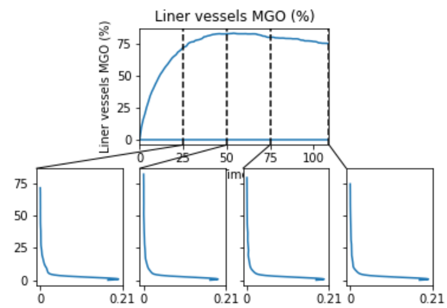


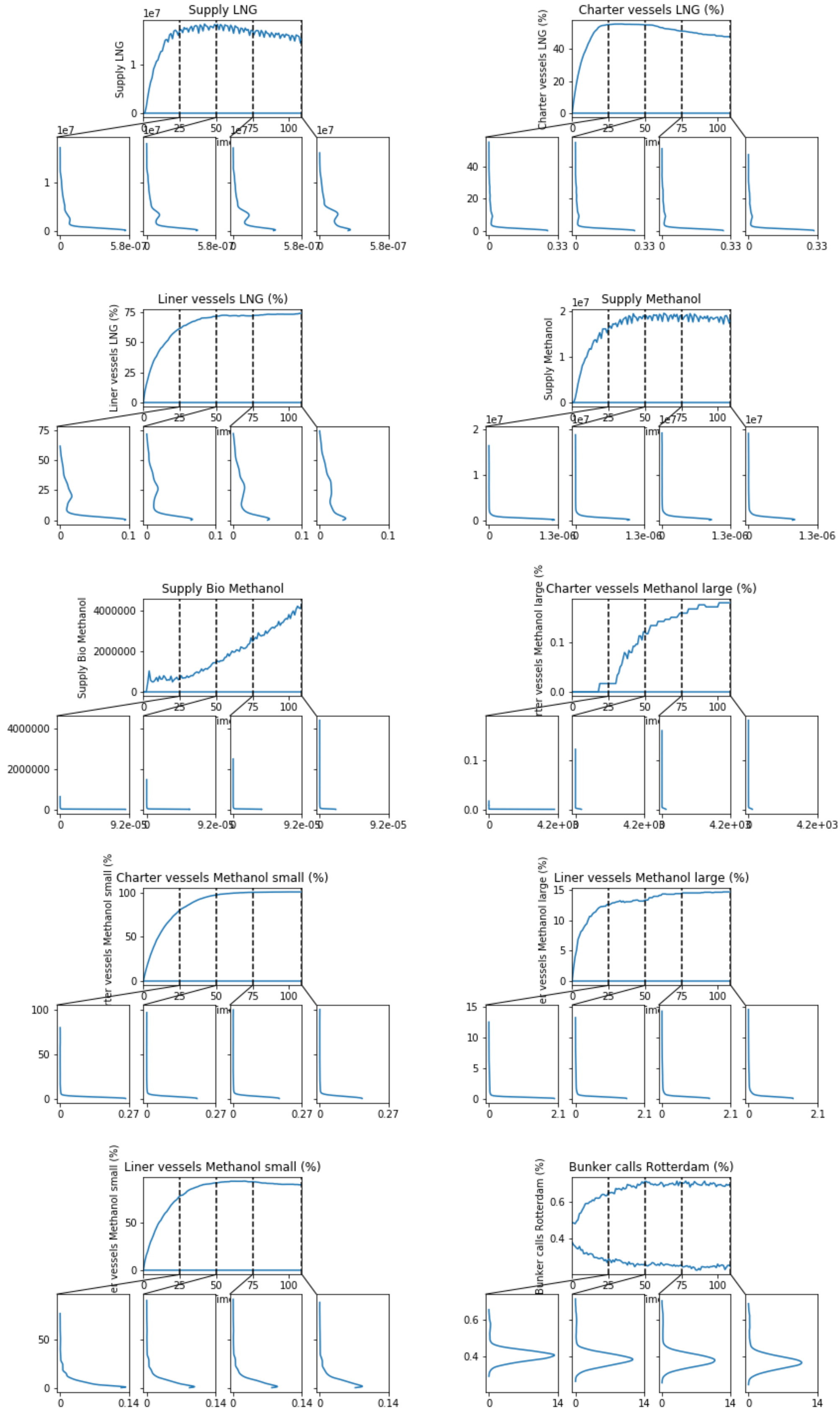










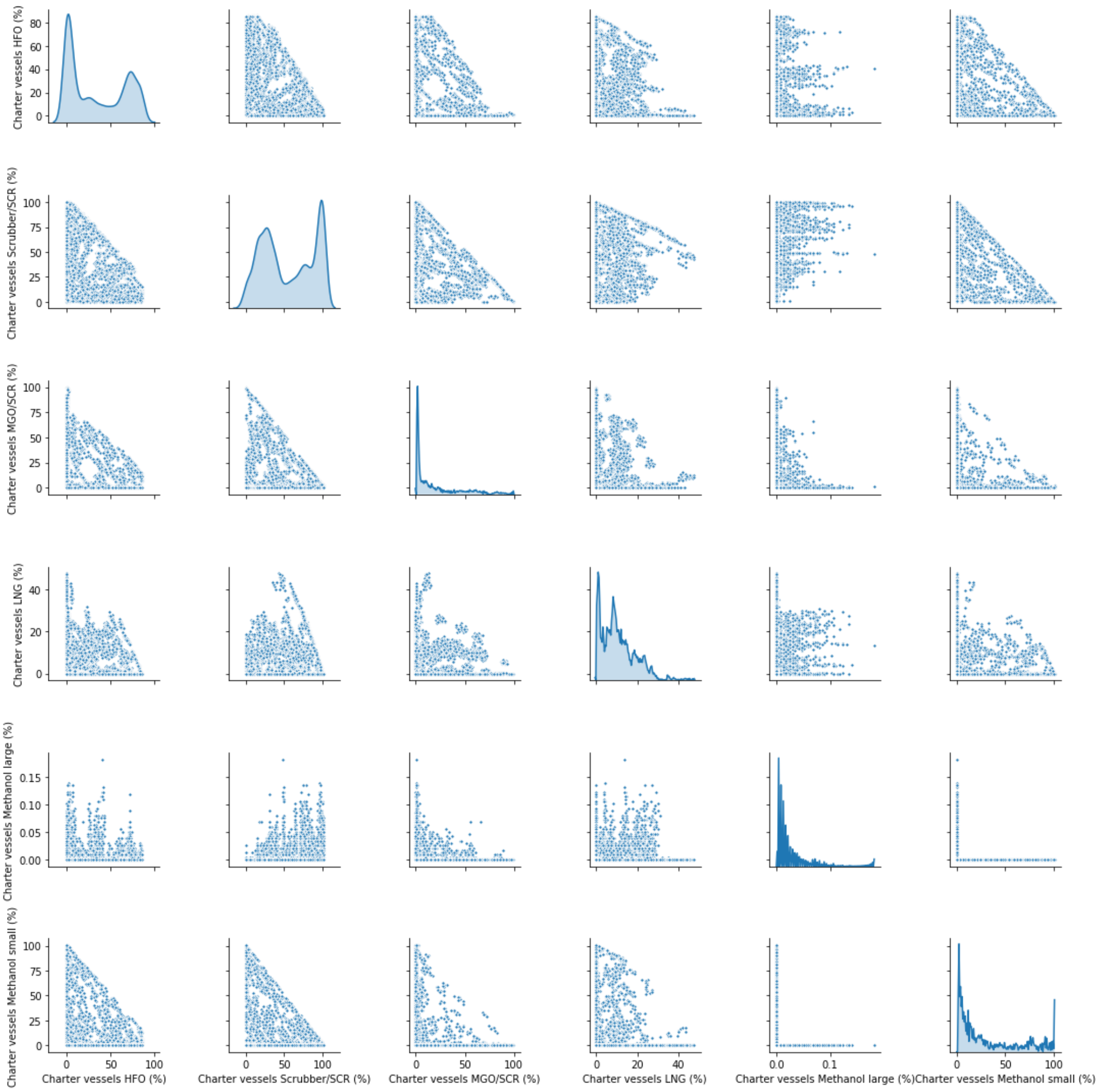

Supply LNG
Charter vessels LNG (%)
Liner vessels LNG (%)
Supply Methanol
Supply Bio Methanol
Charter vessels Methanol large (%)
Charter vessels Methanol small (%)
Liner vessels Methanol large (%)
Liner vessels Methanol small (%)
Bunker calls Rotterdam (%)

Appendix H: Scatter Plots

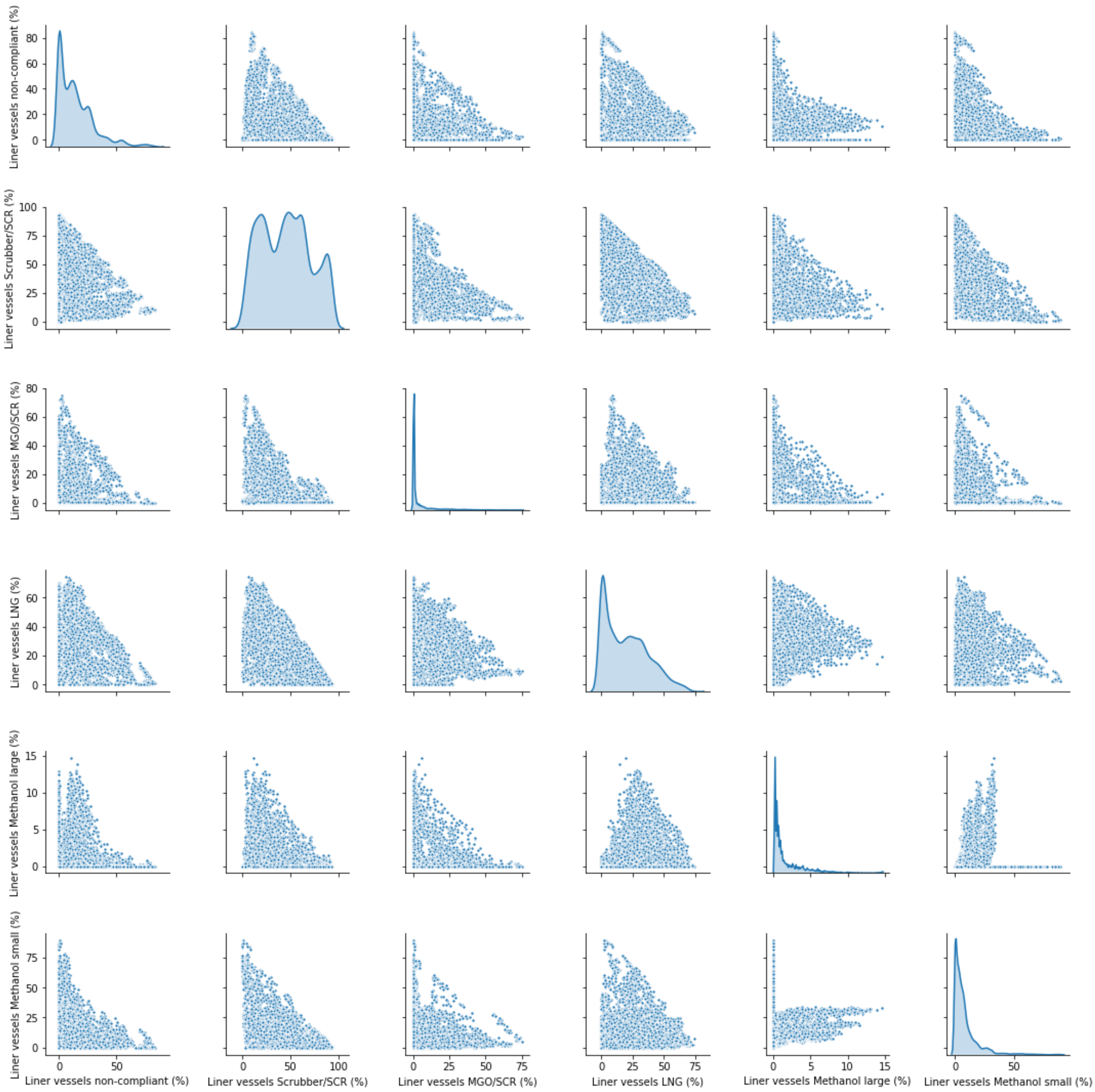
This appendix contains scatterplots which are made in order to obtain insight into the relations between variables. These scatterplots are created to provide insight into the relation between outcomes variables, as well as the relation between input and output variables.

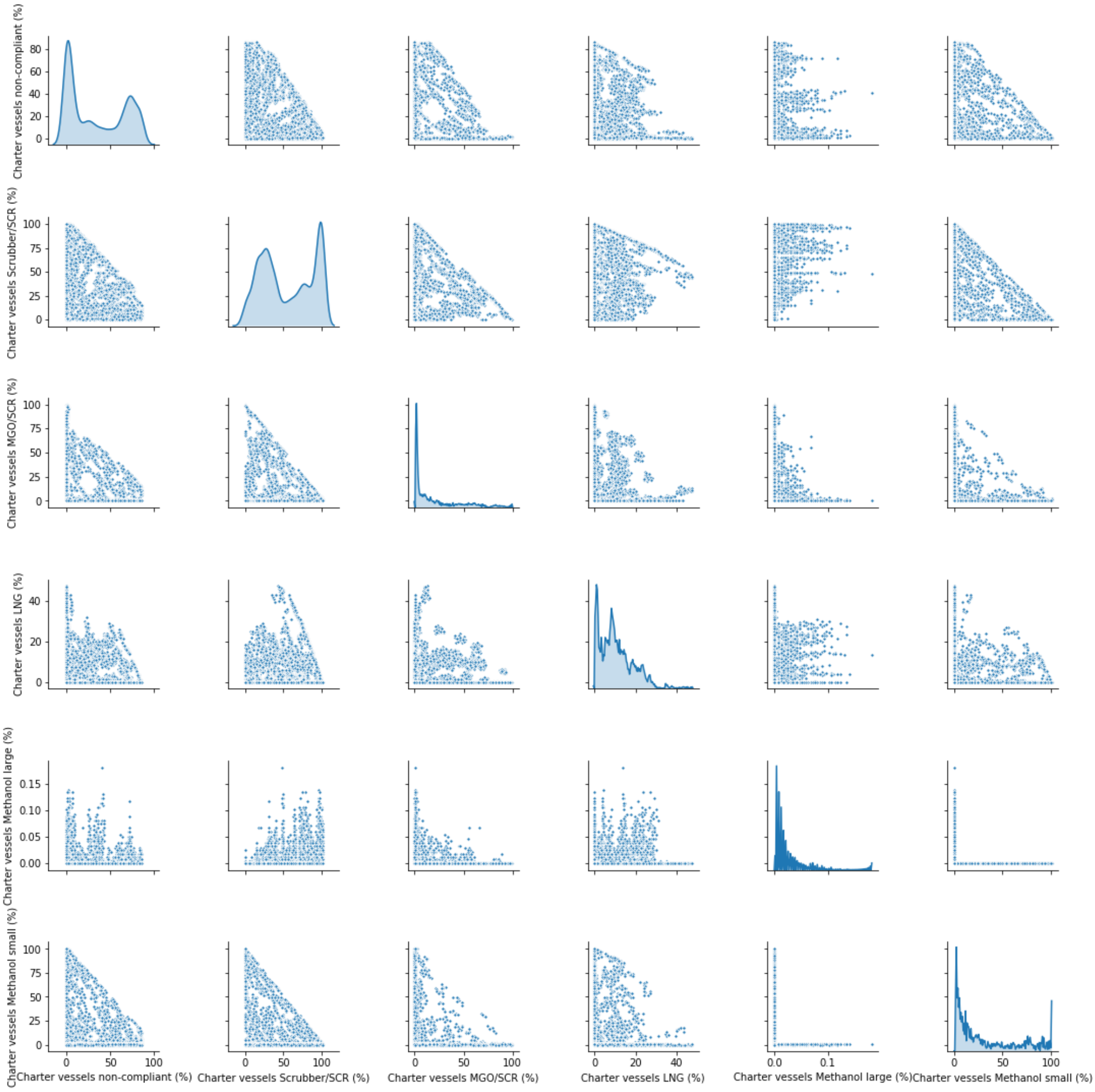
Relation between output variables

The plots depicted in this section show the relations between output. The plot depicted on the diagonals depict the KDE. The values shown are the end values of each model run.

