Strategies towards effective emission reduction of the inland shipping industry in the port of Rotterdam

Using a mixed-integer linear programming model

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Using a mixed-integer linear programming model

by

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Preface

In front of you lies the result of an 8-month lasting process – my graduation project. This document, and relevant study is the last step in my 'career' as a student. The project has been executed in collaboration with the Port of Rotterdam, and for the University of Technology Delft.

First, I want to thank my graduation committee from the university. Their support, guidance and criticism led to the document as it lies in front of you now. A special thanks to Ruud Binnekamp, for always showing his trust towards the process and result of my research. Then, Rob Stikkelman, for his close involvement during the modelling process, his difficult questions and showing me new insights every time we spoke. Last, the chairman of the committee, my professor, Hans Bakker, for his criticism, valuable comments and his experienced view towards my research, which increased the academic quality of my research throughout the process.

Second, I want to thank Port of Rotterdam for allowing me to execute this assignment, providing me with all the resources required and incorporating myself within their organisation. Additionally, they have shown to be very flexible when I adapted the assignment in the initial phases. I want to thank my formal supervisors René Eversdijk and Gert Kramer for providing me the necessary support. A special thanks to my informal supervisor Roland Schuring for his intensive guidance, involvement and dedication.

Finally, I want to thank my family, my friends and my girlfriend for their support throughout this process. A special thanks to, in the meantime, alumnus Kevin van der Kruis for his advice, our discussions on our graduation struggles and his feedback on my documents.

Enjoy reading!

Daniël Baas
Rotterdam, December 2019

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Executive Summary

The objective of this study is to gain insights into the relationship between policy instruments and incentivising technical alternatives. Therefore, this study aims to identify effective emission-reducing strategies based on a mixed-integer linear programming (MILP) model. Effective refers to the degree of cost-effectiveness and pollution control of this particular strategy. It can be concluded that this study has identified two effective strategies – environmentally differentiated port dues and environmental fees.

The effectiveness of the environmentally differentiated port dues can be allocated to the degree of pollution control. The current program, as executed by Port of Rotterdam, has shown to be too marginal and thus ineffective. The program should be expanded with greenhouse gas emission reduction goals and in-line with the contents of the Green Deal. In order to prevent unfair competition between ports and decrease the biggest shortcoming of this instrument, the geographically limited application, it should be governed nationally or throughout Europe. The second effective strategy, the implication of an environmental fee on carbon dioxide (CO_2) emissions, has led to a reduction in greenhouse gas and pollutant emission as well. The degree of pollution control is relatively less compared with the environmentally differentiated port dues. This instrument increases the degree of fuel efficiency, reduces the demand for conventional diesel and incentivises to seek for alternative techniques. Therefore, alternative synthetic fuels become more attractive and lead to lower costs.

This study came to the above conclusion completing three phases. First, the available literature was conducted in order to identify technical, policy and subsidy measures that focus on the reduction of emissions from ships. The technical configurations found can be divided into seven retrofit options and seven alternative energy carriers. The options that hold the most potential refer to an exhaust gas treatment system (EGTS), an all-electric system (AES) and the implementation of multiple small Stage V engines (STA5). Amongst the alternative energy carriers, biodiesel (B100) and gas-to-liquid (GTL) have been identified and are both commercially available. Besides, the literature covers seven economic incentive instruments. An emission trading scheme (ETS) and environmentally differentiated port dues were identified as the most effective and suitable in terms of the problem's context. Unfortunately, not all policy instruments can be applied by Port of Rotterdam. Therefore, the emission-controlled area (ECA), a command-and-control instrument, and environmentally differentiated port dues are assessed using model. An environmental fee is assessed as well, due to the contents of the Green Deal.

Second, the relationship between the technical alternatives and the policy measures was assessed. The problem was formulated as a MILP problem and modelled using the software Linny-R. This software is a tool that uses the linear programming optimisation technique to calculate at what level processes maximise their benefits, i.e. optimising costs. The demand characteristics of the Port Authority are incorporated, and the model covers eleven vessels from the fleet owned by Port of Rotterdam. In total, five technical alternatives and three alternative fuels have been implemented. In addition to the technical alternatives identified above, the outdated CCR2 engine alternative is incorporated as well.

Furthermore, the most recent regulations are implemented. In total, four verification experiments were conducted that confirmed the integrity of the model. A distinct scenario was assessed using the model in order to assess the effects of the latest regulations. Model variations have been applied, holding distinct constraints and additional constants in combination with cost coefficients to assess, in total, two scenarios and two strategies. These

are the political landscape scenario, environmental fee scenario, environmentally differentiated port due strategy and the penalisation strategy respectively.

Third, the results and acquired insights from the model are then presented, evaluated and discussed. The results indicate that the political landscape scenario requires, relatively, a substantial amount of investments to comply with the long-term. Irrespectively, a solution space is available, and thus an optimum is available considering the variables, constraints and coefficients. Furthermore, the current port due program in the port of Rotterdam is too marginal and thus ineffective, and that a possible environmental fee incentivises the industry to reduce the demand for conventional diesel fuel. In total, four combined bar– and pie charts are presented, followed by three bar charts indicating the relative sensitivity analysis. Moreover, the method used, and results extracted from the model have been validated using interviews with experts. These interviews were required to guarantee the integrity and reliability of the model.

The critical variables identified refer to the fuel costs, and therefore the fuel consumption. It has a significant effect on the financial viability of investment decisions, and its relation to the operational costs. The constraints are indicating the Port Management Regulations (PMR) show hampering characteristics in the energy transition towards more emission-reducing technologies, hampering means that it incentivises to invest in relative 'dirty' alternatives and will show no beneficial contribution towards the reduction of emissions in the long-term. Last, the environmental fee scenario based on the amount emitted CO_2 per alternative has shown to be beneficial towards the energy transition.

The current model should be modified in order to be expanded towards (a partition of) the whole inland shipping industry. The structure of the model should be adapted to the vast difference in scale. Besides, the demand criteria are not feasible for the industry and should be adapted towards the required operating hours or a similar criterion. The purpose of the model studied could be expanded with an additional objective. Instead of solely focussing on the relationship between technical alternatives and policies, the model could be used to structure policy instruments. Thus, it can act as a steering tool that allows accomplishing the goals as intentioned.

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List of Abbreviations

The following list of abbreviations gives an overview of all the abbreviations used in this document with their corresponding (full) description.

AES	All-Electric System
AUS40	40% Aqueous urea solution
B100	100% Biodiesel
CCNR	Central Commission for Navigation on the Rhine
CH_3OH	Methanol
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
DOC	Diesel Oxididation Catalyst
DPF	Diesel Particulate Filter
ECA	Emission Controlled Area
EC	European Commission
EGR	Exhaust Gas Recirculation
EGTS	Exhaust Gas Treatment System
EICB	Expertise & Innovatie Centrum Binnenvaart
EN590	Automotive diesel fuel
ETS	Emission Trading Scheme
GTL	Gas-to-liquid
H_2O	Water
HAM	Humid Air Motor
HC	Hyrdo carbons
HVO	Heavy Vegetable Oil
IWA	Inland Water Auxiliary engine
IWP	Inland Water Propulsion engine
kW	Kilowatt
LNG	Liquified Natural Gas
LNT	Lean NO_x Trap
MILP	Mixed-Integer Linear Programming
N_2O	Nitrous oxide
N_3	Azide
NH_3	Ammonia
NO_x	Nitrogen oxides
NRE	Non-Read Engine
O_3	Ozone
PM	Particulate matter
PMR	Port Management Regulations
PN	Particulate Number
PTO/I	Power Take-Off/In
RPM	Rounds Per Minute
S	Sulphur
SCR	Selective Catalytic Reduction
SO_x	Sulphur oxides
VIV	Vereniging Importeurs Verbrandingsmotoren

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Phase I

Problem

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1

Introduction

Port of Rotterdam is Europe's largest seaport. The port's position is outstanding in terms of accessibility for sea-going vessels and intermodal connections (Port of Rotterdam, 2019b). The objective of Port of Rotterdam is to enhance the port's competitive position as a logistics hub and world-class industrial complex. Their core tasks are to develop, manage and exploit the port in a sustainable way and to deliver speedy and safe services for shipping (Port of Rotterdam, 2019c).

In 2011, the Port Vision for 2030 has been published by Port of Rotterdam. This document describes the prospects of the port and its area and what ambitions it has (Port of Rotterdam, 2011). One of the major ambitions of Port of Rotterdam is the reduction of environmental emissions. Port of Rotterdam wants to be the most sustainable industrial area in the world by 2030. These ambitions will be achieved due to the provision of (inland) vessels with sustainable transportation fuels, such as liquified natural gas (LNG) and (bio)diesel (Port of Rotterdam, 2011). Additionally, the nitrogen oxides (NO_x) and fine particles (PM) will be reduced to a minimum to improve the local air quality. Port of Rotterdam wants to be a global showcase for innovation, sustainability and added value. In effect, this means the use of renewable and clean fuels and improvements in energy efficiency (Port of Rotterdam, 2011).

Hence, Port of Rotterdam also published new Port Management Regulations (PMR) together with the Municipal Council of Rotterdam. These regulations are also indicating a restriction of the emissions caused by inland ships and are based on the requirements as specified by the European Commission (EC) and Central Commission for Navigation on the Rhine (CCNR). The purpose of this policy is the reduction of emissions from propulsion engines in the port's area. However, this policy has a substantial impact on the inland shipping industry. Shipowners are forced to invest in compliant solutions or will have to face the consequences. These consequences could be the penalisation of the (individual) ship owners or even prohibiting their access to the port's area. However, are firm regulations the most effective approach to achieving the relevant reduction? Or, which strategies would engage ship owners to behave cooperatively and invest in more sustainable techniques?

This study aims to suggest strategies that accomplish a reduction of emissions caused by the engines in inland ships, taking into account the development of the recently published regulations, the available policy instruments and the available technical alternatives. The purpose of this study is to give insights into the relationship between policy instruments and incentives to apply technical alternatives in the current system and its context. Based on this objective, the relevant (main) research question is formulated as follows: 'Which strategies could effectively reduce the emissions in the port of Rotterdam caused by the inland shipping industry?'.

1.1 Problem definition

Nowadays, organisations attach more value to the environmental footprint of their activities and their physical assets. Especially when these physical assets refer to conventional diesel propulsion systems, from which the environmental impact due to their emissions are barely regulated, and their impact is substantial. In the world that we live, and especially in Europe, logistical modalities are experiencing sustainable transitions. Except for the inland shipping industry, which still relies on conventional combustion engines and diesel fuel. As previously described, the European Commission and Port of Rotterdam have published plans and regulations to reduce these emissions of these physical assets active in the logistical industry.

The regulatory landscape forces shipping companies and ship owners to invest in alternatives that make their vessel(s) compliant. Shipowners can choose between a variety of solutions; replacing the engine, retrofitting the current engine or choosing an alternative fuel. Multiple studies (Alkaner & Zhou, 2006; Bengtsson, 2011; Corbett, Fischbeck, & Fischbeck, 2002; Cullinane & Cullinane, 2013; Reşitoglu, Altinişik, & Keskin, 2015) have been conducted on methods that can effectively lower the emissions of engines on ships.

In-line with the previously written ambitions, the EC has published a new regulation called EU2016/1628, or also to be referred to as the Stage V standard, which applies to Non-Road Mobile Machinery (NRMM). This regulation replaces the previous directory which was called 97/68/EG, or to be referred to as Stage IIIA standard. NRMM refers to machinery and equipment such as locomotives, construction equipment and inland vessels. This policy specifies limitations to the emission of certain levels of carbon monoxide (CO), hydrocarbons (HC), particle matter (PM) and nitrogen oxides (NO_x). In addition to previously published policy, a limitation on the particle number (PN) for the relevant emissions is specified as well. These emission requirements are applicable for (diesel- and LNG-powered) engines with a power output less than 300 kilowatts (kW) that are placed on the market after 1st of January 2019 and for engines with a power output more than 300 kW after 1st of January 2020 (European Commission, 2016). At the moment, there are no engines available that are Stage V certified. However, Stage V compliant engines are available.

Port of Rotterdam has also specified emission limitations for the inland shipping industry in their most recent PMR which was published in 2010. This document is a set of rules to achieve effective port management and assures the quality of service (Municipal Council of Rotterdam, 2010). These rules provide requirements for activities, safety and environment in the port's industrial area and its surroundings. The PMR specifies that an inland ship is rejected from the port's area if it does not have engines that are at least compliant with the emission standards CCR2 or Stage IIIA. These standards are specifying slightly different levels of emissions but are legally defined as equal. The policies differ per publishing authority, CCR2 is published by CCNR and Stage IIIA by the EC. As described in the previous paragraph, the Stage IIIA standards were replaced in 2016 by the stricter Stage V standard. However, the Stage V requirements are only applicable for newly produced engines, and the requirements specified in the PMR are applicable for all engines in inland vessels irrespective what the corresponding manufactured/purchased date is. The PMR will be applied and governed from 1st of January 2025 and is applicable for all inland vessels, which are intended for commercial transport, as their engine is running in the port's area (Municipal Council of Rotterdam, 2010).

The relevant emission limit values are implemented in the PMR as a result of the land reclamation project in the North Sea, called Maasvlakte 2. These requirements for the inland shipping industry are a compensating measure for the resulting damage done to the natural environment as an effect of this reclamation project (Municipal Council of Rotterdam, 2010). When the land reclamation project opted, multiple parties were against this project because of environmental consequences. The assumption is that this compensatory measure is used as a negotiation item and is part of the package that consists of multiple measures in order to comply with the air quality requirements as described in the Environmental Management Act (Municipal Council of Rotterdam, 2010).

The status quo of the content of both regulations (PMR 2010 & EU2016/1628) means that inland vessels can be compliant according to European regulations but at the same time are forbidden to operate in the port's area. Moreover, the methods and consequences of enforcing the emission specifications by the Port of Rotterdam Authority are not known yet (Municipal Council of Rotterdam, 2010). The extent and method of enforcement could positively or negatively influence the cooperative behaviour of the relevant actors within the industry. In the worst case, the inland shipping industry could avoid using the port of Rotterdam and deviate towards Antwerp or Amsterdam. This could have severe effects because, on a yearly basis, 40% of all the container handling is executed by the inland shipping industry (Port of Rotterdam, 2019a).

The tension field that is currently ongoing within the industry is that on the one side, the inland shipping industry wants to be more sustainable but does not have the required resources to be more sustainable. The logistical chain in which they operate does not allow financial investments for modifications or alternative fuels in order to still generate revenue. On the other side, the European Commission, the Central Government, the Municipal Council of Rotterdam and the Port of Rotterdam wants to achieve a reduction of emissions within the inland shipping industry. Therefore, they are implementing several command-and-control instruments which are obligatory regulations. There are several indications that these regulations are not achieving the intended results. In short, the inland shipping industry is not sufficiently incentivised to invest in sustainable technologies in order to reduce their emissions.