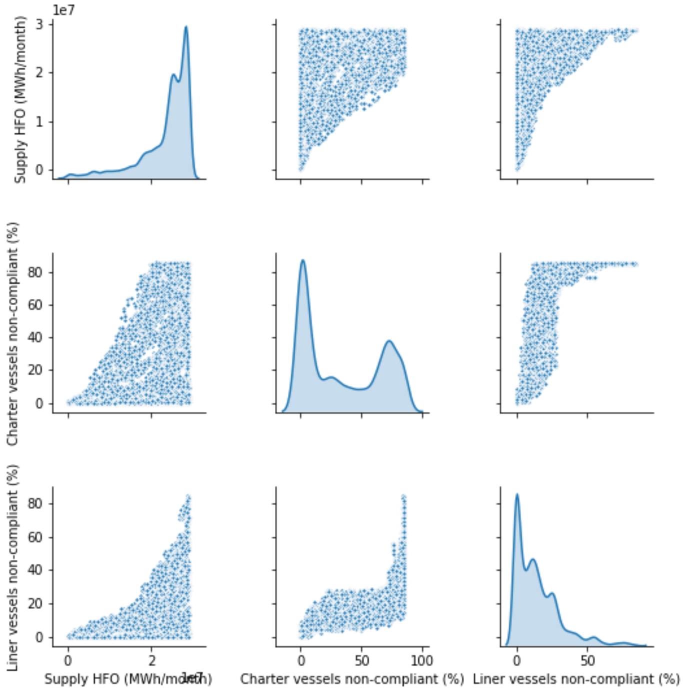


Relation between emission abetment technology of charter vessels

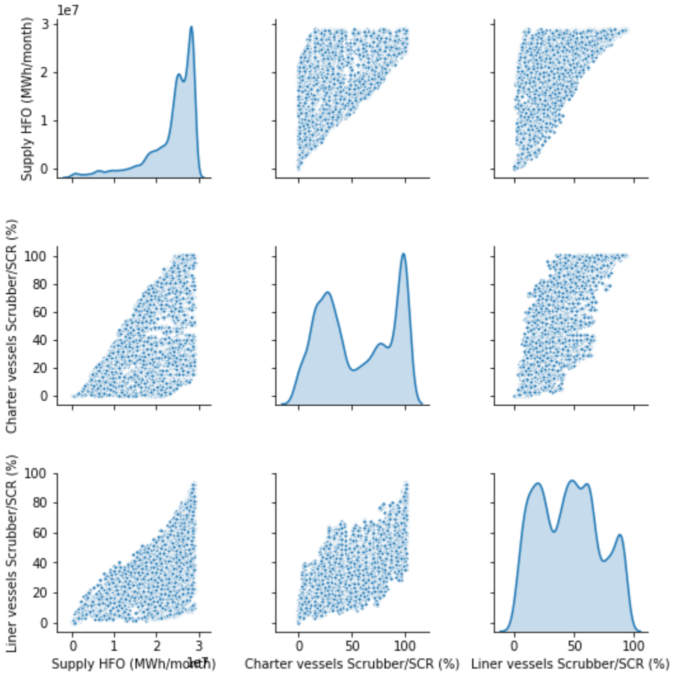

Liner vessels non-compliant (%)
Liner vessels Scrubber/SCR (%)
Liner vessels MGO/SCR (%)
Liner vessels LNG (%)
Liner vessels Methanol large (%)
Liner vessels Methanol small (%)



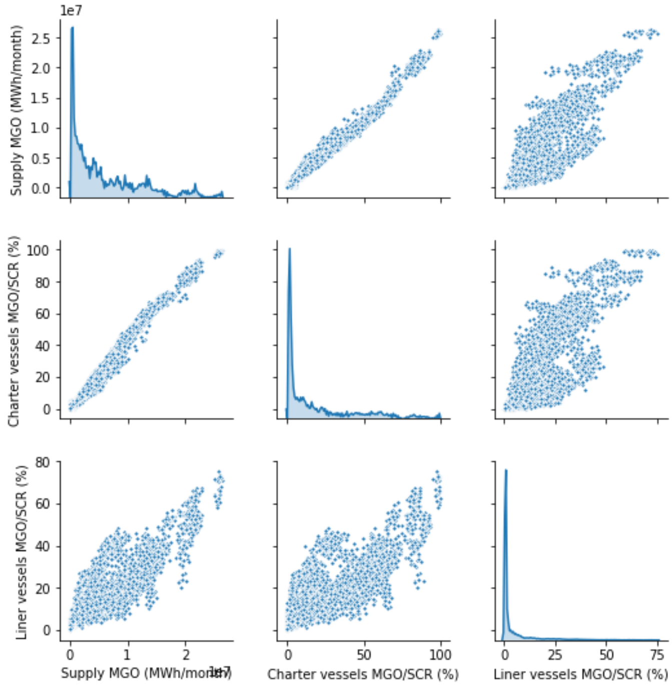
Relation between emission abetment technology of liner vessels



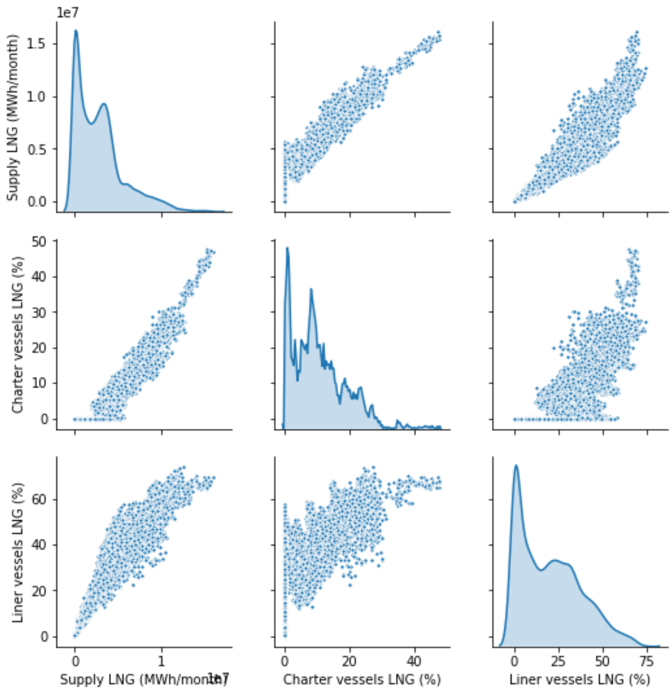
Relation between HFO supply and non-compliant vessels



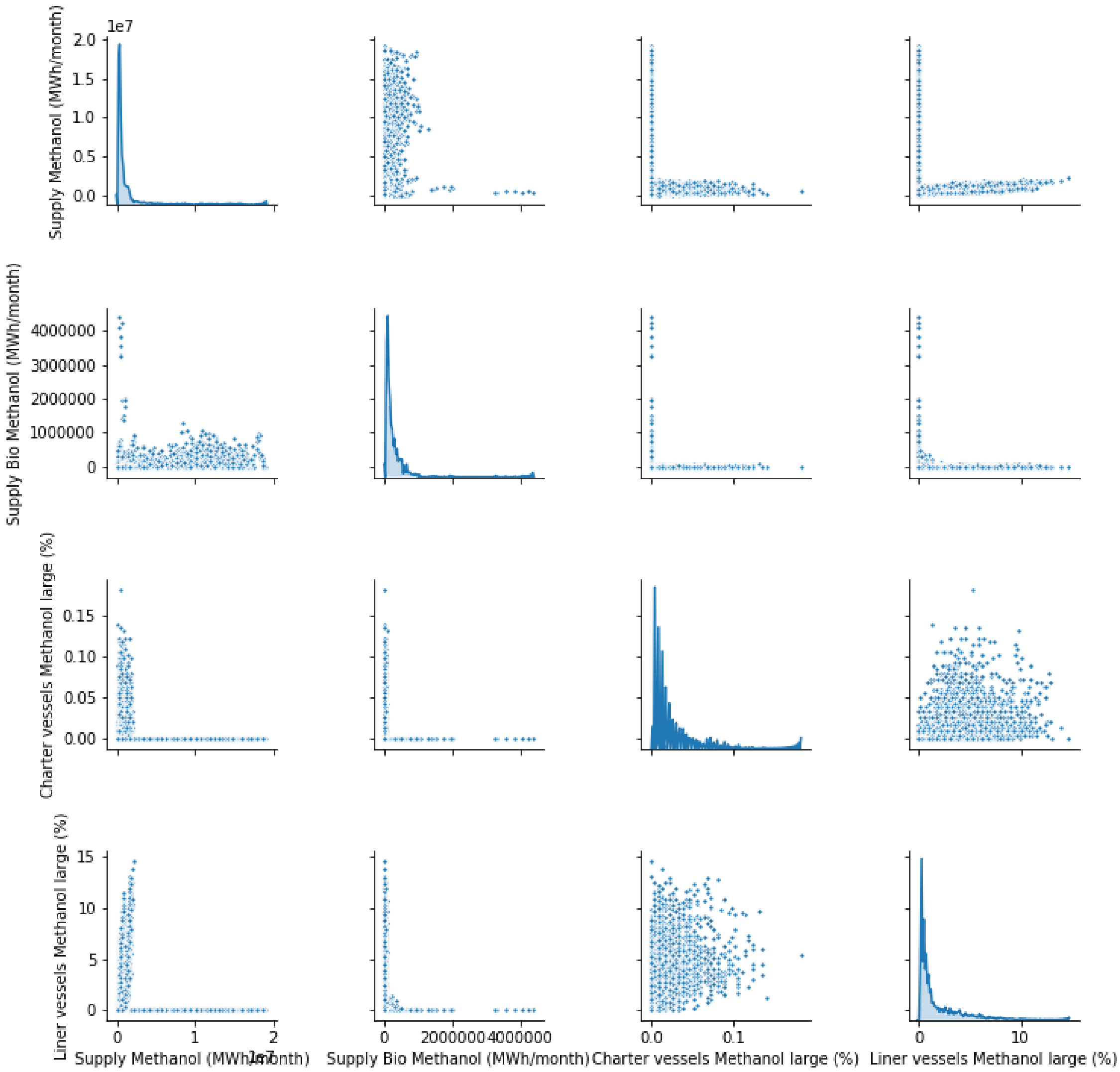
Relation between HFO supply and scrubber/SCR vessels



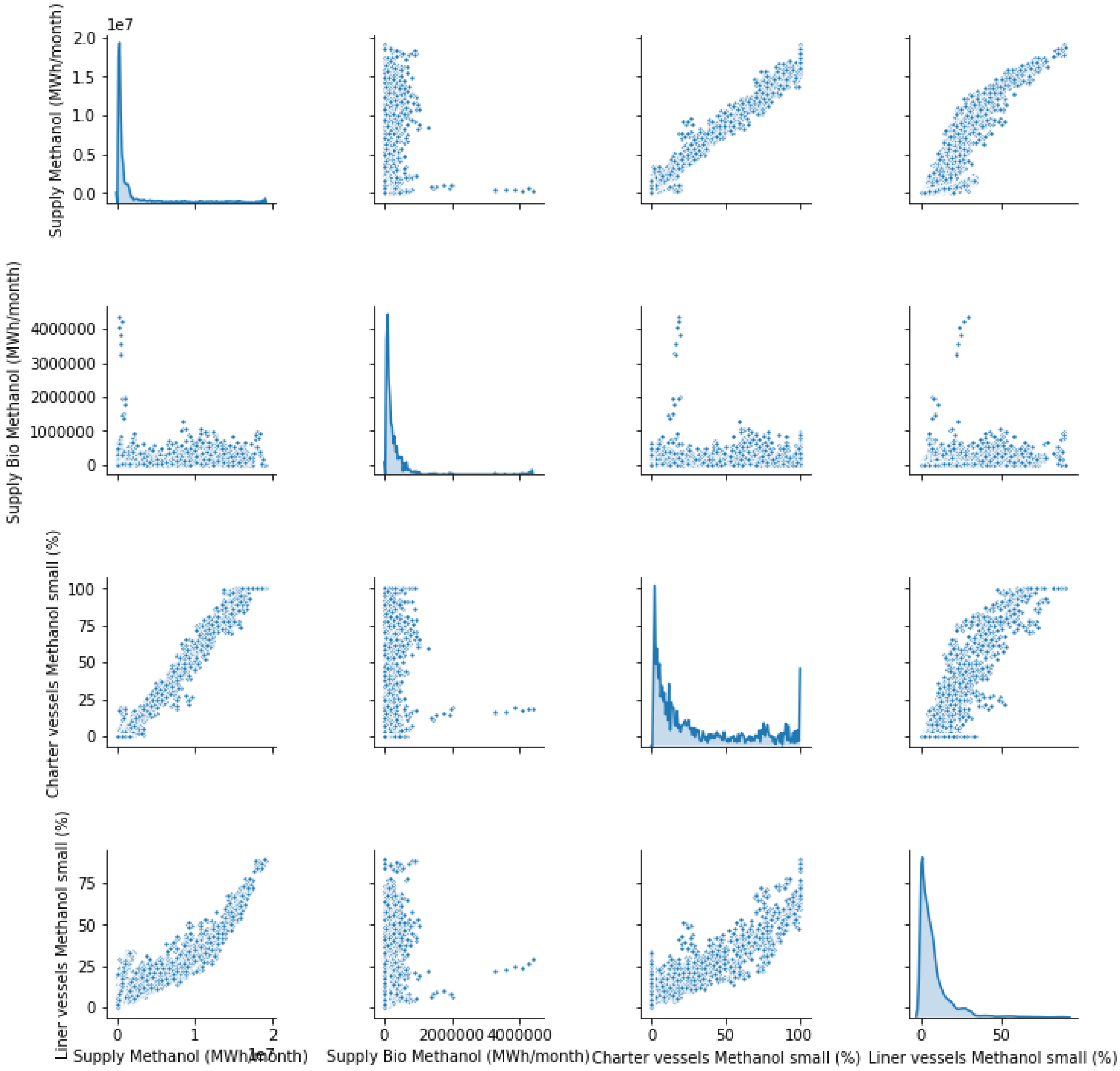
Relation between MGO supply and MGO/SCR vessels



Relation between LNG supply and LNG vessels



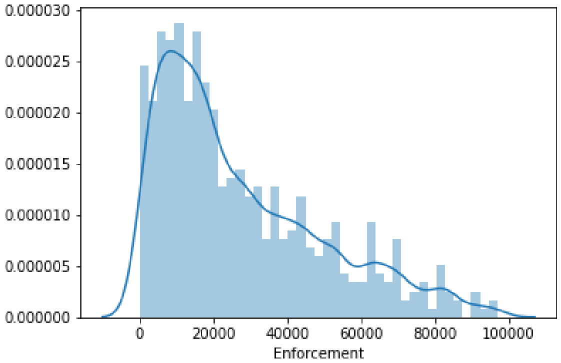
Relation between (bio) methanol supply and methanol large fuel tank vessels



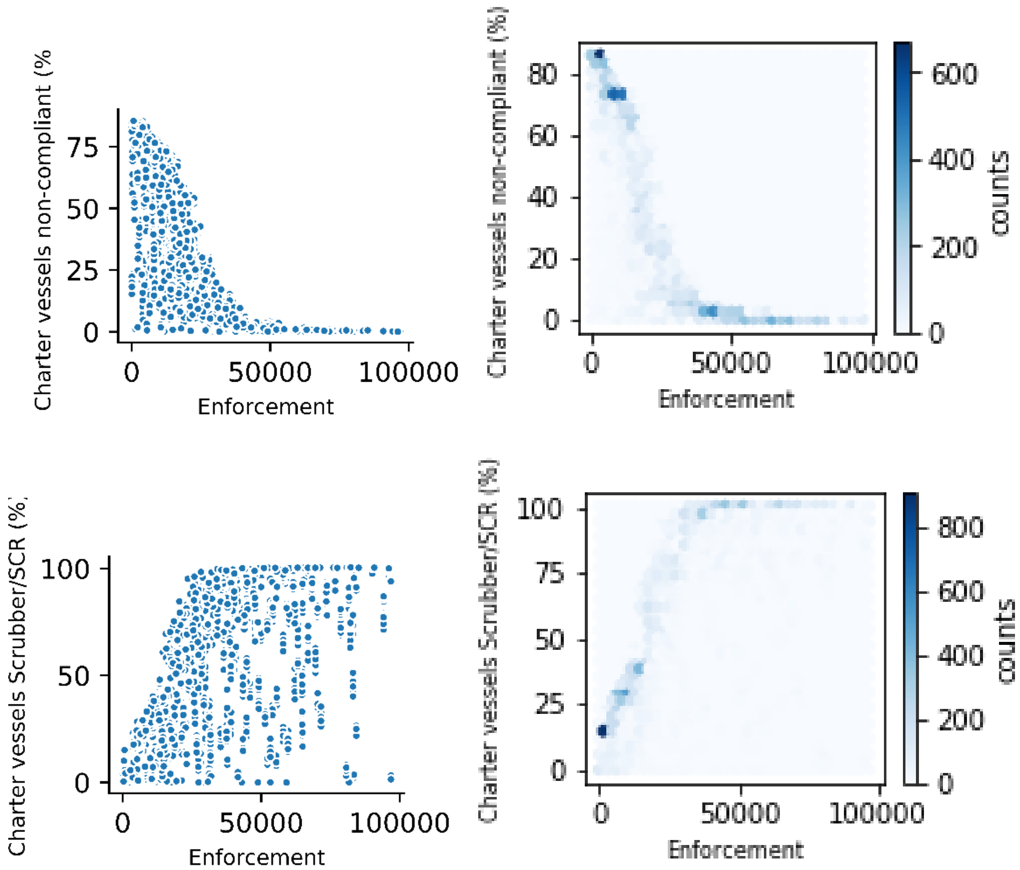
Relation between (bio) methanol supply and methanol small fuel tank vessels