1.1.1 Case study

The policies as described do not only affect the inland shipping industry, but the fleet owned by Port of Rotterdam as well. The fleet owned by the Port of Rotterdam will be used as a case study to explore the recommendations of this study. This section illustrates the fleet and its current configuration. Port of Rotterdam operates and owns in total sixteen floating physical assets, i.e. vessels; three patrol vessels, nine incident response vessels, two hydrographic measuring vessels, one representation vessel and one fast response vessel. The patrol and incident response vessels are operational 24-hours a day, 7-days a week and are operationally based on a double shift basis, i.e. a day and a night crew.

In general, the patrol vessels are responsible for general surveillance and enforcing activities, the incident response vessels for emergency response, emergency support and (fire) extinguishing activities, the hydrographic measuring vessels for measurement and data collection purposes and the representation vessel for public relational activities. The clustering of floating physical assets is to be further referred to as the (sailing) fleet.

The vessels need to comply with specific requirements set by the Harbour Master, which is the internal client of Port of Rotterdam and operator of the patrol and incident response vessels. These requirements refer to certain availability, response time and a required volume of extinguishing liquid at a specific location in the port in case of an emergency. Furthermore, the incident response vessels are also supporting the local fire department and other services with supply of extinguishing volumes.

The fleet of Port of Rotterdam represents for inland ships operating in the port’s area, due to the variety of the individual life cycle stages, the variety of installed power output, the variety of functionalities, and the variety in the propulsion systems. The current propulsion and auxiliary engine configuration of the fleet do not comply with the regulations as previously described, apart from three hybrid vessels from which two are recently refitted with hybrid propulsion systems (diesel-electric). Moreover, some vessels are at the point of a major overhaul service focussing on the propulsion and auxiliary engines, and some vessels are approaching the end of their life cycle. The combination of overhaul services, vessels approaching the end of their life and in compliance with latest regulations have all a significant influence on the decision that has to be made considering engine replacement options, retrofit options or disposal of a particular vessel and invest in a new one.

1.2 Objectives and Questions

The problem, as described in the previous sections, can be formulated into objectives. The focus of this study is set on the relation between available technical alternatives and policy instruments. Operational measures, contractual measures and optimisations in the logistical chain are not incorporated. The technical alternatives refer to retrofit options or alternative (drop-in) fuels. Therefore, this study aims to give insights into emission-reducing technical alternatives and policy instruments that can incentivise ship owners.

The main objective of this study is to gain insights into the relationship between policy instruments and incentivising technical alternatives. Therefore, effective policy instruments refer to the degree of pollution control and the amount of cost-effectiveness. Technical configurations refer to the required inputs (i.e. fuels) of the propulsion system, and variations on the actual system configuration (e.g. retrofitting options). The relation between the technical configurations and policy instruments will eventually lead to mutual effectiveness. In addition to the main objective, another objective is studied as well. Given the current political landscape, how can, in this case, a fleet of vessels comply with the obligatory regulations implementing a variety of technical alternatives (retrofit options) or alternative fuels (drop-in fuels).

The study focusses on the case as described, but the goal is to achieve an understanding of strategies that could be applied to the inland shipping industry. In order to expand the system towards that level, certain aspects have to be considered and will be considered throughout this study.

To accomplish the objectives as mentioned above, the following (main) research question (RQ) is defined:

RQ Which strategies could effectively reduce the emissions in the port of Rotterdam caused by the inland shipping industry?

To be able to answer the (main) research question, the following sub-questions (SQs) have been established:

SQ_1 What configurations (i.e. technical) and conditions (i.e. policies and subsidies) are available to reduce emissions of ships?

SQ_2 How can the current system be presented in a mathematical model?

SQ_3 What are the critical variables, constraints and scenarios of the relevant system?

SQ_4 How can the current model be expanded towards a (practical) representation of the inland shipping industry?

1.3 Methodology

First, the focus will be put on gathering all the relevant information and data published in the available literature. The literature study conducted in this phase will create an understanding of the main aspects of the study. This literature study focusses on studies and documents related to the problem, the available technical configurations that will reduce the current emissions, and the available conditions, indicating policies and subsidies, that could facilitate this reduction. The result of this first phase is an overview of all the relevant technical configurations and conditions. The feasible configurations and conditions will be implemented in the mathematical model, as described in the following paragraph. This first phase will give an answer to SQ_1.

Second, a model will be created, representing the current situation. This model will be created using a software called Linny-R. Linny-R is a tool for industrial process optimisations and allows to create a representation of a production system as a process with inputs and outputs. The optimisation technique linear programming is used to calculate at what level the process will maximise the benefits. The modelling process contains two-stages: (1) the current situation and (2) implementing configurations and conditions towards an optimum composition. The input for this model is the gathered data from the first phase plus the relevant case data provided by Port of Rotterdam. The system will be modelled from a technical perspective, which means that the ships are the centre of the process. When the practical situation is approached as closely as possible, the selected configurations and conditions will be implemented. Also, different scenarios will be taken into account, and eventually, the model will be analysed. This analysis will create an understanding of what configurations, conditions and scenarios have the most influence on the system and will create the largest reduction of emissions. The result of this second phase is a complete model representing the actual system from a technical perspective with the relevant insights as a result of the implementation of system variations. The second phase gives an answer to SQ_2.

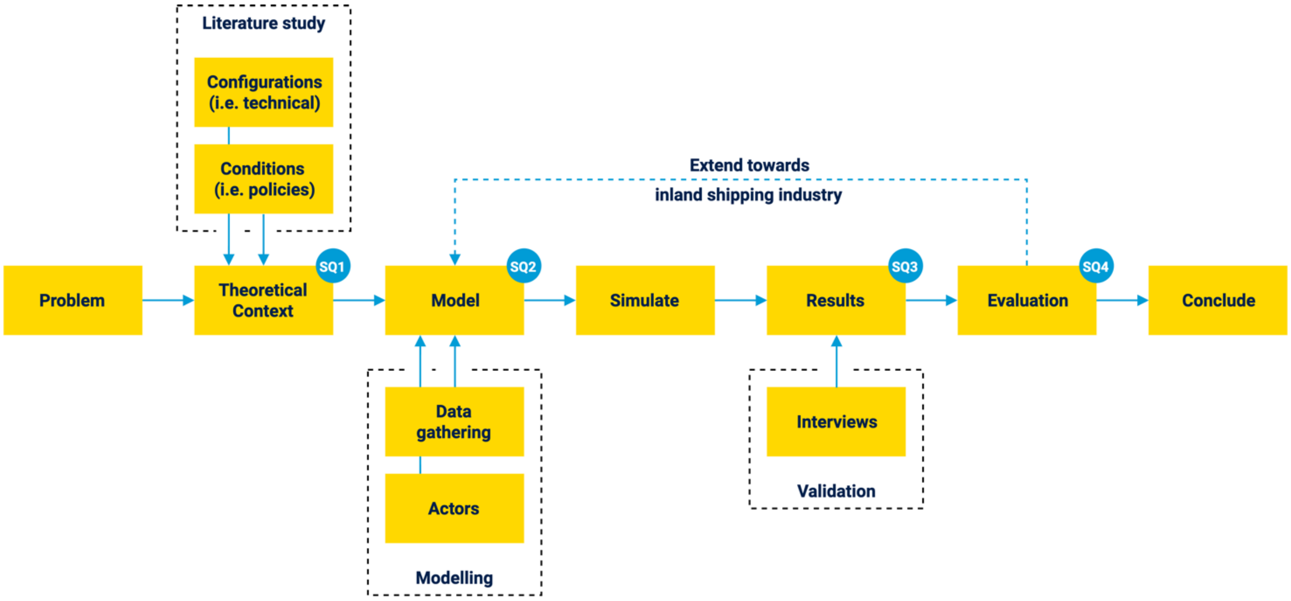


Figure 1.1

Research methodology

Third, the findings from the model will be presented and thoroughly evaluated. Moreover, the results will be validated by means of interviews with experts. This validation is required to discuss and confirm the results of the model. Furthermore, the necessary modifications to expand the model towards the inland shipping industry will be studied and proposed. These steps will define the different interfaces between the fleet of Port of Rotterdam and the inland shipping industry. The third phase gives answers to SQ_3 and SQ_4.