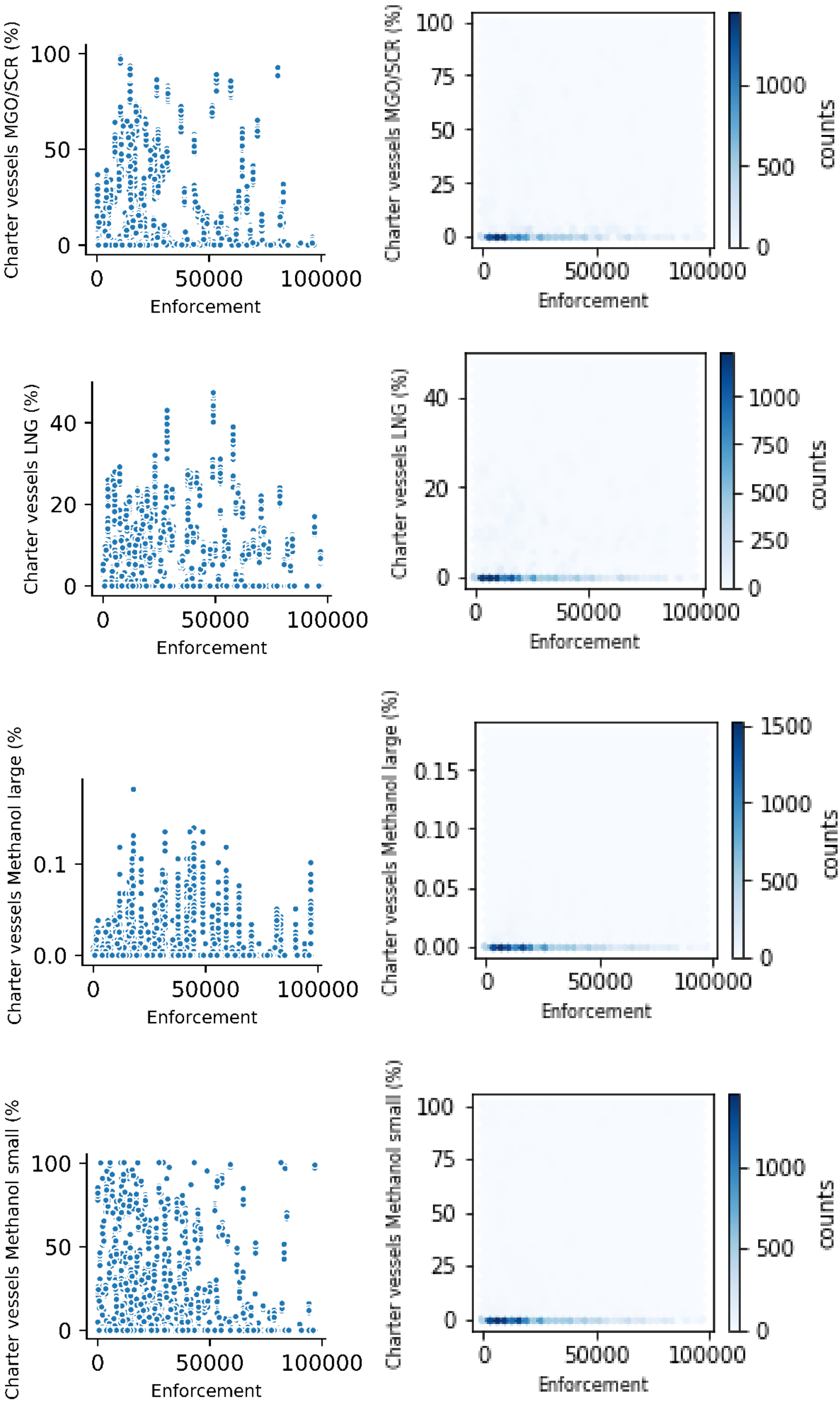
Regulation enforcement

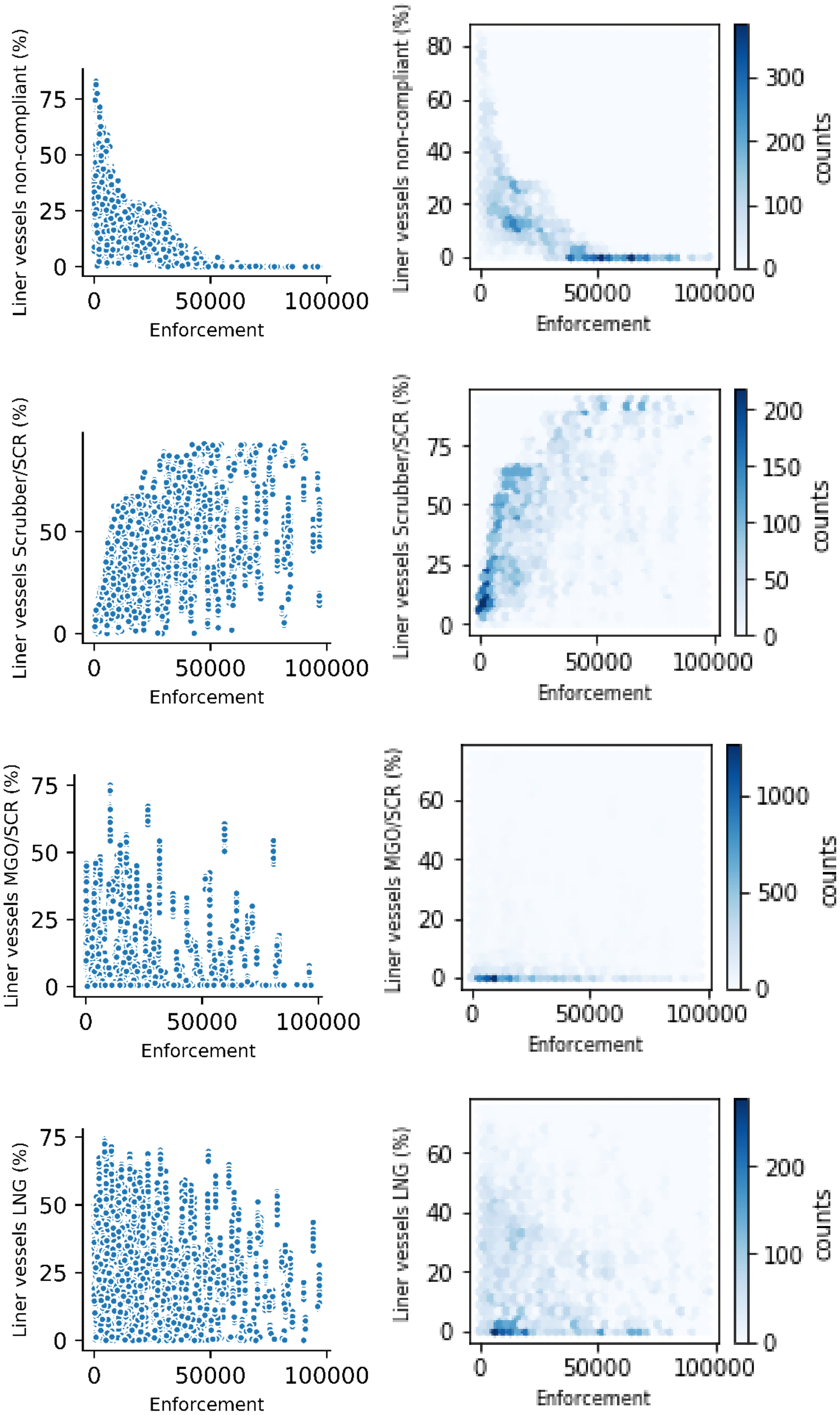
This section included the plots related to the regulation enforcement. The first plot shows the distribution of the amount of enforcement in the experiments. Since the variable enforcement is created by multiplying the variables "fine" and "control percentage", many experiments exist with a lower enforcement, that with a higher enforcement. The distribution of the amount of enforcement between the experiments is thus not uniform. This should be taken into account when interpreting the plots. For this reason, both a scatterplot and a hexbin plot show the relation between the amount of enforcement and vessels with a certain emission abatement technology.



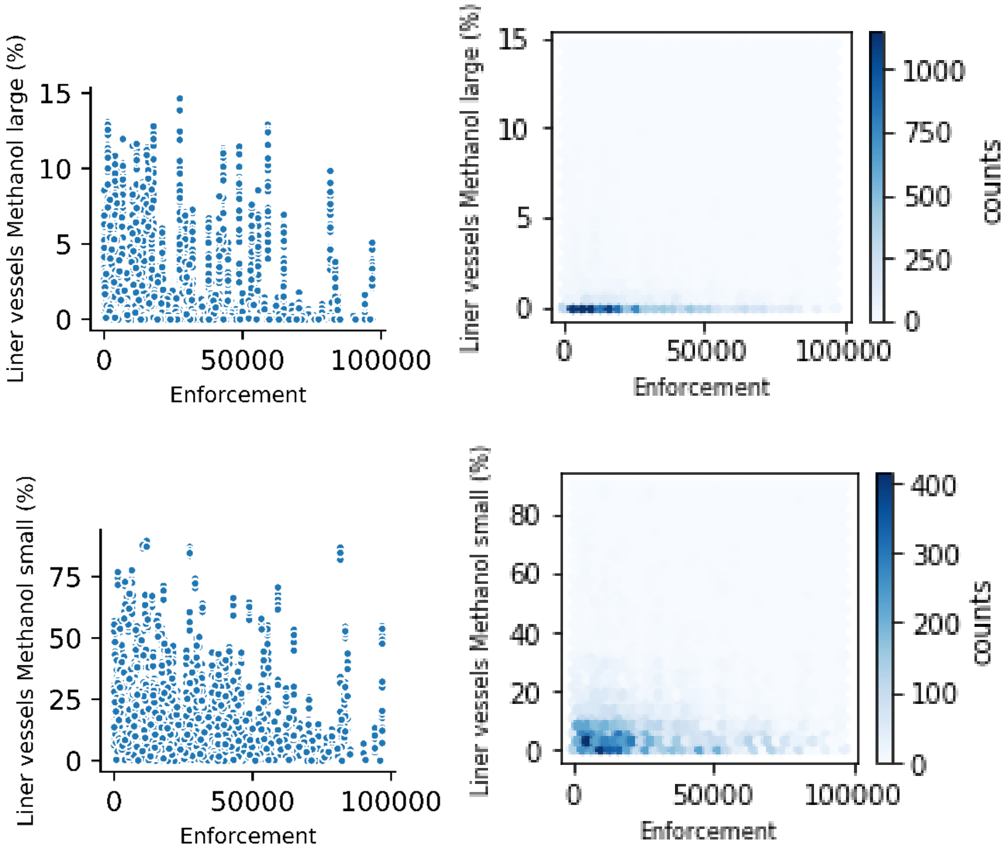
Distribution of the amount of enforcement in the experiments




Charter vessels MGO/SCR (%)
Enforcement
counts
Charter vessels LNG (%)
Enforcement
counts
Charter vessels Methanol large (%
Charter vessels Methanol large (%)
Enforcement
counts
Charter vessels Methanol small (%
Charter vessels Methanol small (%)
Enforcement
counts

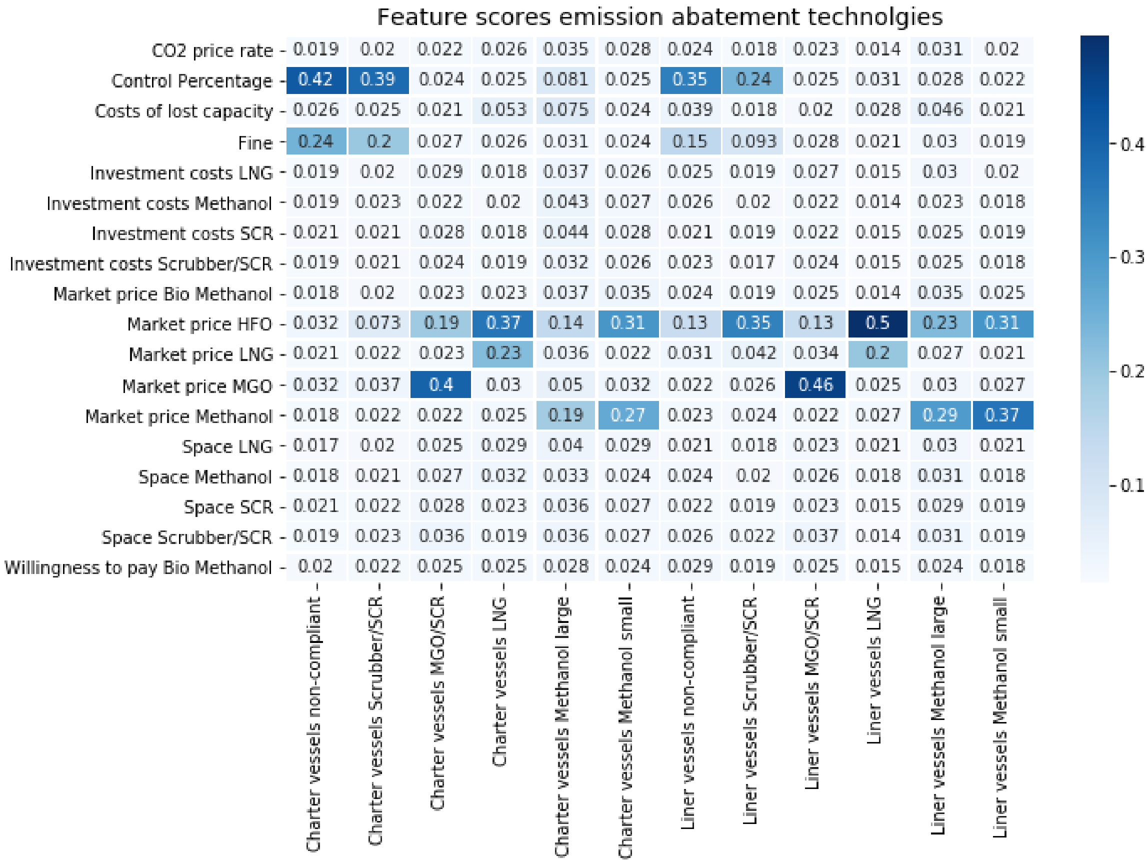


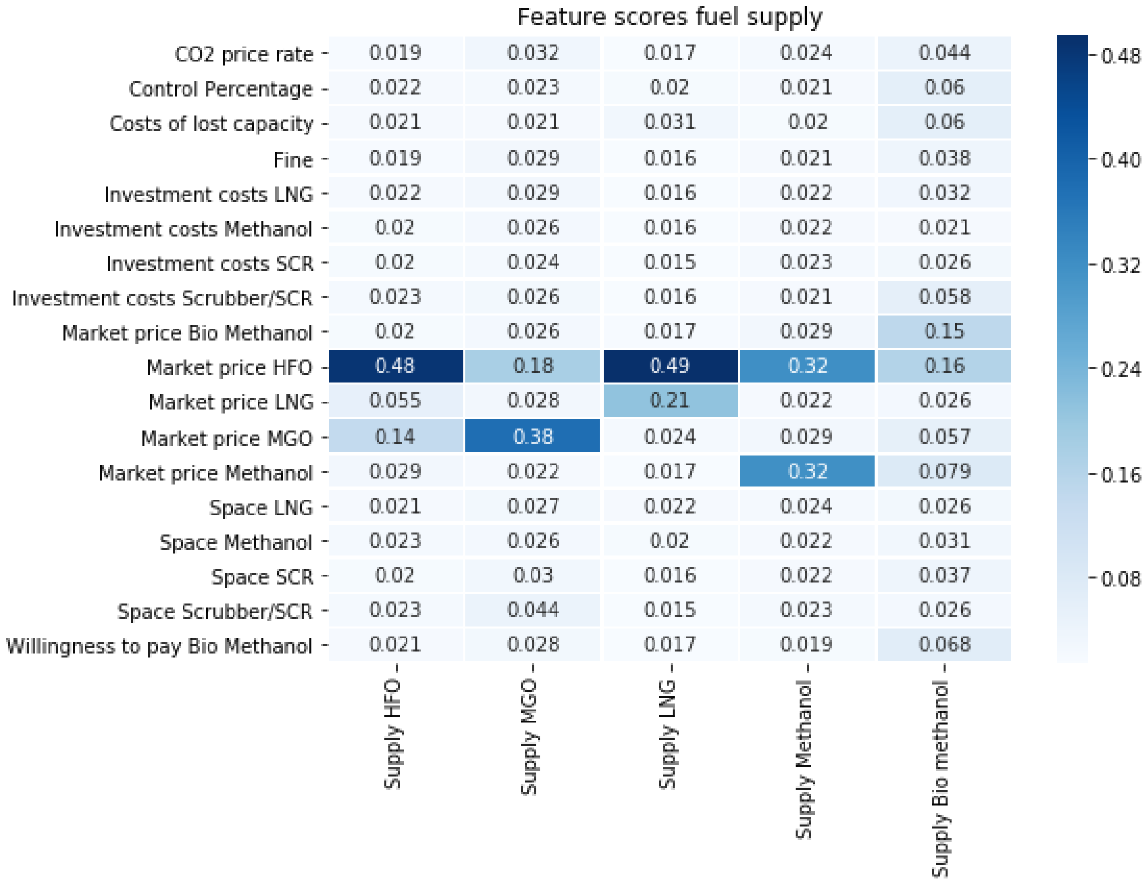
Liner vessels non-compliant (%)
Enforcement
counts
Liner vessels Scrubber/SCR (%)
Enforcement
counts
Liner vessels MGO/SCR (%)
Enforcement
counts
Liner vessels LNG (%)
Enforcement
counts


Liner vessels Methanol large (%)
15
10
5
0
0
50000
100000
Enforcement
Liner vessels Methanol large (%)
15
10
5
0
0
50000
100000
Enforcement
1000
750
500
250
0
counts
Liner vessels Methanol small (%)
75
50
25
0
0
50000
100000
Enforcement
Liner vessels Methanol small (%)
80
60
40
20
0
0
50000
100000
Enforcement
400
300
200
100
0
counts

Appendix I: Feature Scores

This appendix presents the results of the feature score analysis of each outcome of interest. The variables on the y-axis relate to the uncertainties, and the values on the x-axis to the outcomes of interests. The values and colours of each cell indicate the influence of the uncertainty on the y-axis on the outcome on the x-axis.

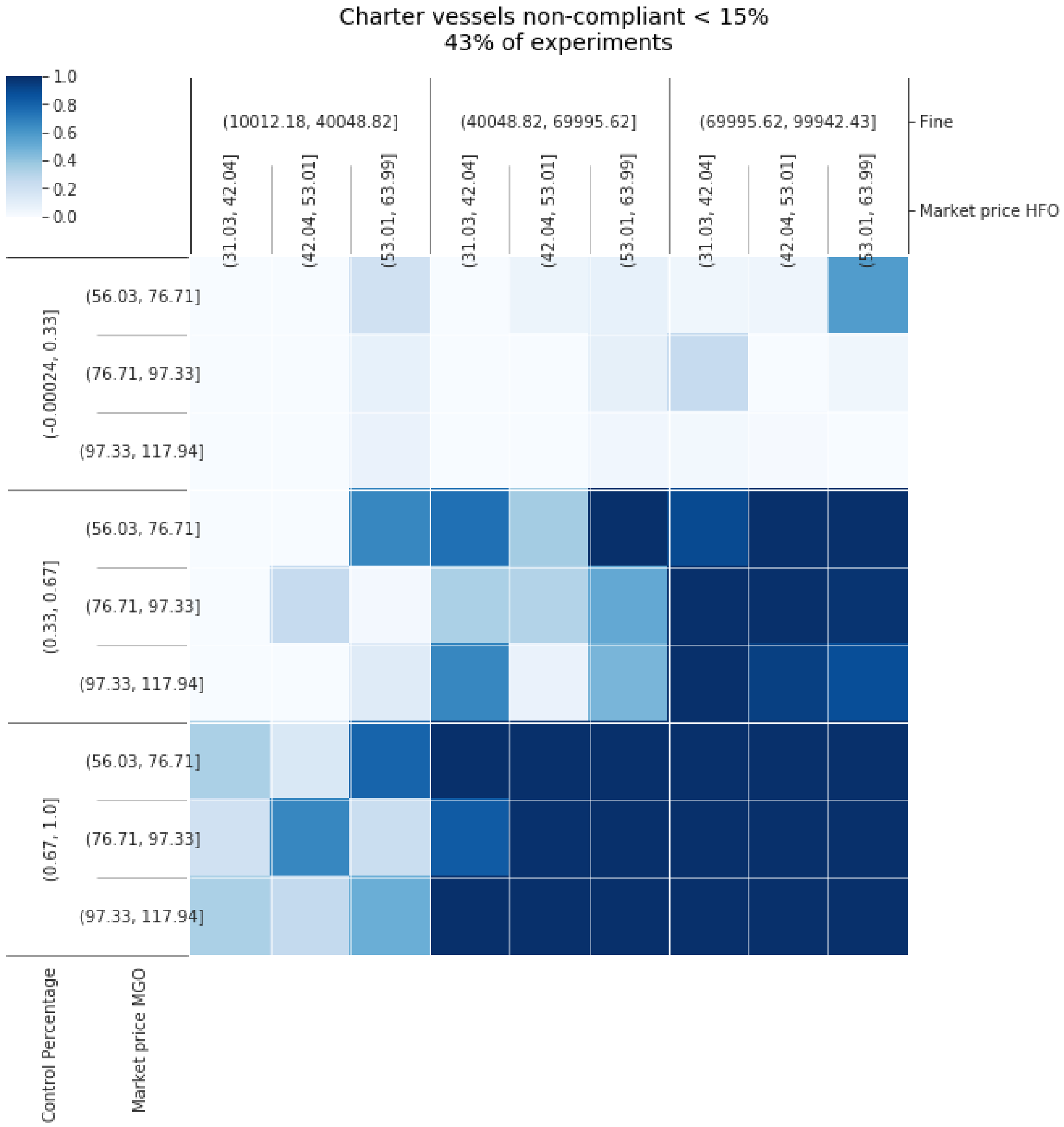


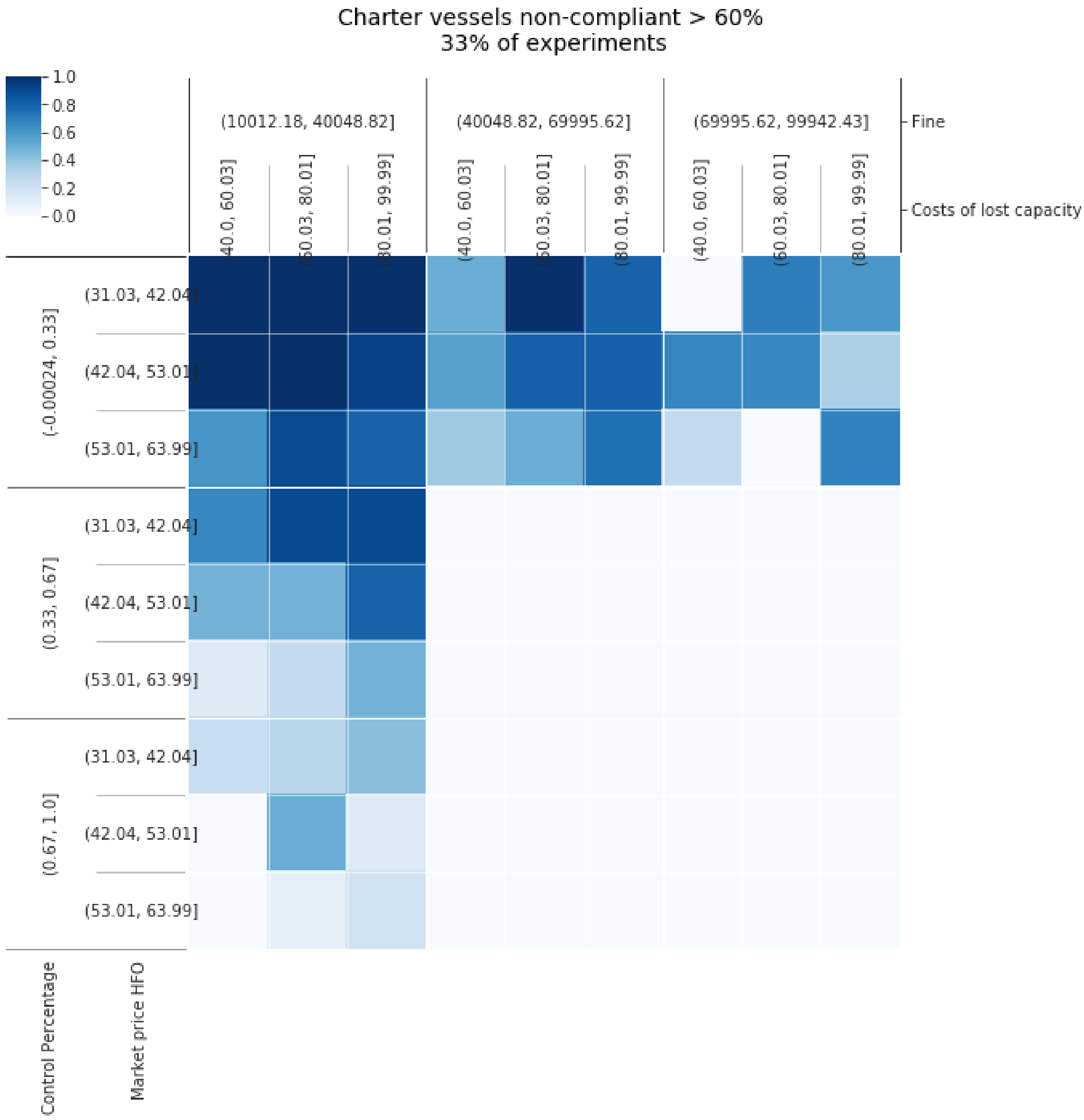

Feature scores fuel supply
CO2 price rate 0.019 0.032 0.017 0.024 0.044
Control Percentage 0.022 0.023 0.02 0.021 0.06
Costs of lost capacity 0.021 0.021 0.031 0.02 0.06
Fine 0.019 0.029 0.016 0.021 0.038
Investment costs LNG 0.022 0.029 0.016 0.022 0.032
Investment costs Methanol 0.02 0.026 0.016 0.022 0.021
Investment costs SCR 0.02 0.024 0.015 0.023 0.026
Investment costs Scrubber/SCR 0.023 0.026 0.016 0.021 0.058
Market price Bio Methanol 0.02 0.026 0.017 0.029 0.15
Market price HFO 0.48 0.18 0.49 0.32 0.16
Market price LNG 0.055 0.028 0.21 0.022 0.026
Market price MGO 0.14 0.38 0.024 0.029 0.057
Market price Methanol 0.029 0.022 0.017 0.32 0.079
Space LNG 0.021 0.027 0.022 0.024 0.026
Space Methanol 0.023 0.026 0.02 0.022 0.031
Space SCR 0.02 0.03 0.016 0.022 0.037
Space Scrubber/SCR 0.023 0.044 0.015 0.023 0.026
Willingness to pay Bio Methanol 0.021 0.028 0.017 0.019 0.068
Supply HFO
Supply MGO
Supply LNG
Supply Methanol
Supply Bio methanol
0.48
0.40
0.32
0.24
0.16
0.08

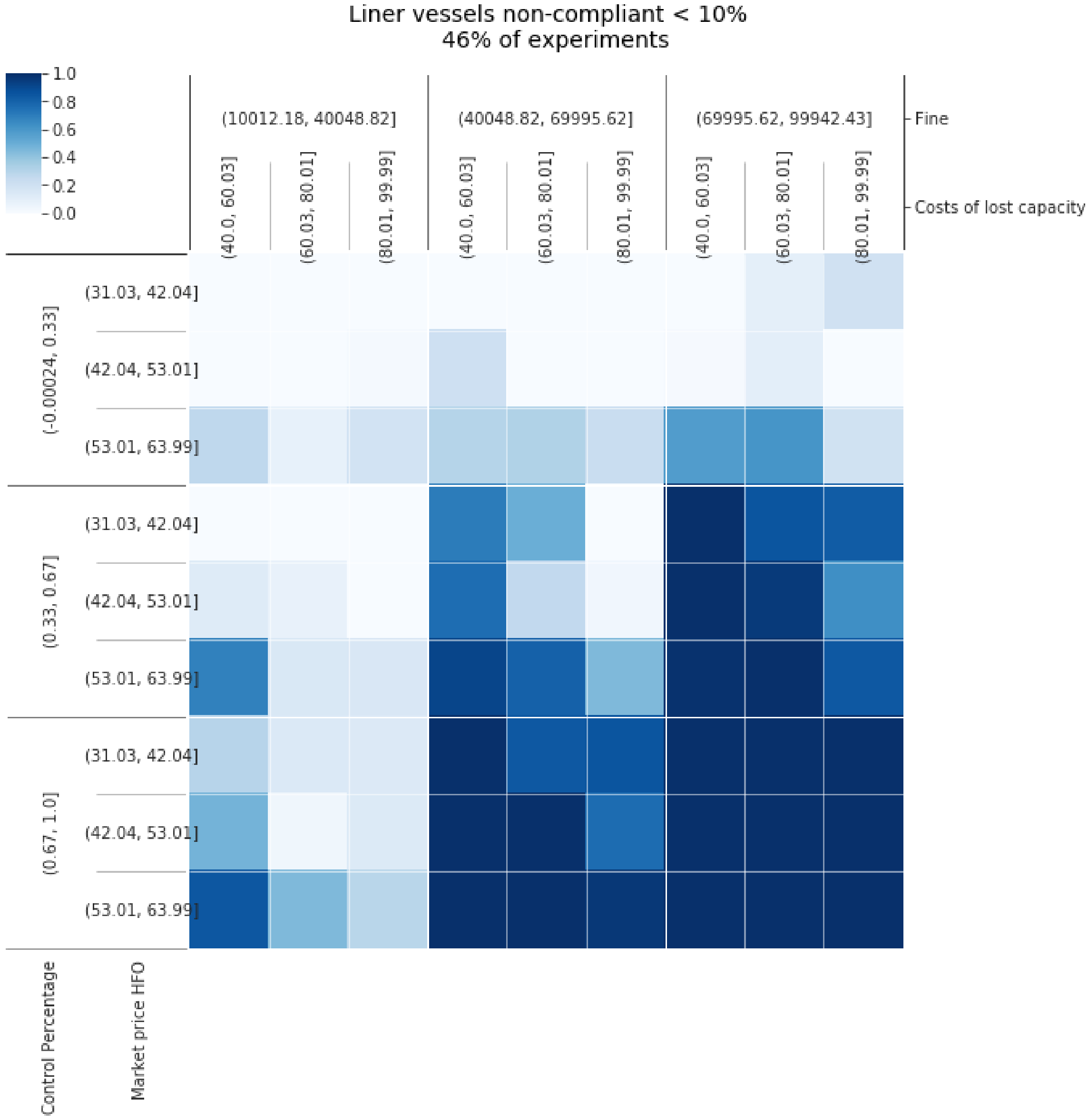

Feature scores % Bunker calls Rotterdam
Market price Methanol 0.31
Market price HFO 0.27
Market price MGO 0.047
Market price Bio Methanol 0.033
Control Percentage 0.028
Willingness to pay Bio Methanol 0.027
Space Methanol 0.025
Investment costs Methanol 0.025
Costs of lost capacity 0.025
Space LNG 0.024
Space Scrubber/SCR 0.024
Fine 0.024
Market price LNG 0.024
Investment costs Scrubber/SCR 0.022
CO2 price rate 0.022
Investment costs SCR 0.022
Investment costs LNG 0.022
Space SCR 0.022
0
Bunker calls Rotterdam
0.30
0.25
0.20
0.15
0.10
0.05