The combination of the answers to these sub-questions will consequently give an answer to the main research question. The research methodology is designed, as illustrated in Figure 1.1. This visualisation will give a more precise overview of the research methodology and order of steps that will be taken. Furthermore, all the activities and steps taken are characterised by an iterative approach. This means that during all steps, reflective moments are incorporated in order to ensure the quality and the final result of this study.

1.3.1 Structure

This section illustrates the structure of this document which is related to the methodology of the research and the relevant sub-questions. The full structure of this document, including the corresponding chapter numbers, can be found in Figure 1.2.

This study, and therefore this document, is divided into three phases. The first phase is the introduction. In Chapter 1, the introduction to this study is elaborated and followed by the literature study in Chapter 2. The second phase covers the analysis. The system analysis can be found in Chapter 3. The results are elaborated in the third and final phase. Chapter 4 presents the results. They are followed by the elaboration of the results and the relevant discussion in Chapter 5. Last, a conclusion is drawn, and the main research question is answered in Chapter 6. The reflection towards the whole graduation process can be found in Chapter 7.

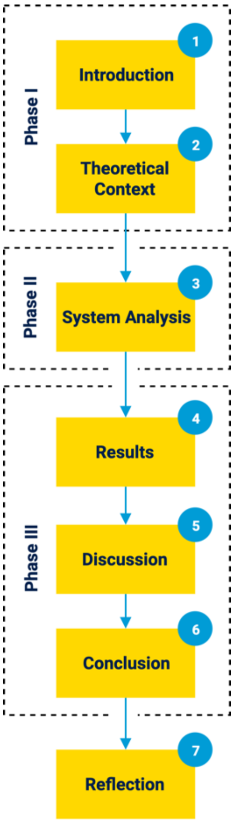


Figure 1.2
Document structure

2

Theoretical Context

A literature study is performed in order to identify the research gap in the available (scientific) literature and give an answer to SQ_1. Thus, the aim of this literature study is to give insights into what methods are available in the (scientific) literature to reduce the emissions of ships. Especially, focus on technical, policy and subsidization measures. This chapter will first discuss the theoretical relevance of the problem as proposed in Chapter 1 and will then extensively discuss the measures as studied by scientists. The goal is to create an overview of measures that are nowadays available and feasible in the context of the problem.

Several procedures have been followed in order to ensure the quality of the review of the literature focussing on the scientific relevance of the problem and answering SQ_1. Three databases are used, including IEEE Xplore Digital Library, Web of Science and Google Scholar. Several criteria are formulated for the selection of the publications. First, the articles must have a direct or indirect relation to either inland ships and sea ships considering their propulsion systems and the relevant emissions. Second, the articles must have been peer-reviewed and published in a journal. Third, the articles must be less then fifteen-year-old. This period is chosen because policies applicable on pollutants and greenhouse gasses emitted by (inland) ships is a development and implication of the past fifteen years. Thus, the articles published before this timeframe will most likely be irrelevant due to the course of technical innovations. Except, the technical and political measures that have been proven for a larger time-frame and are applicable for the course of this study are considered as relevant.

The problem is characterised by the absence of scientific literature. Due to the latter, instead of articles and publications, a total of four documents published by the governments (incl. workgroups) and another six studies performed by renowned institutions and authorities have been used. To answer SQ_1, a total of nineteen scientific publications and one book have been used. Thus, this results in a literature study covering a total of thirty-one documents.

2.1 Theoretical relevance

At this moment in time, global warming is the most trending topic amongst the global society, due to the effects of this phenomenon. In Europe, extreme heat waves have been recorded in the last four out of five years, and large parts of the continent experienced severe droughts (European Commission, 2018). According to the Intergovernmental Panel on Climate Change (2014), the highest level of anthropogenic greenhouse gasses in history is recorded and the human-induced global warming is increasing with approximately 0.2 degrees Celsius each decade. Anthropogenic greenhouse gasses have been addressed as the most dominant cause of global warming (Intergovernmental Panel on Climate Change, 2014).

Greenhouse gasses consist of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), together with other anthropogenic drivers (Intergovernmental Panel on Climate Change, 2014). These greenhouse gas emissions have to be reduced in order to slow down the ongoing global warming. Thus, in the (recent) past this topic has been high on the agendas of relevant international governmental parties. This has resulted in multiple agreements and published plans that aim to reduce these emissions (De Rijksoverheid, 2018; European Commission, 2018).

a. **Paris agreement** – is a global agreement between a total of 181 parties that holds plans to reduce the global greenhouse gas emissions with the objective to hold global temperature rise below 2.0 degrees Celsius.
b. **European Union** – aims to reduce their emissions by at least 40% in 2030, and even 60% in 2050, compared to 1990 in accordance with the Paris agreement.
c. **International Maritime Organisation (IMO)**– came to a global agreement between 173 countries that hold the objective to reduce greenhouse gas emissions due to the effects of shipping. They have agreed to reduce their CO_2 emissions with 40% in 2030, and 50% in 2050, compared to 2008

According to Hopman (2017) and European Commission (2018), the shipping industry is responsible for 3% of the total CO_2 emissions worldwide and 10% in the European Union. Indicating that the shipping industry has a substantial contribution. This contribution will increase to 17% of the worldwide quantity in 2050 when no additional measures are taken (Hopman, 2017). The national government in the Netherlands has expressed that a substantial environmental gain is feasible in the shipping industry, inland shipping industry and ports (De Rijksoverheid, 2019). The latter has resulted in a reaction from the government and largest European sea-port (De Rijksoverheid, 2018; Port of Rotterdam, 2011).

a. **Port of Rotterdam** – wants to reduce their CO_2 emissions in the port and industrial complex by 50% in 2025 and even 60% in 2030 compared to the values in 1990.
b. **Green Deal** – consists of agreements between parties concerning the sea shipping industry, the inland shipping industry and ports, and describes pathways to accomplish a CO_2 reduction of 40% in 2030.

In general, the Green Deal for ships, inland ships and ports will focus on the reduction of pollutants (NO_x and PM) affecting the (local) living environment and greenhouse gas emissions (CO_2) affecting the climate (De Rijksoverheid, 2019).

The current composition of the inland shipping industry in the Netherlands consists of 4,463 ships (Panteia, 2019). Panteia (2019) has come to the conclusion that only 18% has the required power output matching their sailing profile (i.e. matching the required power demand). The quantity that not matches their sailing profile is inefficiently loading their engines, which results in increased fuel consumption and after treatment installations not working effectively (Panteia, 2019).