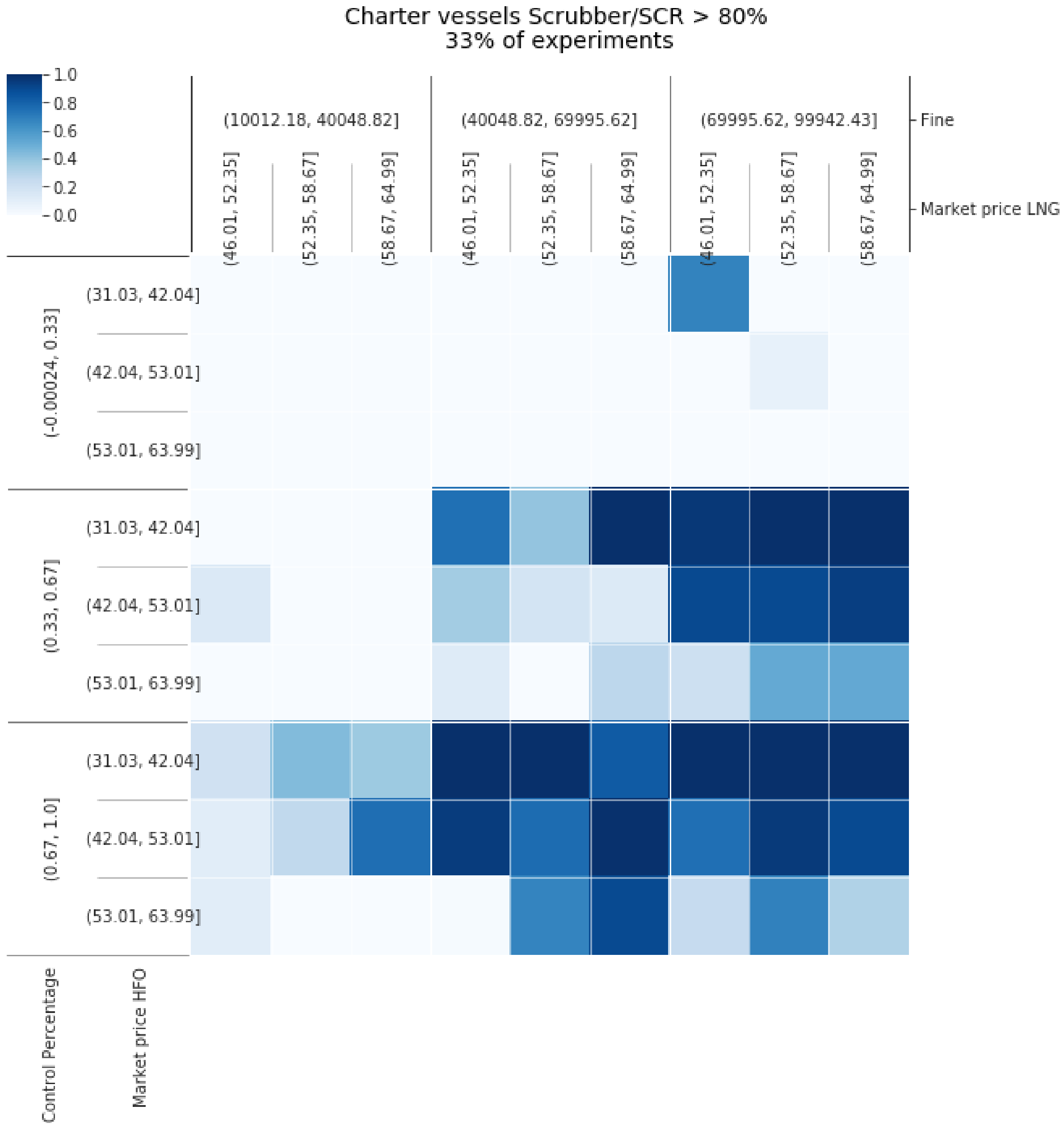
Appendix J: Dimensional stacking

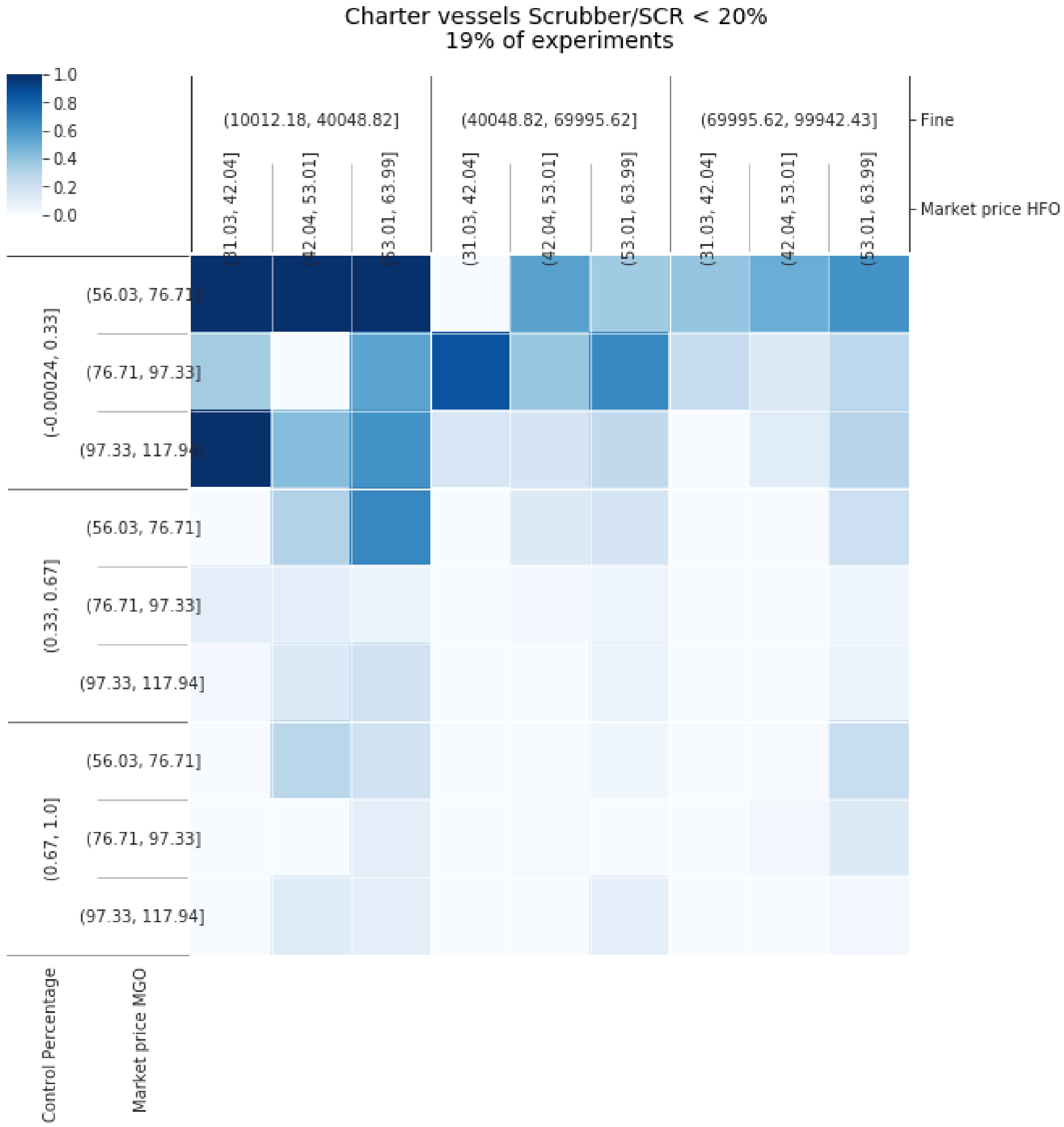
By means of scenarios discovery, combinations of uncertain parameters and policies which results in regions of interests in the outcome space are identified. A method that enables to easily find these scenarios is dimensional stacking. This appendix contains the dimensional stack plots. The parameters related to the uncertainties, as well as parameters related to the policies are included in this analysis. The outcomes on the x-axis and y-axis show the most influential variables for the outcomes of interests. The darkness of each cell relates to the region in which most outcomes of interest can be found

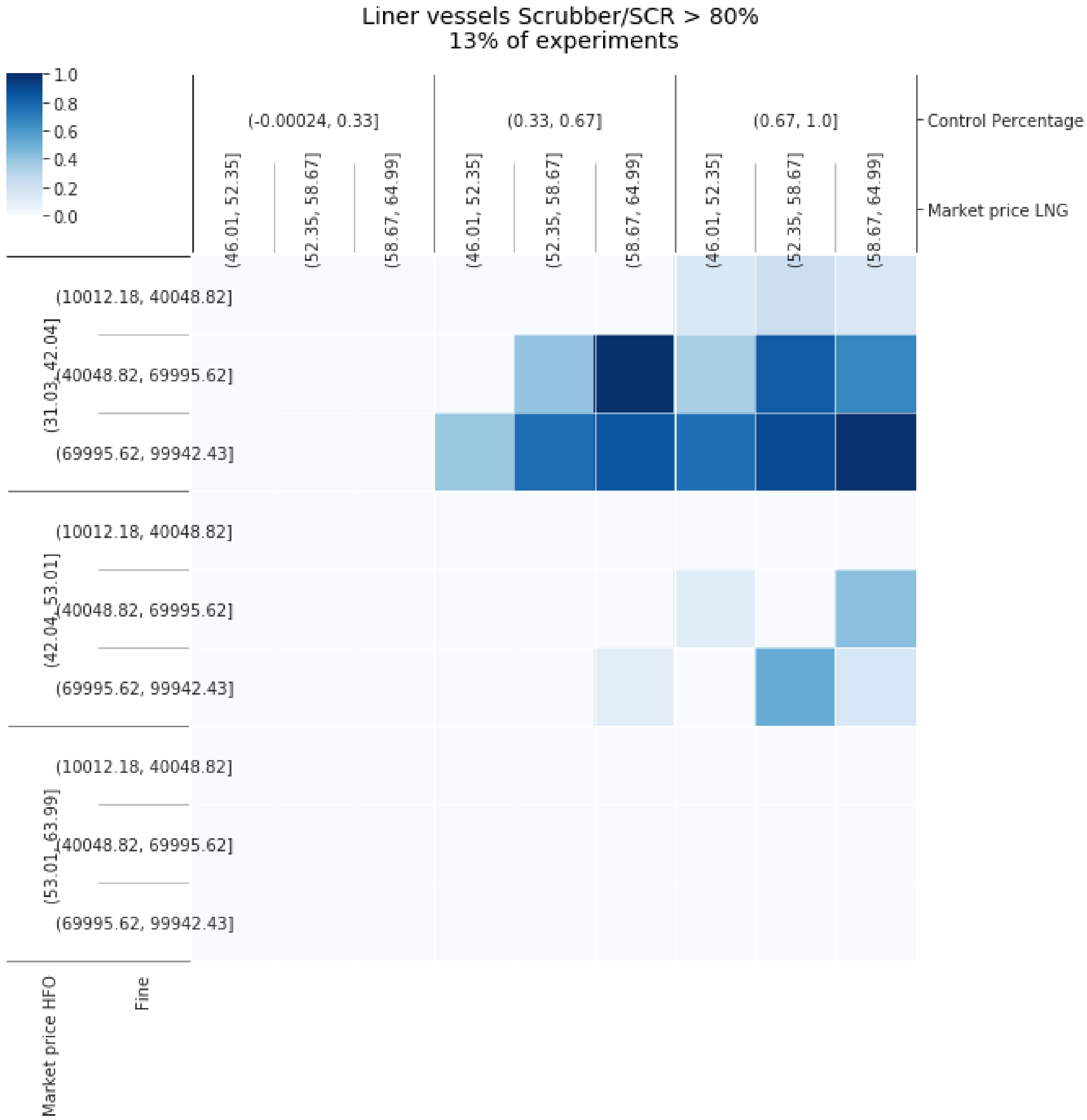


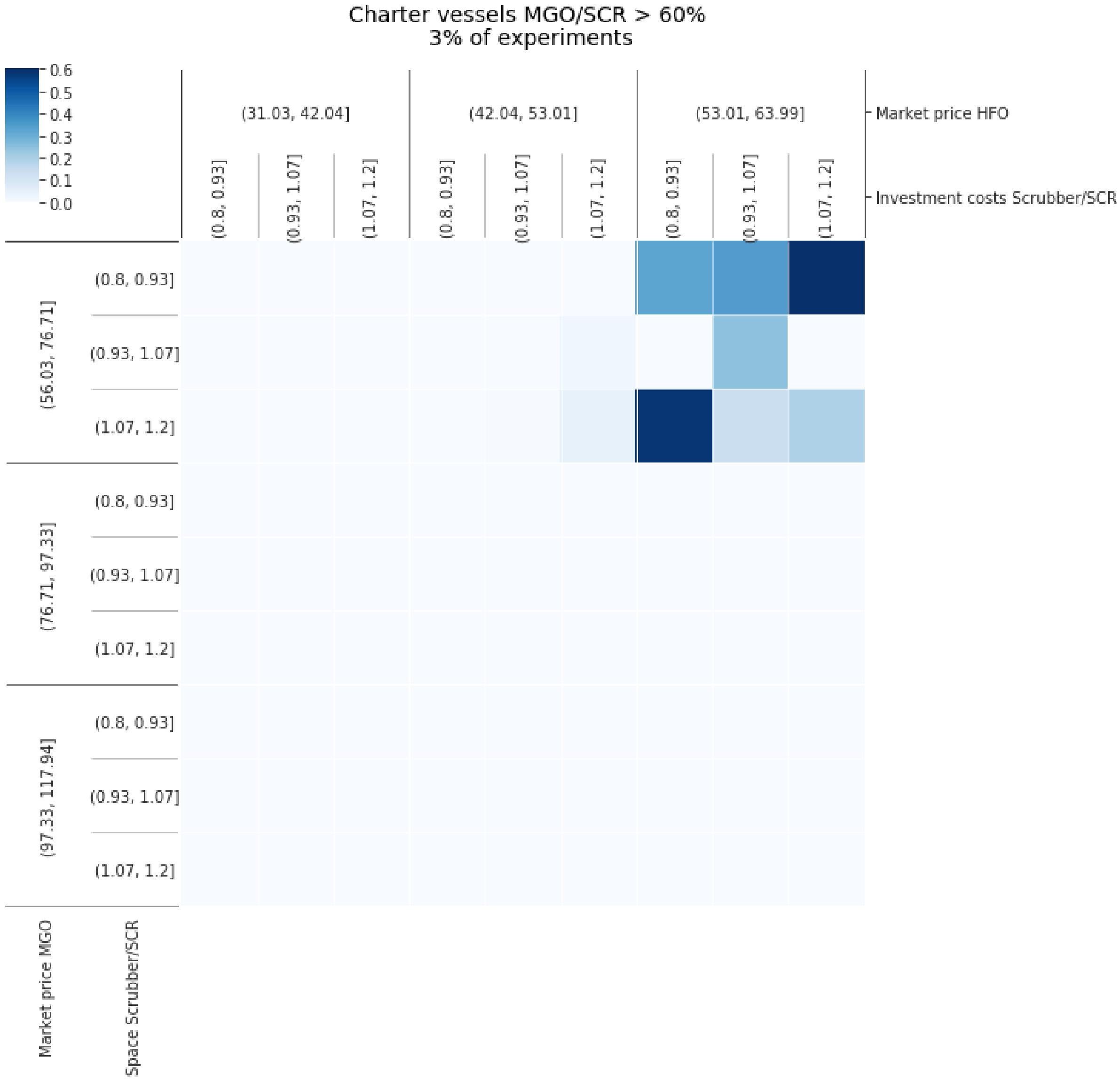

Charter vessels non-compliant > 60%
33% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(10012.18, 40048.82]
(40048.82, 69995.62]
(69995.62, 99942.43]
Fine
(40.0, 60.03]
(60.03, 80.01]
(80.01, 99.99]
Costs of lost capacity
(-0.00024, 0.33]
(0.33, 0.67]
(0.67, 1.0]
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Control Percentage
Market price HFO

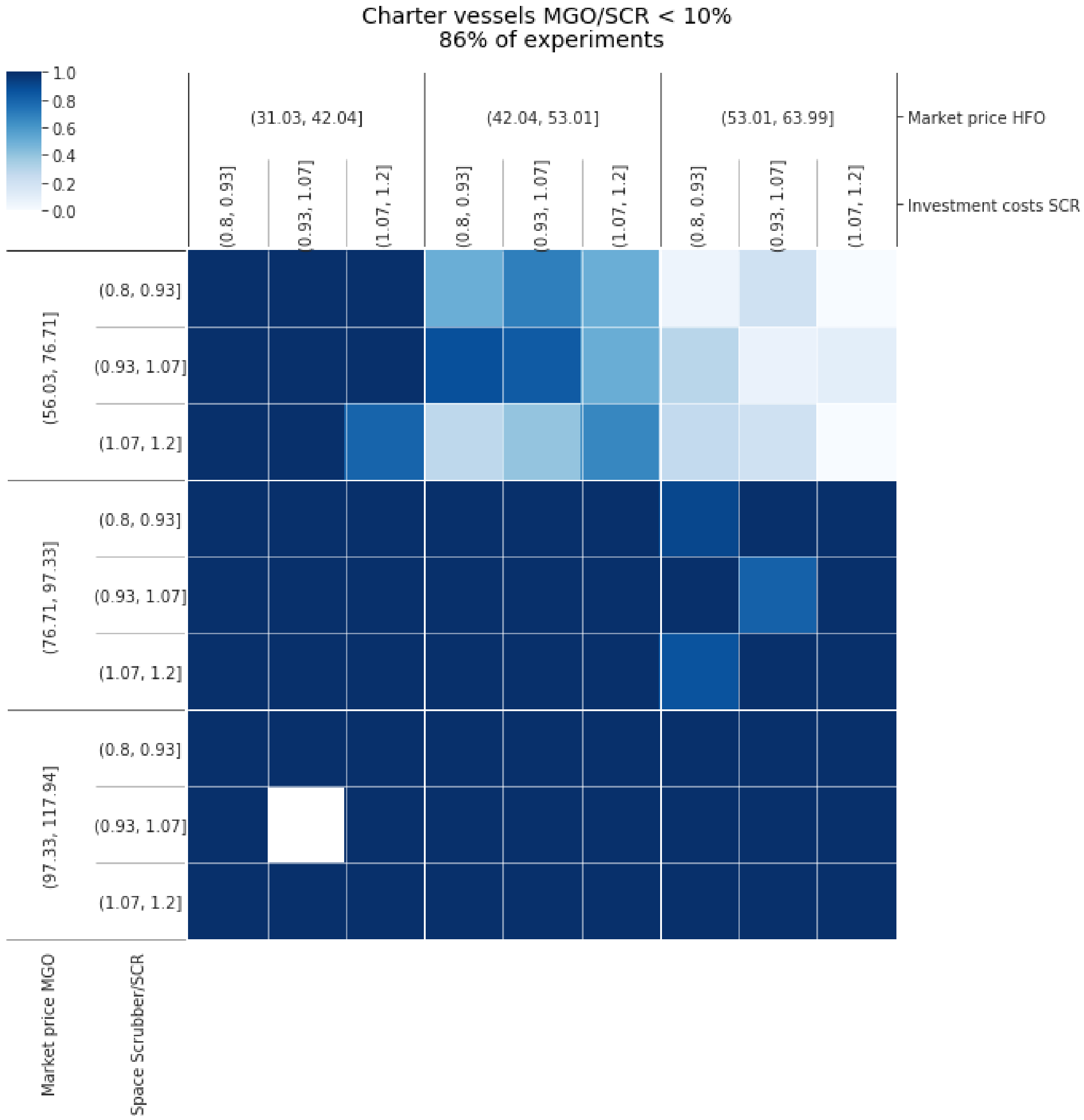

Liner vessels non-compliant < 10%
46% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(10012.18, 40048.82]
(40048.82, 69995.62]
(69995.62, 99942.43]
Fine
(40.0, 60.03]
(60.03, 80.01]
(80.01, 99.99]
Costs of lost capacity
(-0.00024, 0.33]
(0.33, 0.67]
(0.67, 1.0]
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Control Percentage
Market price HFO