According to a study executed by Panteia (2019), approximately 65% of the engines installed in these inland ships are not compliant with the CCR2 emission requirement and have an engine installed equivalent with CCR1 or less. Based on these statistics and the current market developments, 87% reduction of CO_2 emissions in this segment could be achieved, and even 97% with supplementary policies (Panteia, 2019). Unfortunately, according to multiple parties (Hopman, 2017; Panteia, 2019; TNO, 2015), it is unlikely that CO_2 reduction in the short-term will take place. Hopman (2017) and TNO (2015) state that the possible gains in the inland shipping industry are obstructed by the fragmented characteristics of this market and insufficient financial assets in combination with bank loans offering insufficient room for investment in sustainable solutions.

The biggest obstruction, according to Hopman (2017), is the insufficient financial room for investments in new ships or making existing ships more sustainable. The current market conditions do not allow that the required investment can be passed on towards the logistical operator (Hopman, 2017). In addition to these statements, TNO (2015) also identifies that the current uncertainties surrounding future regulations are an obstruction for ship owners to act and invest. De Rijksoverheid (2019) comes to the conclusion that the economic infeasibility of sustainable solutions is an obstruction and that the current business cases do not allow investments. The financial infeasibility and the current market means that the government has to act, and is investigating the options to facilitate the transition towards a more sustainable industry in terms of financial support and subsidies (De Rijksoverheid, 2019).

The current market is steering towards the installation of CCR2 certified engines incentivised by European regulations (EU2016/1628) and Port of Rotterdam regulations (PMR2011). The CCR2 standard is already outdated and was introduced in 2007. The latest standard, Stage V, is at least 80% less pollutant (NO_x and PM) and uses less fuel (Hopman, 2017). A large-scale transition towards these CCR2 engines is undesirable because this puts a brake on the growth towards Stage V (De Rijksoverheid, 2019).

Several studies (De Rijksoverheid, 2019; Hopman, 2017; Intergovernmental Panel on Climate Change, 2014; Panteia, 2019; TNO, 2015) are concluding that the CO_2 emissions will increase when no measures are taken. These studies unanimous dedicate the problem to financial aspects and the market situation. The latter due to the insufficient financial room in the current business cases. Additionally, a part of these studies (Panteia, 2019; TNO, 2015) consider a range of possible technologies but come to the conclusion that there is not a 'best' technical option or proven 'best practice'. The considered technical measures are still under development. Then, TNO (2015) indicates the possibilities of changing the behaviour of implementing new logistical concepts but is not considering them any further. Furthermore, De Rijksoverheid (2019); Hopman (2017) and Panteia (2019) are appointing the lack of sustainable investments made by shipowners towards the uncertainties surrounding current and upcoming regulations and the current market conditions. In addition to this conclusion, Hopman (2017) proposes a new financial instrument that introduces taxes and advice on the development of certain subsidies. Hopman (2017) does not elaborate on the latter and he did not study the effects of such a policy in terms of considering their business cases. The relevant studies, executed by Hopman (2017) and Panteia (2019), are focussing on the market from a wide perspective and offer measures that speculate on specific transition pathways and single solutions. These studies lack the implementation of technological measures in combination with specific policy instruments. According to Cullinane & Cullinane (2013) will a combination of regulation and technological innovation provide sufficient potential to dramatically reduce the environmental impact of the inland shipping industry.

This study tries to facilitate the segment of ship owners that have engines installed equivalent with CCR1 or less towards feasible sustainable solutions. The statistics provided by Panteia (2019) indicate that the most gain is possible within this segment, as supplemented by the statements from De Rijksoverheid (2019). The study will consider the different technical possibilities that will make this segment compliable with the CCR2 requirements, and what is additionally required to meet the Stage V requirements. It will contribute to the current knowledge indicating feasible technical solutions in combination with a required policy. This will fill the current gap in the literature and meets the current demand of the market, that is seeking for a solution fitting their business case and reduce their emissions within the political limits.

2.2 Policy instruments

A combination of the current state of regulations, technical solutions and the relevant business cases give the indication that both regulations or technical solutions will not create an incentive for the inland shipping industry to invest in sustainable solutions (STC Nestra & Rebel Group, 2015). Prior research, executed by Shi (2016), agrees to this conclusion and suggests that the adoption of technical and operational measures alone will not be sufficient to reduce the current emissions. STC Nestra & Rebel Group (2015) conclude that these approaches have to create a certain magnitude of economic gain in order to create incentives among ship owners and fit in the current business cases.

The bottleneck can be assigned to economic motives. A number of authors (Cullinane & Cullinane, 2013; Shi, 2016; STC Nestra & Rebel Group, 2015) have recognized that in order to reduce greenhouse gas emissions and pollutant emissions due to the shipping industry complementary policies have to be adopted. According to STC Nestra & Rebel Group (2015), an improvement in the financial situation will have to come from public funds and/or the relevant sustainable solution must provide commercial added value for the ship owners. Moreover, Zhu, Li, Shi, & Lam (2017) state that subsidies and preferential taxation policies are required in order to increase the shipping company's cost affordability. It is important to mention and consider the effects of emission-reducing policies. As comes forward in the study by Shi (2016), emission reducing policies affect the operational ability, negatively affects the supply chain and disrupts the competition in the shipping market.

The traditional division of policy instruments in order to achieve climate protection objectives is two-fold: command-and-control instruments and economic incentives (Hahn & Stavins, 1992). The latter is also called by a variety of authors (Hahn & Stavins, 1992; Koesler, Achtnicht, & Köhler, 2015; Miola, Marra, & Ciuffo, 2011; Nikolakaki, 2013; Shi, 2016) as market-based mechanisms.

A command-and-control instrument is a measure limiting how much could be emitted and the processes that are allowed to be used. This policy instrument lacks the provision of incentives or rewards for meeting the permitted reduction target (Hahn & Stavins, 1992; Nikolakaki, 2013). An economic incentive, or market-based mechanism, grants the industry the autonomy in deciding how to meet a set of targets and provides it with incentives to search for cost-effective ways to meet them (Nikolakaki, 2013). The primary focus of market-based mechanisms lies in the implications of operations and organizations (Koesler et al., 2015).

Nikolakaki (2013) divides the economic incentive policies into two categories: charging alternatives and trading alternatives. In the case of a charging alternative, participants respond to a charge or price linked to a particular emission. The other alternative, participants can trade quantities which represent either a particular emission or the right to emit. Charging alternatives cover the policies that charge environmental taxes, fees, charges 'en route' and environmentally differentiated port or fairway dues. Credit programs, benchmarking programs and cap-and-trade programs are illustrative of trading alternatives (Nikolakaki, 2013; Shi, 2016). Shi (2016) adds to this division made by Nikolakaki (2013) a hybrid form between the charging and trading alternatives as a possibility and Miola, Marra, & Ciuffo (2011) adds emission crediting as a climate change policy.

The study performed by Miola et al. (2011) states that, from a political science point of view, economic incentives outperform command-and-control instruments in terms of cost-effectiveness for pollution control. A number of authors (Koesler et al., 2015; Miola et al., 2011) have recognized that economic incentives are preferable and more effective than fixed rules, and should pave the way for a more sustainable climate. However, there exists considerable opposition to the introduction of economic incentives as many industry players feel them to be excessive (Cullinane & Cullinane, 2013).

An environmental fee, or emission charge, can take various forms. In general, this policy provides the polluter with an incentive to reduce their emissions in order to pay lower fees. These fees can be a contribution, a levy or a penalty (Shi, 2016). A form of this kind of policy is a tax on the purchase of fuel at the point of sale. The volume of emissions from shipping is closely related to their fuel consumption. Thus, the goal of such an incentive method is to reduce the demand for fuel which will result in more fuel efficiency. The reduction of emissions through the reduction of fuel consumption, which results in the reduction of costs is called the 'green gold' paradigm (Cullinane & Cullinane, 2013). An emission tax is also considered as an effective instrument. A charge on emissions will create an incentive to increase efficiency or seek alternative technical measures, which will reduce emissions Nikolakaki (2013) also proposes another alternative, an emission charge that will be charged 'en route'. These charges are calculated based on the distance travelled by a particular vessel. Environmentally differentiated port dues also fall under this last category. These incentive programs have been shown key in multiple successful implications of environemtal policies in Nordic countries (Nikolakaki, 2013).

A form of a trading alternative is the benchmarking program. A benchmarking program requires that the average emission level from the covered activities of a certain shipowner should not exceed a certain level while setting a specific emissions rate applicable to these activities (Harrison, Radov, & Patchett, 2004). Prior research suggests (Nikolakaki, 2013) that such a program usually set a legislative limit requirement as an opposing measure to the voluntary nature of a credit-based program. Moreover, Nikolakaki (2013) states that such a program is often implemented as precursors to a full trading scheme.

The European Commission has proposed an emission trading system as a method to reduce emissions (European Commission, 2018). Such a trading policy option is indicated as a cap-and-trade program and operates in the market in order to achieve emission reduction (European Commission, 2018; Shi, 2016; Zhu et al., 2017). The system sets a fixed number of emission allowances and aligns the relevant number of permits. The distribution of a sufficient number of tradeable permits allocates the pre-set emission quota (Nikolakaki, 2013; Shi, 2016). Each allowance offers its owner the right to emit a unit of emissions. Within the cap, every emitter is free to trade allowances and thus allow their own emissions level to be covered. The value of the emission reductions available is determined by market forces and cost transparency. The driver behind this system is that it would appear that it is more cost-effective to invest in emission reduction technologies rather than purchase allowances (Nikolakaki, 2013; Shi, 2016). Tradeable permits are likely to increase market liquidity and will encourage firms to participate in trading emission permits (European Commission, 2018; Nikolakaki, 2013; Zhu et al., 2017). According to Nikolakaki (2013), the downside to this system is that it would appear that it is more cost-effective to purchase the permits instead of reducing the emissions, which will result in an offset of emissions rather than a reduction. The environmental effectiveness of the scheme is guaranteed: the cap defines the overall amount of permitted emissions in the system (Koesler et al., 2015). Furthermore, the emitters are permitted and incentivized to pursue the most cost-effective emission reduction strategies (Koesler et al., 2015; Nikolakaki, 2013). The flexible nature of the emission trading system and its proven success provides a definite window of opportunity without placing an unnecessarily high burden on the sector (Miola et al., 2011). Several studies (Koesler et al., 2015; Miola et al., 2011) indicate that emission trading is often associated with high transaction costs for the regulated entity, due to the expenditures for monitoring and the costs induced by the trading activities. However, Koesler et al. (2015) conclude that because of a fixed number of emission permits, no extra administration efforts for monitoring are necessary, due to the direct relation between bunker fuel use and shipping emissions. On the other hand, (Miola et al., 2011) expresses their concerns that the operating authority has to take caution when it comes to the allocation of permits, due to the variety in ship sizes, types, and usage.

Another form of a trading alternative is a credit program, which is widely known as an emission credit system. In an emission credit system, the activities of a shipping company are recorded when their emissions are below 'business as usual' and certain credit can be provided to these companies. Governments could consider these credits as a benchmark when providing subsidies and preferential tax treatments (Nikolakaki, 2013; Zhu et al., 2017). According to Zhu et al. (2017), this method has two advantages, because it will incentivize the adoption of reduction technologies and will give insights to the government to monitor the shipping industry. Additionally, Nikolakaki (2013) also indicates the voluntary nature of the system as an advantage. The Port of Rotterdam already applies a form of this method for the inland shipping industry located in their port's area; a reduction of port dues based on the Green Award. The Green Award grants certifications to extra clean and safe vessels based on a series of environmental requirements. The bonus system applied gives ship owners, relevant towards their Green Award level, a reduction on the port dues. This system could be expanded in the future to create a larger economic incentive for ship owners. STC Nestra & Rebel Group (2015) states that the current scheme must be expanded with the introduction of a malus scheme on gas oil in order to efficiently implement the polluter pays principle to stimulate green ships. According to Nikolakaki (2013) the Green Award incentive program, in combination with the reduction on the port dues, has a lot of perspectives based on future prospects. Nikolakaki (2013) insists on further discounts and reduced prices for marine services, which will create more economic incentives. Hence, Nikolakaki (2013) states that a financial profit for ship owners also has to be introduced in such a way that a market preference for quality and environmentally friendly cargo will be created.

Instruments	**Studies**
Command-and-control instruments	Hahn & Stavins (1992); Nikolakaki (2013)
Emission controlled area	Hahn & Stavins, (1992); Nikolakaki (2013)
Economic incentive instruments	Nikolakaki (2013); Koesler et al. (2015)
Environmental fee	Shi (2016)
Emission tax	Nikolakaki (2013)
Emission charge 'en route'	Nikolakaki (2013)
Environmentally differentiated port dues	Zhu et al. (2017); Harrison et al. (2014); Nikolakaki (2013)
Benchmarking program	Harrison et al. (2004); Nikolakaki (2013)
Cap-and-trade program	European Commision (2018); Shi (2016); Zhu et al. (2017)
Credit program	Nikolakaki (2013); Zhu et al. (2017)

Table 2.1
Policy instruments

Several studies (Cullinane & Cullinane, 2013; Nikolakaki, 2013) have indicated that there is also a role for the port when it comes to policy measures. 55 to 77% of the total emissions in port regions can be attributed to seagoing and inland ships. Nikolakaki (2013) states that the role of ports is vital and important with respect to environmental policies because their position allows differentiating environmental port dues. The policy instruments that have been identified within the literature are presented in Table 2.1.

2.2.1 Subsidization

The provision of subsidies that can be granted by governments or other authorities is also form of financial incentive. According to Nikolakaki (2013), a subsidy program could be used to reward the reduction of discharges, whereas the charges or taxes are mainly focused on penalties. The same study (Nikolakaki, 2013) indicates that a subsidy can take the form of a grant or a soft loan that can be used to cover (partial) costs linked to the investment of emission reduction. Harrison et al. (2004) state that these can be applied simultaneously with charging or trading incentives. At which Nikolakaki (2013) adds that it can facilitate the acquisition of emission credits or as an additional incentive on emission taxes or charges.

STC Nestra & Rebel Group (2015) would like to see a fund for the greening of inland navigation at a European level. One central funding authority, which bundles all the existing individual investment projects. This will create and guarantee a 'level playing field' in order to receive financial support. According to STC Nestra & Rebel Group (2015) are the biggest advantages that the risks can be shared, the long-term loans can be taken out and a reduced interest rate can be applied.

2.3 Configurations

European Commission (2018) suggests that a feasible pathway in order to tackle shipping emissions is the usage of advanced technologies, called configurations in this section, and fuels. In order to understand technologies and fuels, it is important to give some insights into the pollutant emissions that a diesel engine emits first. An engine running on diesel fuel is the most popular form of the propulsion system in the inland shipping industry, as supported by the numbers of previous studies (Panteia, 2019; STC Nestra & Rebel Group, 2015).

In an ideal thermodynamic equilibrium, the combustion of diesel fuel will only generate CO_2 and water (H_2O). Due to several reasons during the combustion process, harmful pollutants are generated and indicated as CO, HC, PM and NO_x (Reşitoglu et al., 2015).