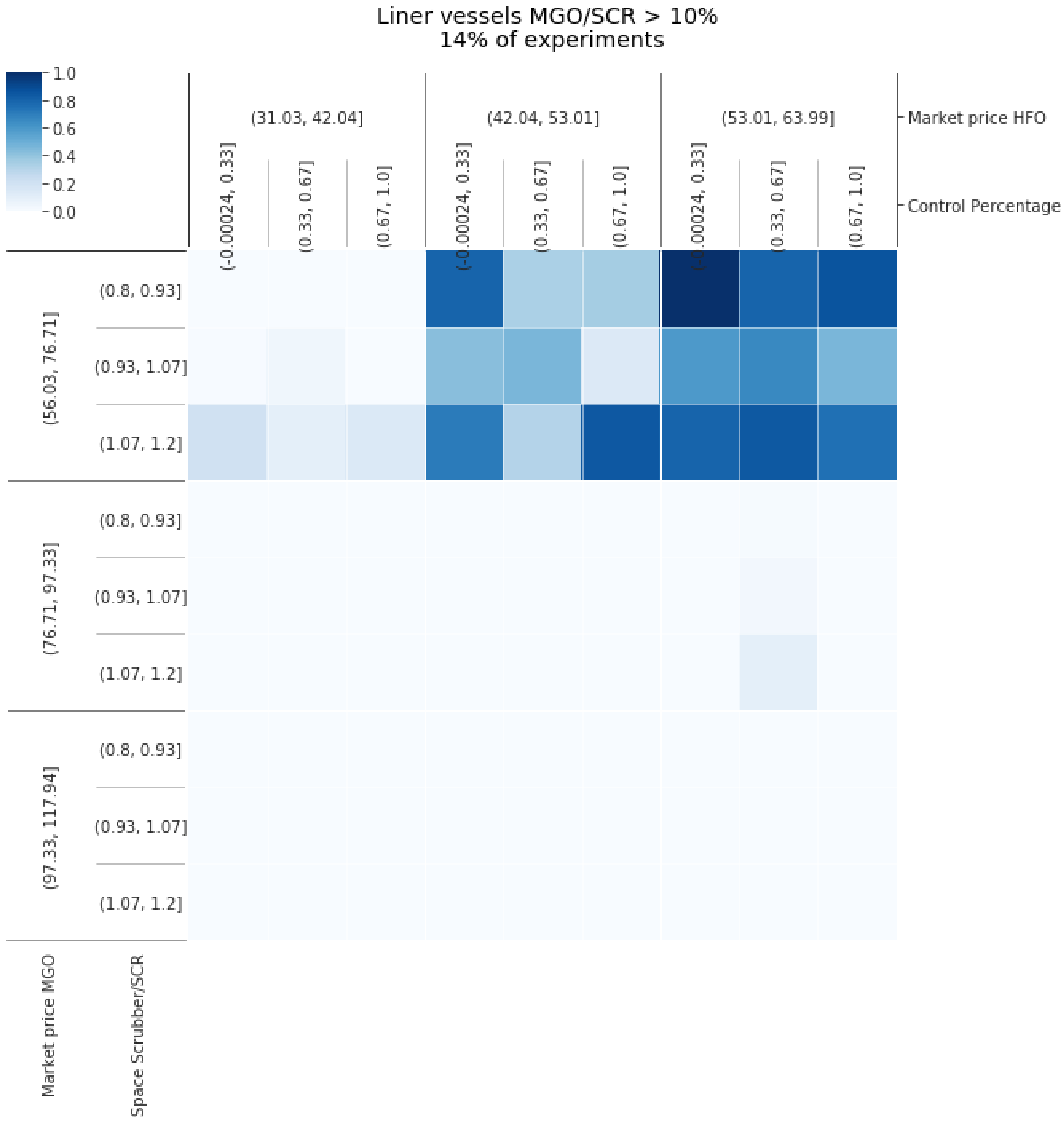

Charter vessels Scrubber/SCR > 80%
33% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(10012.18, 40048.82]
(40048.82, 69995.62]
(69995.62, 99942.43]
Fine
(46.01, 52.35]
(52.35, 58.67]
(58.67, 64.99]
Market price LNG
(-0.00024, 0.33]
(0.33, 0.67]
(0.67, 1.0]
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Control Percentage
Market price HFO

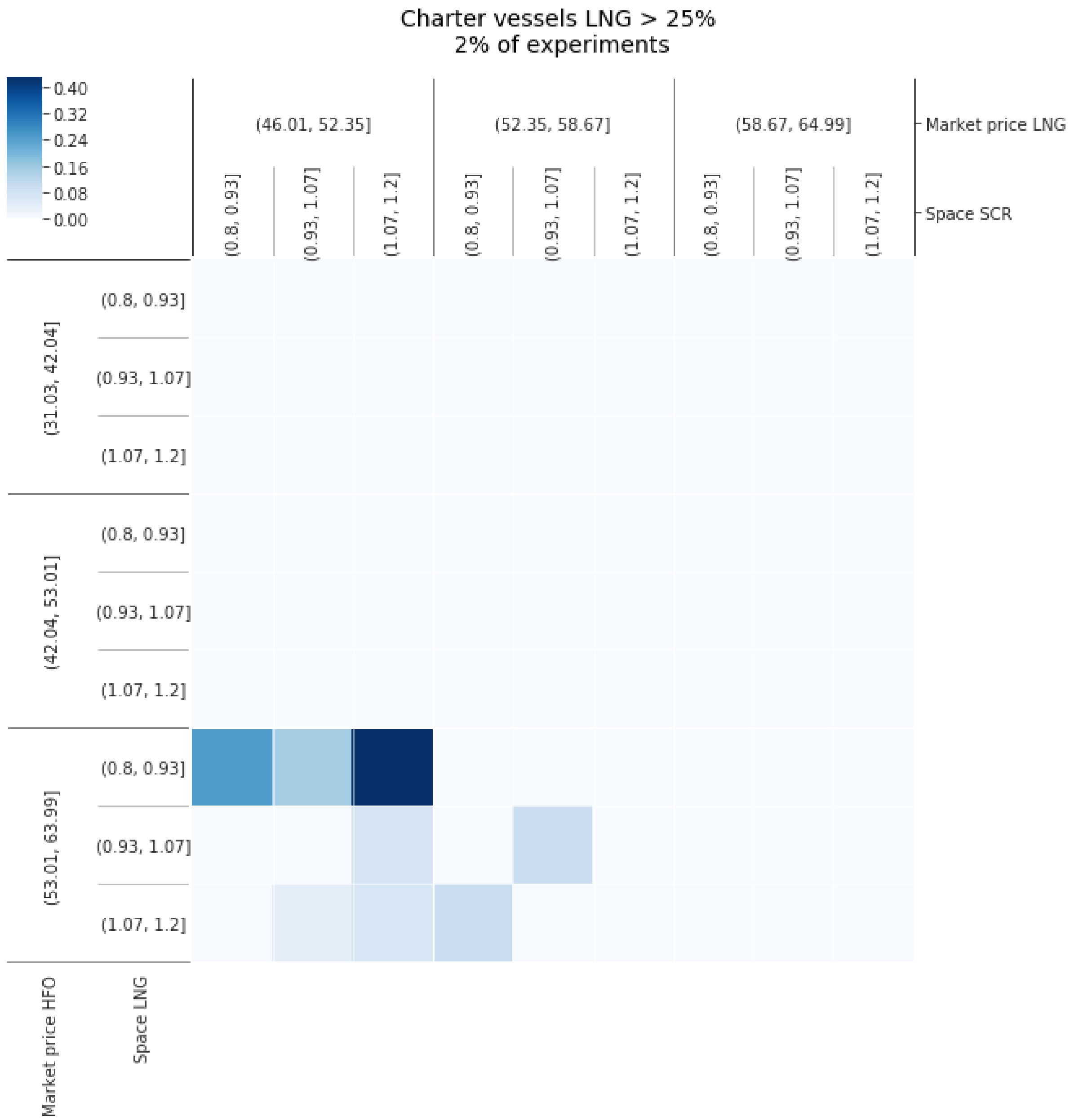

Charter vessels Scrubber/SCR < 20%
19% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(10012.18, 40048.82]
(40048.82, 69995.62]
(69995.62, 99942.43]
Fine
Market price HFO
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
(-0.00024, 0.33]
(0.33, 0.67]
(0.67, 1.0]
(56.03, 76.71]
(76.71, 97.33]
(97.33, 117.94]
Control Percentage
Market price MGO


Liner vessels Scrubber/SCR > 80%
13% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(-0.00024, 0.33]
(0.33, 0.67]
(0.67, 1.0]
Control Percentage
(46.01, 52.35]
(52.35, 58.67]
(58.67, 64.99]
Market price LNG
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
(10012.18, 40048.82]
(40048.82, 69995.62]
(69995.62, 99942.43]
Market price HFO
Fine

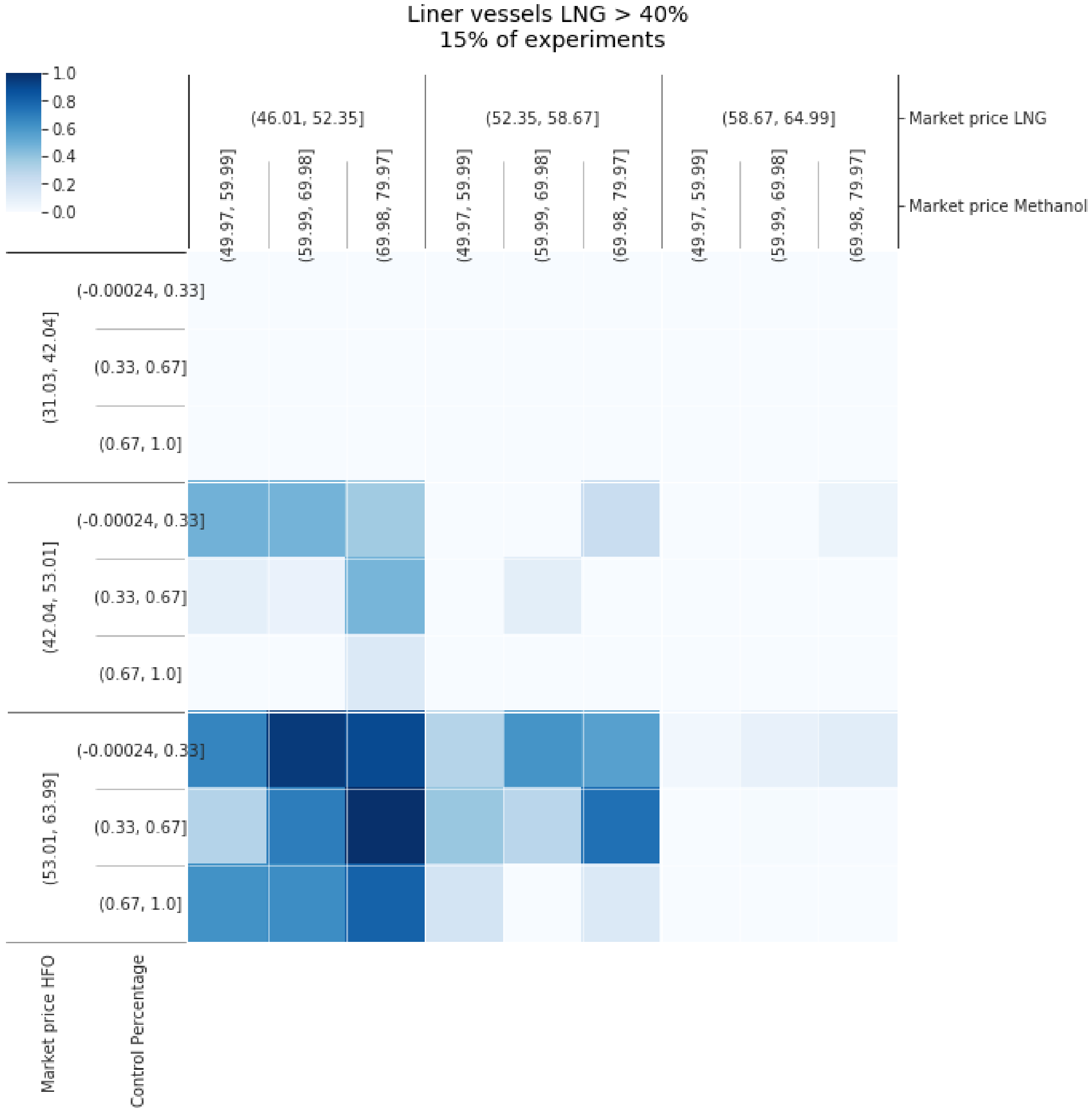

Charter vessels MGO/SCR > 60%
3% of experiments
0.6
0.5
0.4
0.3
0.2
0.1
0.0
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Market price HFO
(0.8, 0.93]
(0.93, 1.07]
(1.07, 1.2]
Investment costs Scrubber/SCR
(56.03, 76.71]
(76.71, 97.33]
(97.33, 117.94]
Market price MGO
Space Scrubber/SCR

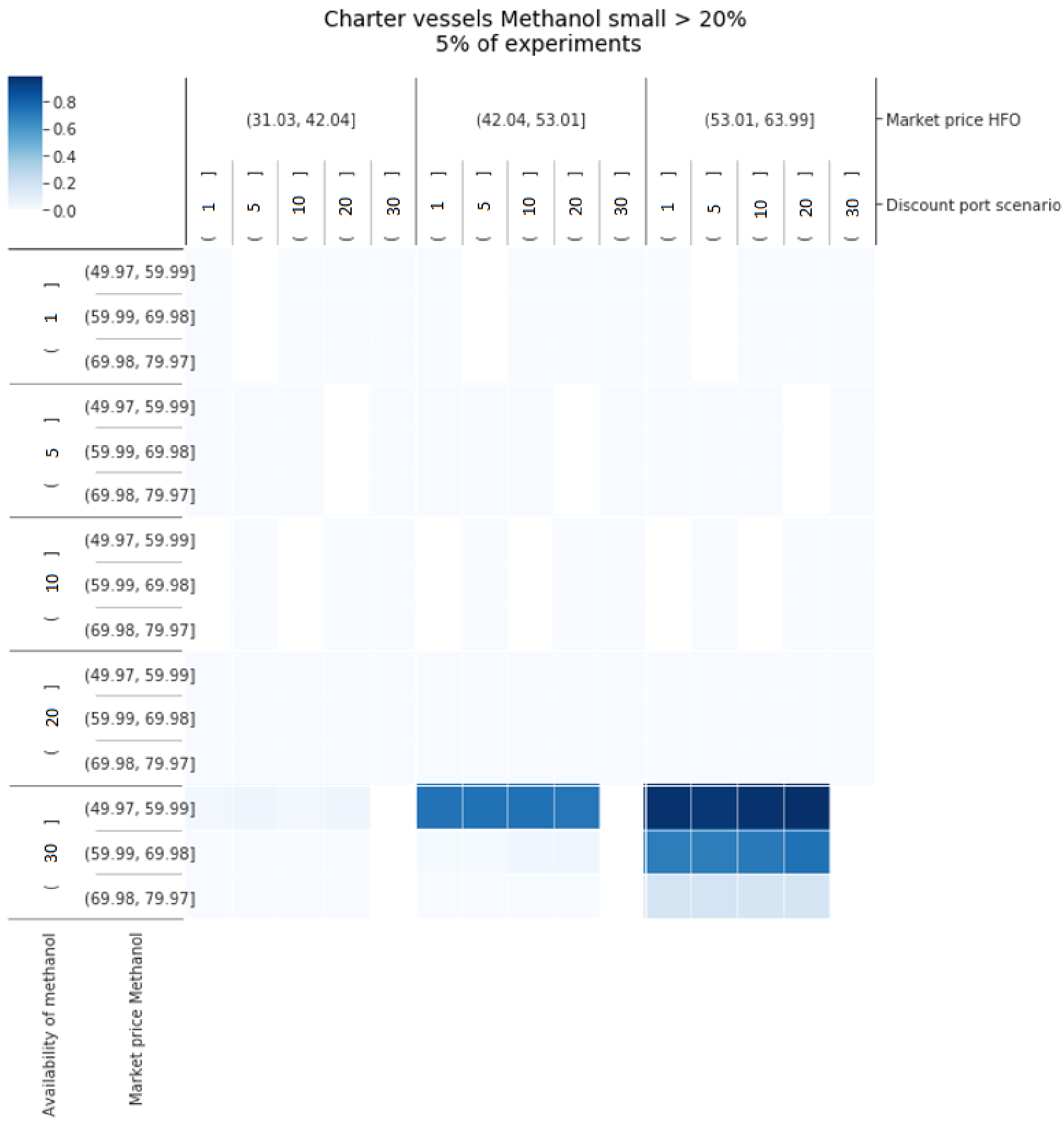

Charter vessels MGO/SCR < 10%
86% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Market price HFO
(0.8, 0.93]
(0.93, 1.07]
(1.07, 1.2]
Investment costs SCR
(56.03, 76.71]
(76.71, 97.33]
(97.33, 117.94]
Market price MGO
Space Scrubber/SCR