CO and HC emissions are the results of incomplete combustion of the diesel fuel. CO is emitted when the oxidation process does not occur completely and HC when the fuel is not completely combusted. The latter as a result of insufficient temperature near the cylinder wall. NO_x originates due to a too high combustion temperature (above 1,600 degrees Celsius). In detail, dependent on the temperature and the concentration of oxygen, the nitrogen in the air could not react completely with the oxygen and is thus emitted identically out of the engine. PM is the agglomeration of HC in the fuel and lube oil as a result of their incomplete combustion (Reşitoglu et al., 2015). Inhalation of these particles may cause premature death, asthma, lung cancer or other cardiovascular issues (Reşitoglu et al., 2015). The emission of these gasses is highly correlated with the amount of fuel consumed. Furthermore, sulphur is converted into sulphur dioxide (SO_x) when the fuel is burned in the cylinder containing suphur (Cullinane & Cullinane, 2013). Nowadays, the fuel used within the inland shipping industry is regulated with a maximum content of sulphur, which is equal to the same content as used in the automotive industry (Panteia, 2013). Thus, the reduction of these pollutants is not considered.

The different options available to reduce the different pollutant and greenhouse gas emissions are divided amongst two forms. First, configurations that allow the current system with a modification, addition of equipment or replacement to emit fewer emissions, which are further to be referred to as retrofitting options. Second, the implementation of an alternative energy carrier which in most cases requires a form of modification or (partial) replacement to the current propulsion system.

2.3.1 Retrofitting

According to Reşitoglu et al. (2015), most studies have been focusing on the reduction of NO_x because amongst the pollutants this matter holds the highest percentage. The study performed by Reşitoglu et al. (2015) comes to the conclusion that the most effective technologies to substantially reduce NO_x are exhaust gas recirculation, lean NO_x trap and selective catalytic reduction. Additionally, a study executed by Cullinane & Cullinane (2013) proposes an alternative called the humid air motor.

Exhaust gas recirculation (EGR), as the name says, is the recirculation of the exhaust gasses back into the combustion chamber (Reşitoglu et al., 2015). This happens during the intake stroke of the cylinder and will reduce the efficiency of the combustion process (Reşitoglu et al., 2015). As a result, the temperature in the combustion chamber will be reduced, and thus due to the lower temperature, the formation of the pollutant NO_x is reduced. Consequently, the emissions of this pollutant are then reduced. On the other hand, due to the worse efficiency of the combustion process, the fuel consumption of the engine is increased.

A lean NO_x trap (LNT) is a method that can reduce the formation of NO_x under lean conditions. Under these conditions, the NO_x can be stored on a special coating inside the catalyst. Then, when the engine is loaded with more fuel-rich conditions the catalyst will release and react the NO_x. According to Reşitoglu et al. (2015), is the LNT, such as EGR, insufficient in terms of providing the required NO_x reduction.

Selective catalytic reduction (SCR) is a method that minimizes NO_x emissions in the exhaust gasses due to the utilization of ammonia (NH_3) as a reductant. The NH_3 is provided from an aqueous solution of urea (contains 33% NH_3 and 67% H_2O). The NH_3 is mixed with H_2O due to the toxic and flammable characteristics of this matter (Reşitoglu et al., 2015). The reaction of ammonia with the exhaust gasses converts the NO_x into azide (N_3) and H_2O. The efficiency of the reactions that produce NH_3 from urea depends largely on the exhaust gas temperature (Reşitoglu et al., 2015).

The humid air motor (HAM) is a system that reduces the formation of NO_x by introducing three times as much water vapour as fuel in the engine. The system uses this vaporised water to reduce the temperature during the combustion process in the cylinder, and thus reduces the formation of NO_x. A downside towards this method is an increase in the fuel consumption of the engine and additional smoke in the exhaust gas. Cullinane & Cullinane (2013) indicates that this is a proven technology and is used on ships and power plants.

In general, the SCR has, in relation to the above emission control solutions, the highest efficiency when reducing NO_x (Reşitoglu et al., 2015). The above emission control technologies can be used simultaneously to increase the reduction ratio of NO_x (Reşitoglu et al., 2015). Prior study (Cullinane & Cullinane, 2013; Reşitoglu et al., 2015) shows a reduction of nitrogen oxides between 90 and 95%. A major disadvantage aspect of this system is the required deployment space within the engine room.

Furthermore, different emission control technologies are available that are focussing on the other pollutants – HC, CO and PM. To start with, a diesel oxidation catalyst (DOC) focusses on the reduction of all of these pollutants. The main function of this method, as the name already says, is oxidizing the HC and CO. Additionally, the diesel oxidation catalyst also reduces the mass of diesel particulate emissions. Reşitoglu et al. (2015) conclude that this emission control technology is highly preferred amongst heavy-duty engines and it is possible to increase the conversion efficiency when using alternative fuels.

A diesel particulate filter (DPF) is used to remove PM emissions from the exhaust gas. The exhaust gasses are filtered using a physical filter made of either cordierite or silicon carbide constructed in a honeycomb structure. A downside to this method is the accumulation of particle matter PM in the filter that creates back pressure. The back pressure can, as a result, increase fuel consumption, could cause engine failures and stresses in the filter itself. In order to prevent the negative effects that filter has to be regenerated using a burner to burn the particle matters PM. The conversion rate of this emission control technology can be increased using biodiesels or additives (Reşitoglu et al., 2015).

De Rijksoverheid (2019) proposes the installation of Euro VI and non-road engines (NRE) in order to reduce the emissions. These engines are produced for trucks that transport goods over the road, or other application such as a excavator. The installation of these engines in inland ships will be facilitated by the national government and a suitable procedure has to be developed in order to confirm the equivalence of these engines with the maritime purposed engines (De Rijksoverheid, 2019).

Retrofit alternatives	**Studies**
Exhaust gas recirculation (EGR)	Reşitoglu et al. (2015)
Lean NOx trap (LNT)	Cullinane & Cullinane (2013); Reşitoglu et al. (2015)
Selective Catalytic Reduction (SCR)	Cullinane & Cullinane (2013); Reşitoglu et al. (2015)
Humid Air Motor (HAM)	Cullinane & Cullinane (2013)
Diesel Oxidation Catalyst (DOC)	Reşitoglu et al. (2015)
Diesel Particulate Filter (DPF)	Reşitoglu et al. (2015)
Non-Road Engine (NRE)	De Rijksoverheid (2016)

Table 2.2
Retrofit alternatives

The retrofit alternatives that have been identified within the literature are presented in Table 2.2.

2.3.2 Alternative energy carriers

According to Cullinane & Cullinane (2013) has the usage of an alternative energy carrier the potential to reduce emissions from ships and enhance fuel efficiency. De Rijksoverheid (2018) indicates that (sustainable) alternative energy carriers are hydrogen, biofuel and hybrid-electrical. Additionally, Port of Rotterdam (2011) adds the usage of liquified natural gas (LNG) also as an alternative energy carrier in order to reduce emissions. A number of authors (De Rijksoverheid, 2019; Panteia, 2019) have recognized that the usage of biofuel and biofuel blends in order to reduce greenhouse gas emissions caused by inland ships are offering the most chances and is the most feasible solution in the short term. Another option could be the (full) electrification of inland ships when the routes and sailing distances allow these implications. The power to weight ratio of inland ships makes it a feasible solution (European Commission, 2018). The latter refers to the implementation of a medium to store energy on, and use this energy to drive electrical engines. This is not considered in this study, due to financial reasons.