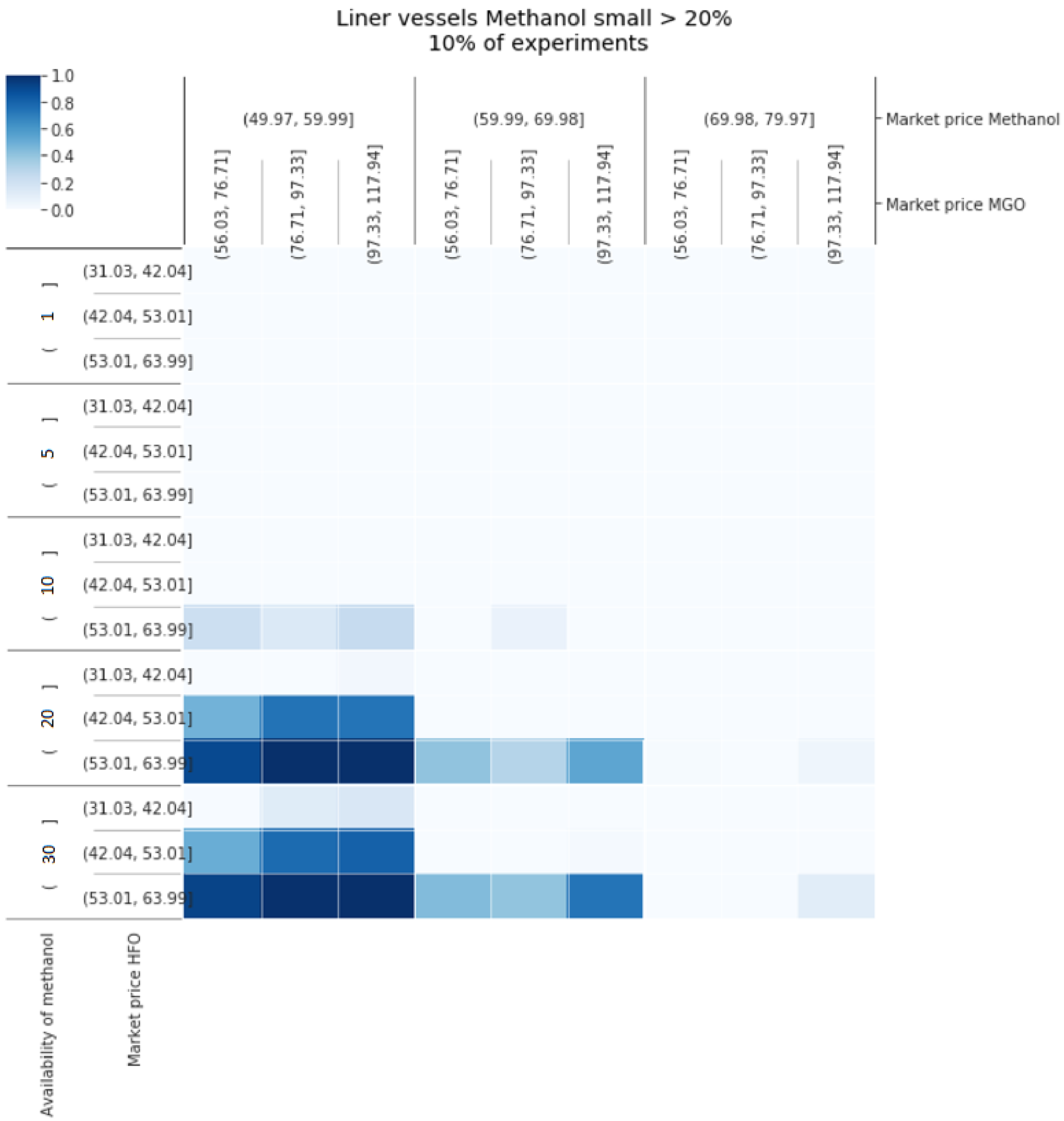

Liner vessels MGO/SCR > 10%
14% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Market price HFO
(-0.00024, 0.33]
(0.33, 0.67]
(0.67, 1.0]
Control Percentage
(56.03, 76.71]
(76.71, 97.33]
(97.33, 117.94]
(0.8, 0.93]
(0.93, 1.07]
(1.07, 1.2]
Market price MGO
Space Scrubber/SCR

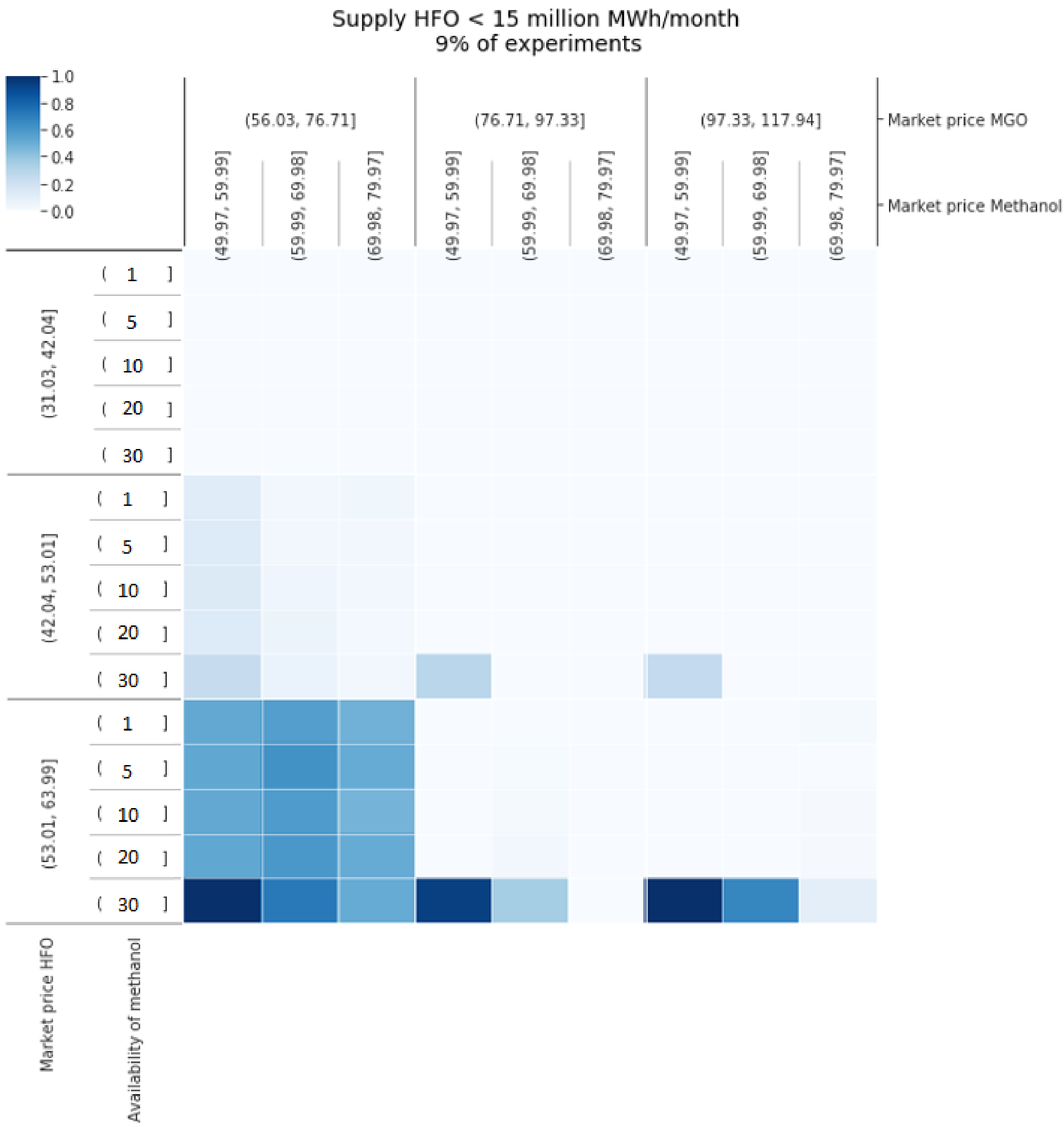


Charter vessels LNG > 25%
2% of experiments
0.40
0.32
0.24
0.16
0.08
0.00
(46.01, 52.35]
(52.35, 58.67]
(58.67, 64.99]
Market price LNG
(0.8, 0.93]
(0.93, 1.07]
(1.07, 1.2]
Space SCR
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Market price HFO
Space LNG

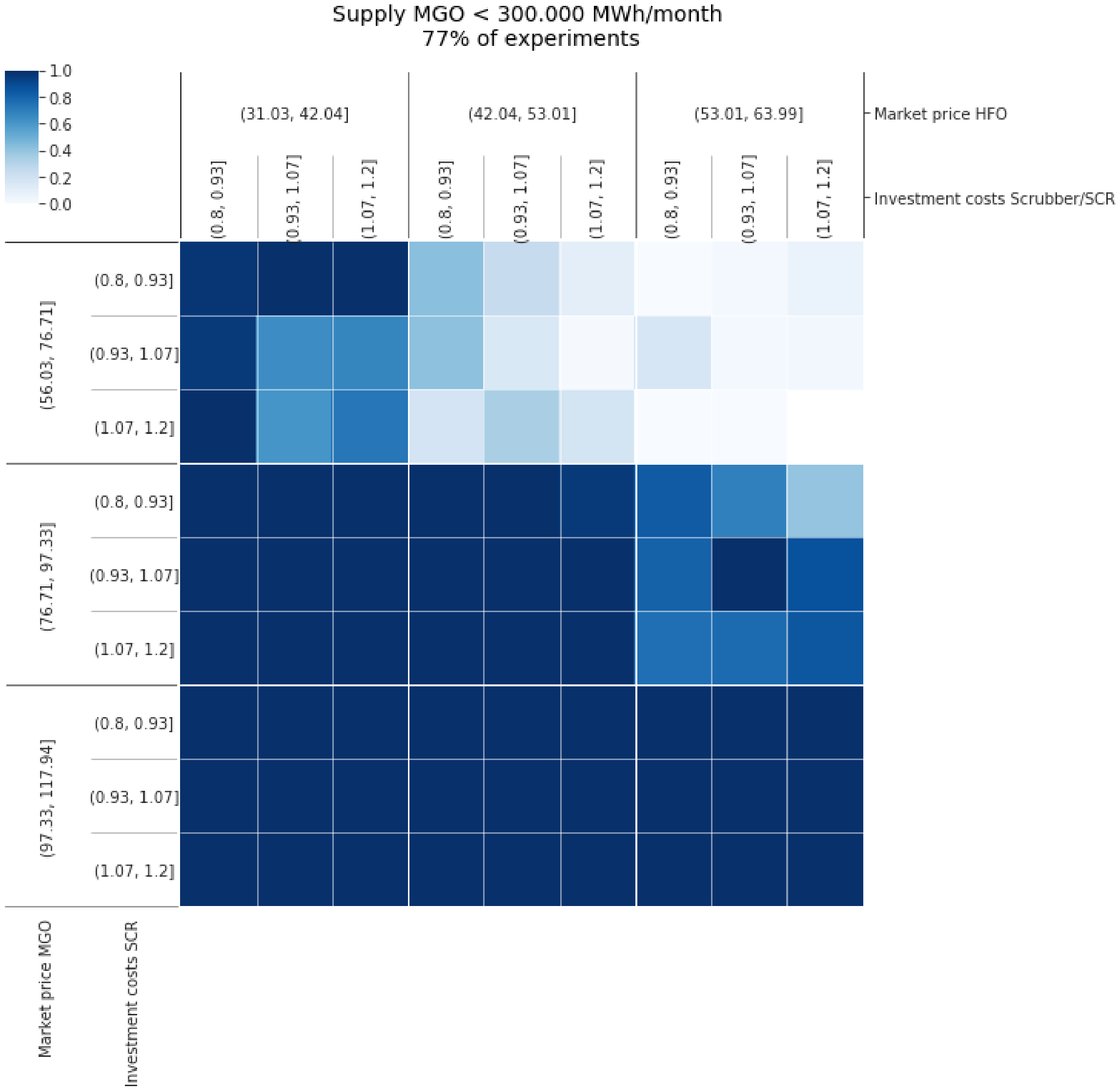

Liner vessels LNG > 40%
15% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(46.01, 52.35]
(52.35, 58.67]
(58.67, 64.99]
Market price LNG
(49.97, 59.99]
(59.99, 69.98]
(69.98, 79.97]
Market price Methanol
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
(-0.00024, 0.33]
(0.33, 0.67]
(0.67, 1.0]
Market price HFO
Control Percentage


Charter vessels Methanol small > 20%
5% of experiments
0.8
0.6
0.4
0.2
0.0
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Market price HFO
(1]
(5]
(10]
(20]
(30]
Discount port scenario
(49.97, 59.99]
(59.99, 69.98]
(69.98, 79.97]
Availability of methanol
Market price Methanol

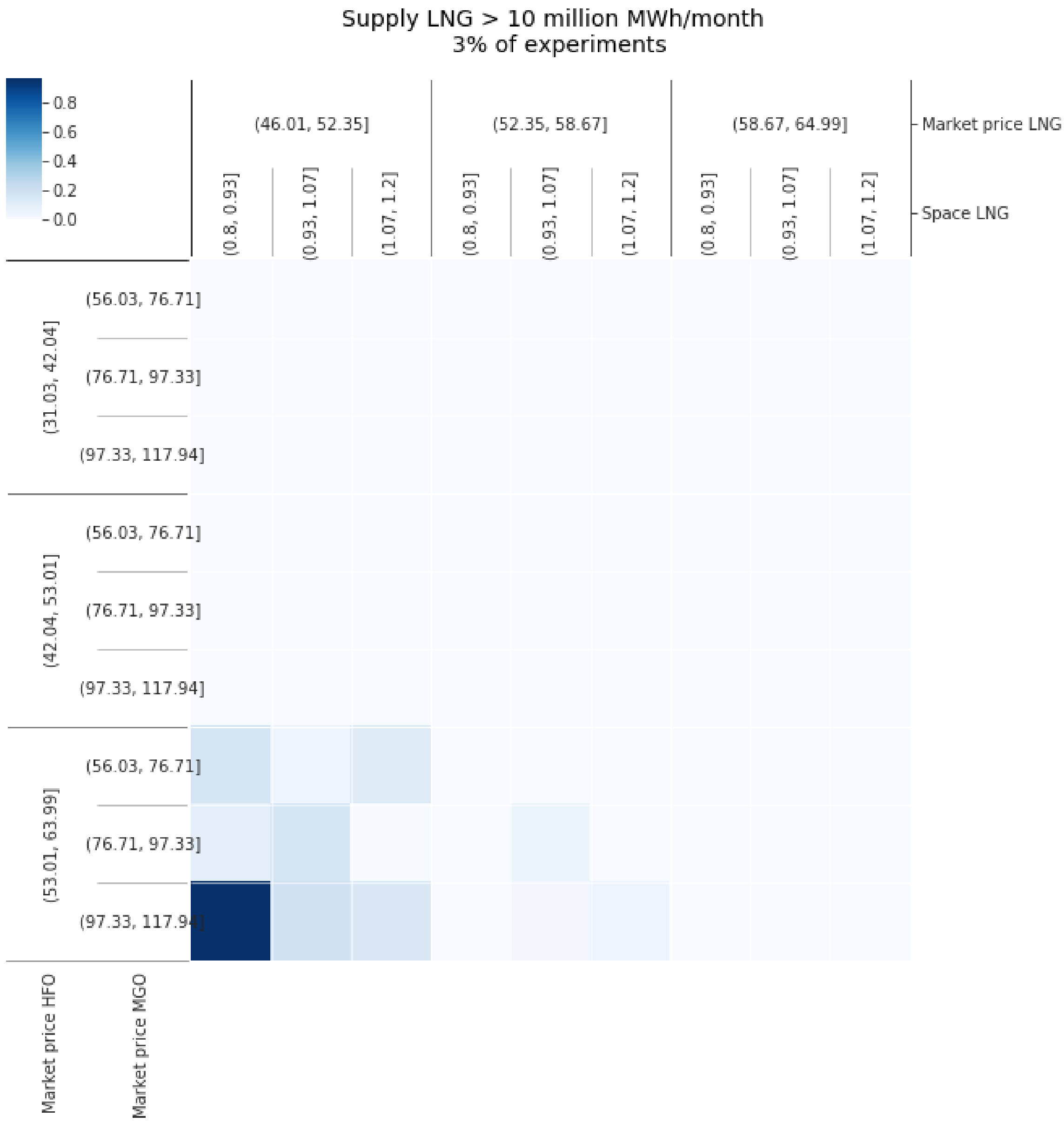

Liner vessels Methanol small > 20%
10% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(49.97, 59.99]
(59.99, 69.98]
(69.98, 79.97]
Market price Methanol
(56.03, 76.71]
(76.71, 97.33]
(97.33, 117.94]
Market price MGO
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
(1]
(5]
(10]
(20]
(30]
Availability of methanol
Market price HFO

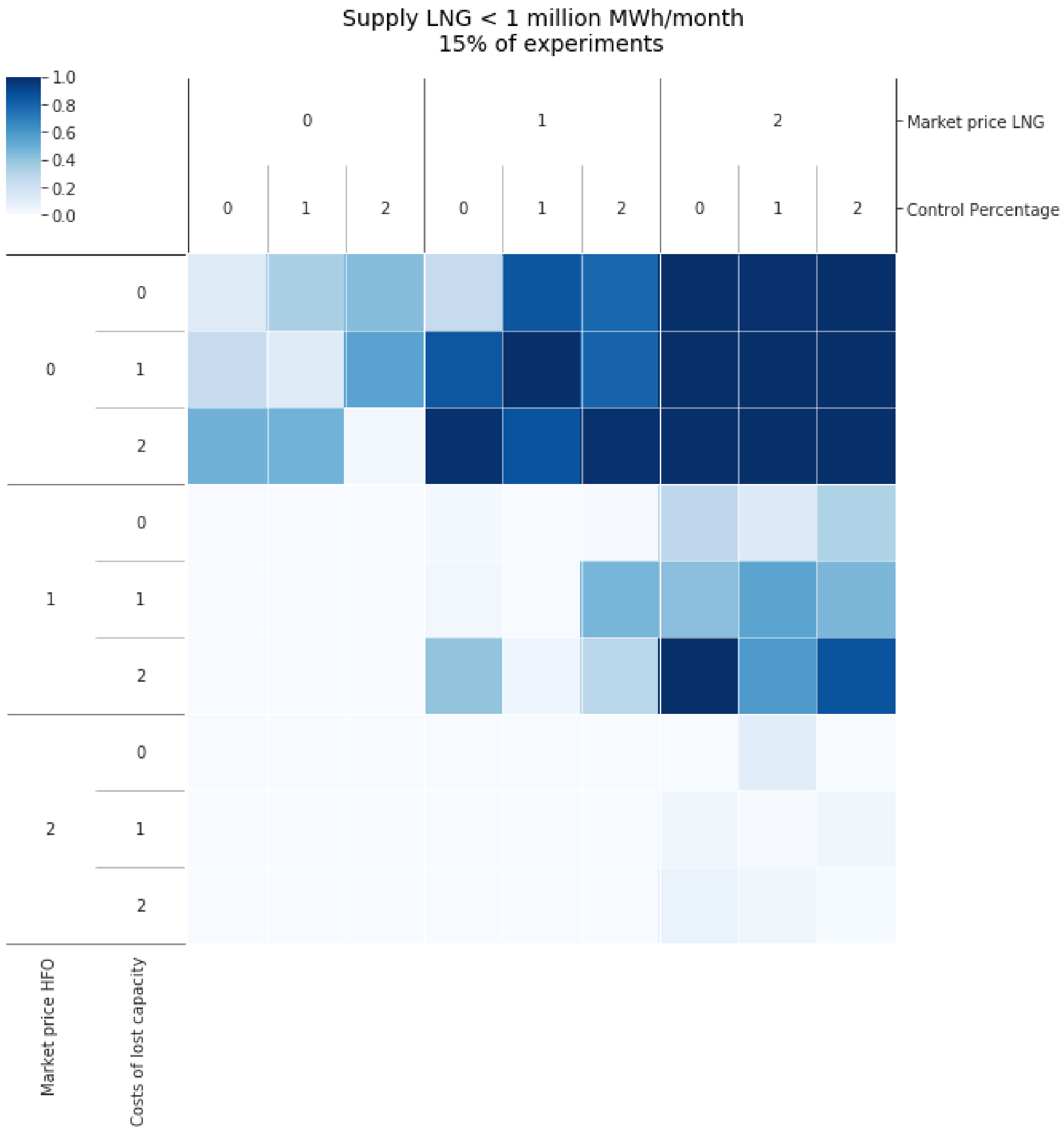


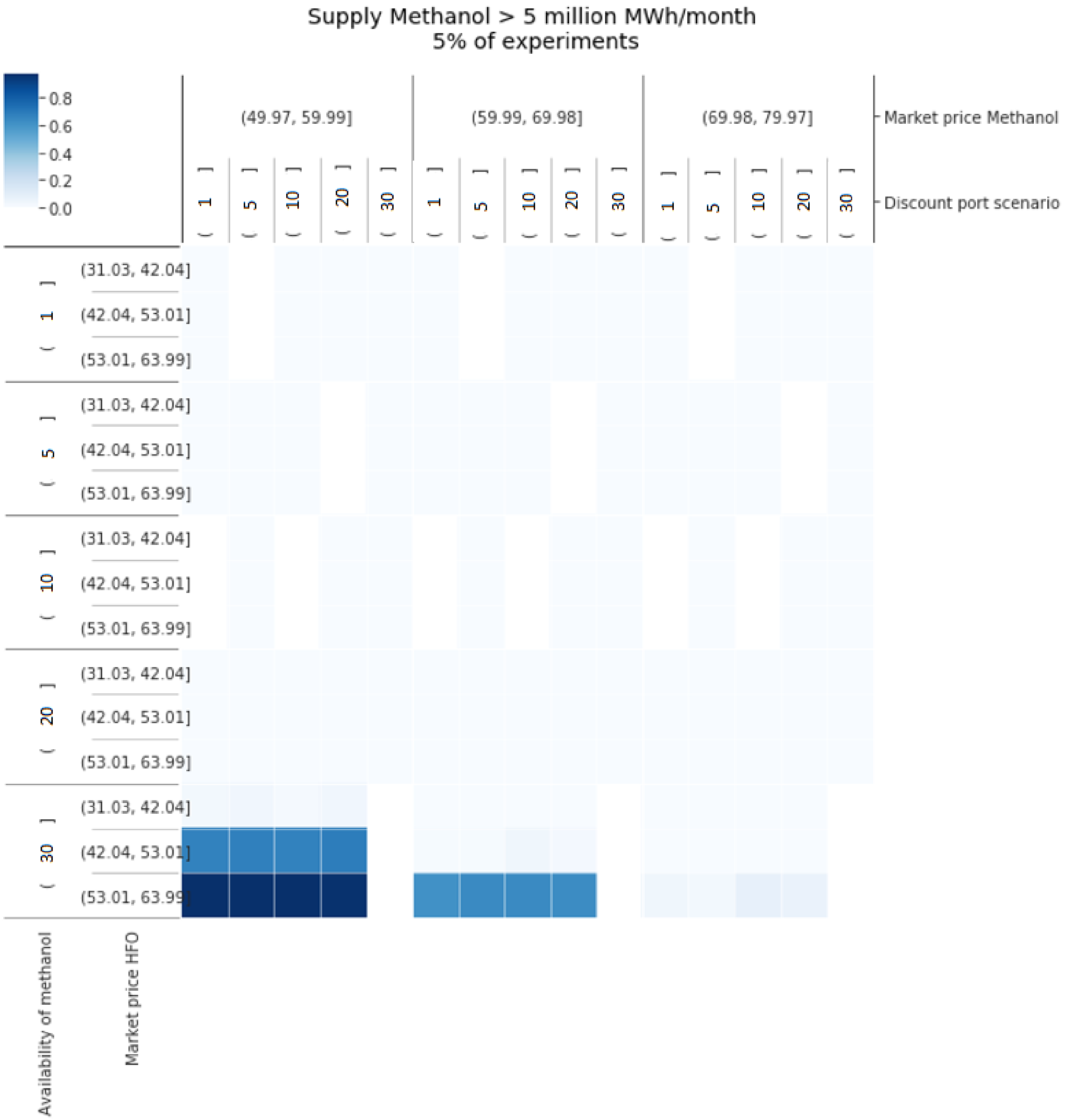
Supply HFO < 15 million MWh/month
9% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(56.03, 76.71]
(76.71, 97.33]
(97.33, 117.94]
Market price MGO
(49.97, 59.99]
(59.99, 69.98]
(69.98, 79.97]
Market price Methanol
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
(1]
(5]
(10]
(20]
(30]
Market price HFO
Availability of methanol

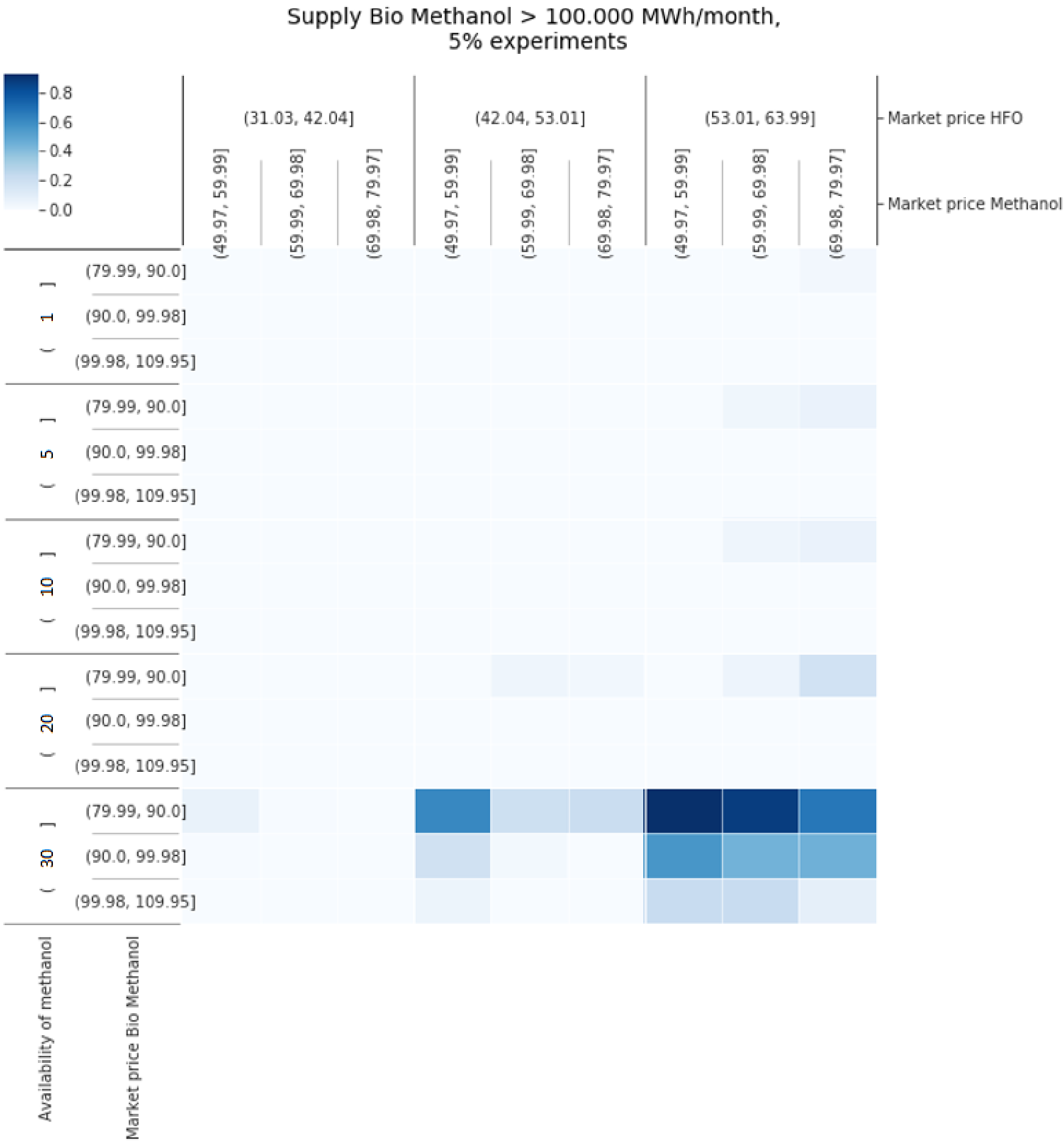


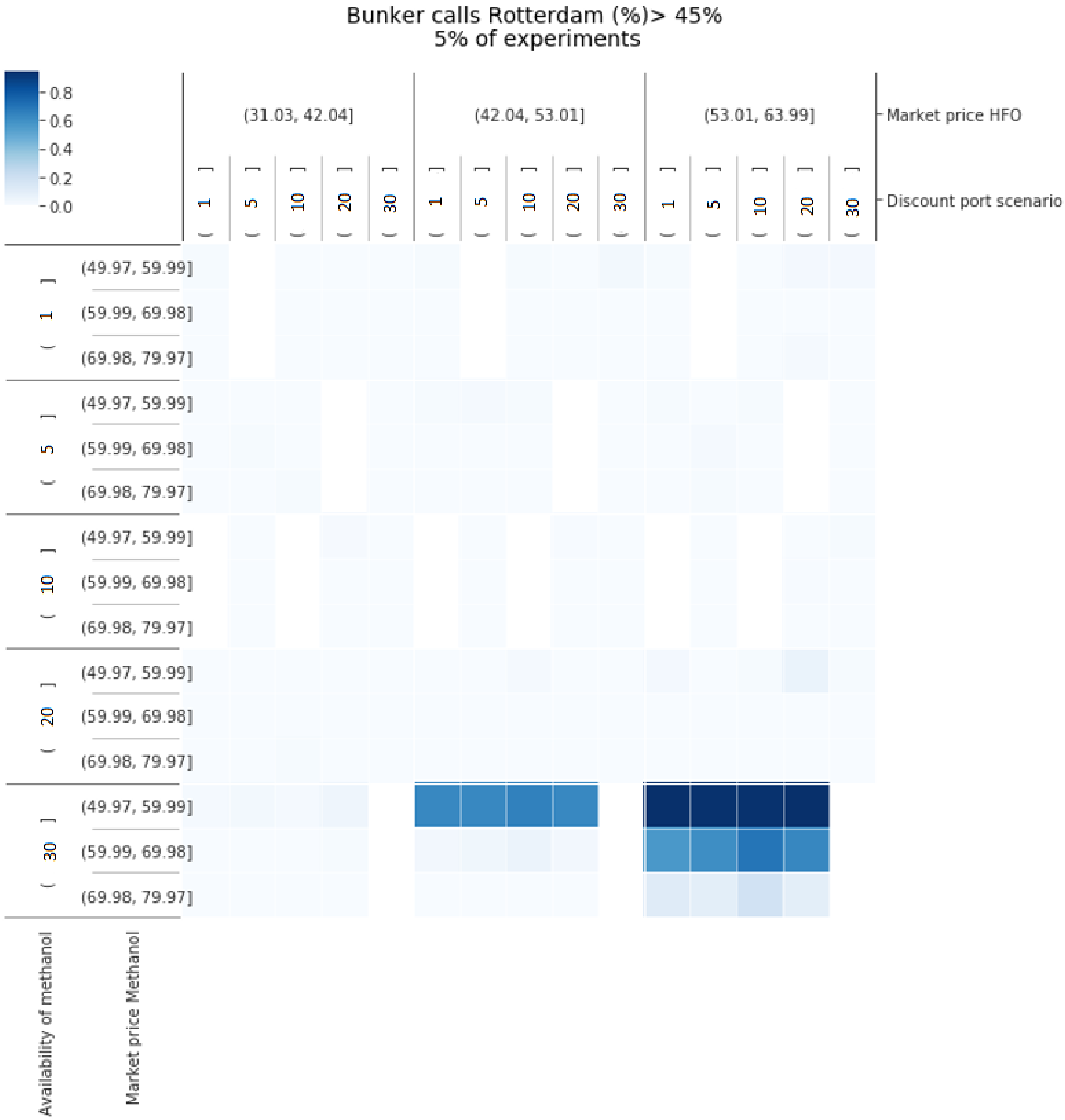
Supply MGO < 300.000 MWh/month
77% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Market price HFO
(0.8, 0.93]
(0.93, 1.07]
(1.07, 1.2]
Investment costs Scrubber/SCR
(56.03, 76.71]
(76.71, 97.33]
(97.33, 117.94]
Market price MGO
Investment costs SCR


Supply LNG > 10 million MWh/month
3% of experiments
0.8
0.6
0.4
0.2
0.0
(46.01, 52.35]
(52.35, 58.67]
(58.67, 64.99]
Market price LNG
(0.8, 0.93]
(0.93, 1.07]
(1.07, 1.2]
Space LNG
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
(56.03, 76.71]
(76.71, 97.33]
(97.33, 117.94]
Market price HFO
Market price MGO


Supply LNG < 1 million MWh/month
15% of experiments
1.0
0.8
0.6
0.4
0.2
0.0
Market price LNG
Control Percentage
Market price HFO
Costs of lost capacity
0
1
2


Supply Methanol > 5 million MWh/month
5% of experiments
0.8
0.6
0.4
0.2
0.0
(49.97, 59.99]
(59.99, 69.98]
(69.98, 79.97]
Market price Methanol
Discount port scenario
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Availability of methanol
Market price HFO


Supply Bio Methanol > 100.000 MWh/month,
5% experiments
0.8
0.6
0.4
0.2
0.0
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Market price HFO
(49.97, 59.99]
(59.99, 69.98]
(69.98, 79.97]
Market price Methanol
(1]
(5]
(10]
(20]
(30]
(79.99, 90.0]
(90.0, 99.98]
(99.98, 109.95]
Availability of methanol
Market price Bio Methanol



Bunker calls Rotterdam (%)> 45%
5% of experiments
0.8
0.6
0.4
0.2
0.0
(31.03, 42.04]
(42.04, 53.01]
(53.01, 63.99]
Market price HFO
(1]
(5]
(10]
(20]
(30]
Discount port scenario
(49.97, 59.99]
(59.99, 69.98]
(69.98, 79.97]
Availability of methanol
Market price Methanol