Hydrogen is used in a hydrogen fuel cell in order to generate electricity during a process called electrolysis. A fuel cell harnesses the chemical energy which results from the electrolysis process that is a reaction between hydrogen and oxygen in the fuel cell. This process transforms the chemical energy into electrical energy and is very efficient. The only emission of this process is water vapour, which makes it extraordinary environmental friendly (Cullinane & Cullinane, 2019). In contradiction to this clean process of generating electrical energy is the production of hydrogen. Hydrogen is not an energy source, but an energy carrier which makes it only as clean as the source fuels of the production process. Another downside of hydrogen is the indirect characteristics as a greenhouse gas. Emissions of hydrogen lead to an increasing burden of CH_4 and ozone (O_3) (Cullinane & Cullinane, 2019). Prior research (Cullinane & Cullinane, 2013) concludes that the current state of the technology of the fuels does not allow long-distance travel, due to the limited range. Additionally, the current status of the refuelling infrastructure is insufficient and underdeveloped.

Cullinane & Cullinane (2013) state that bio-diesel works well in ship engines. Biofuels are usually derived from waste, biomass, plants or organisms (Cullinane & Cullinane, 2019; Moirangthem & Baxter, 2016). A ship's conventional diesel engine can operate on 100% bio-diesel or a mixture. The usage of bio-fuel will result in a reduction of CO_2. The main concern, according to Cullinane & Cullinane (2013) and Balcombe et al. (2019), is the increased price in relation to conventional fuels. Even when the production capacity is increased. Another concern is an increase in demand by cars in combination with an insufficient supply, which can result that cars will get the priority over ships. Additionally, Cullinane & Cullinane (2019) come to the conclusion that there is a significant increase in the usage of methanol as a specific form of biofuel for shipping. Methanol (CH_3OH) combustion engines produce significantly less CO_2 and low emissions of other pollutants (Balcombe et al., 2019). An advantage of methanol is that it can be produced from several sources, including natural gas.

LNG yields a significant reduction in NO_x and PM and has large reserves. Furthermore, the reduction of CO_2 emissions is also significantly (Cullinane & Cullinane, 2013, 2019). According to Cullinane & Cullinane (2013), it is regarded as the fuel of the future. Despite these statements, there are practical difficulties to fuel ships with LNG. First, the natural gas has storage issues in terms of required space, both onboard as ashore. Second, substantial problems in terms of the logistical chain. The LNG requires specialised handling technologies and the current presence of distribution facilities is insufficient (Cullinane & Cullinane, 2013).

Gas-to-liquid (GTL) fuel is a synthetic liquid derived from natural gas via a process that is called the Fischer–Tropsch process. The main advantages of this fuel is that it can be used in conventional (internal combustion) diesel engines. It contains a higher cetane number and there are no poly-aromatic hydrocarbons in the fuel content compared to diesel fuel. Prior executed studies (Gill, Tsolakis, Dearn, & Rodríguez-Fernández, 2011; Xinling & Zhen, 2009) have shown that under most test conditions GTL fuel can reduce the emissions of CO by 21%, HC by 16%, NO_x 16% and PM by 22% compared to conventional diesel fuel. According to Gill et al. (2011), the properties of GTL fuel offer more reduction potential of particle matter (PM) due to the increased effectivity of EGR. Plus, if after treatment exhaust gas catalyst is present in the propulsion system, the fuel efficiency of this system is improved due to the desulfurization process frequency (Gill et al., 2011).

As previously stated, multiple authorities and parties (De Rijksoverheid, 2019; Panteia, 2019) are seeing opportunities in the electrification of the (inland) shipping industry. The study performed by Dedes, Hudson, & Turnock (2012) and Prousalidis, Hatzilau, Michalopoulos, Pavlou, & Muthumuni (2005) propose two types of hybrid technology applied on ships. First, an all-electric system (AES) which produces the required electrical energy for the propulsion system at the optimum point for the diesel generators. This will result in an optimum in terms of fuel consumption and emissions. An energy storage medium is then installed in order to store excess energy generated by the engines, and can be used when there is more power required (i.e. manoeuvring) or during berthed conditions. With an electrical engine, the generators and batteries are able to drive the propeller of the ship. According to Dedes et al. (2012), are the largest benefits of such a system that the size of the installed power can be decreased because peak demands are covered by the storage medium, and external emission reduction techniques offer the opportunity to operate at their optimum. Second, Dedes et al. (2012) and Prousalidis et al. (2005) discuss the opportunities for a power take-off system (PTO). A power take-off systems make use of conventional diesel engine, but a generator is installed on the shaft between the propulsion engine and the propeller. A variation to this is system is the installation of an additional gearbox in the system. This gearbox connects the propulsion engine and the shaft generator with the shaft which drives the propeller. The shaft generator is used to power the auxiliary systems, and in case of an emergency it can also drive the propeller (Prousalidis et al., 2005). The main advantage of this system is a substantial reduction in fuel consumption, and thus a reduction in emissions.

Alternative energy carriers	Studies
Hydrogen	Cullinane & Cullinane (2013, 2019)
Liquified natural gas (LNG)	Cullinane & Cullinane (2013, 2019);Port of Rotterdam (2011)
Biofuels	Cullinane & Cullinane (2013, 2019); Balcome et al. (2019); De Rijksoverheid (2019); Panteia (2019)
Biodiesel	Cullinane & Cullinane (2013, 2019); Balcombe et al. (2019)
Biomethanol	Cullinane & Cullinane (2013, 2019); Balcombe et al. (2019)
Electrification	Dedes et al. (2012); Prousalidis et al. (2005)
All-electric system (AES)	Dedes et al. (2012); Prousalidis et al. (2005)
Gas-to-liquid (GTL)	Gill et al. (2011); Xinling & Zen (2009)

Table 2.3

Alternative energy carriers

The alternative energy carriers that have been identified within the literature are presented in Table 2.3.

2.4 Interpretation

This section will discuss the measures as proposed by different authors in their studies. These studies discuss if the measures are feasible and have potential as a reduction measure. Either the technical and policy related measures will be covered in this section. The relevant measures that are most feasible and allow implementation nowadays are concerned as input for the mathematical model. The model will be used to optimize between different alternatives in order to simulate the maximum effectivity with the constraints and vaiables set.

International and national authorities (European Commission, 2016; Municipal Council of Rotterdam, 2010) have tried to apply command-and-control instruments. These instruments refer to the implementation of the PMR and introduction of the Stage V standards. According to the statistics acquired in previous studies (Hopman, 2017; Panteia, 2019; STC Nestra & Rebel Group, 2015), is the PMR not achieving the results as beforehand was the intention. Hence, it is hampering the transition of the inland shipping industry towards more sustainable and less polluting engines and thus achieving the opposite of its intention. A wide range of policy instruments have been proposed by a variety of authors. Port of Rotterdam is not capable of implementing and executing all of these instruments due to the limitations of their jurisdictional authority. Thus, some of these policy instruments are assesed as scenarios in this study. Scenarios are external events that could either happen or not happen.

Port of Rotterdam has two policy instruments at their disposal from a legal perspective. These instruments refer to two economic incentive instruments. Either of these instruments will be assessed in the model. The first instrument is the implication of an emission controlled area (ECA), as already proposed in the most recent PMR. An ECA is only accessible for specific ships that are compliant with the requirements predefined for this area. These requirements refer to the specific emission standards for their ship's engines. A ship owner will be penalised if a ship does not comply with the requirements of the ECA.

The second ecnomic incentrive instrument is a differentiation in port dues. A differentiation program is already operational in the port's area and is called the Green Award incentive program. This program is a differentiation of the port dues in combination with a credit program. A reduction or increase in port dues is charged for the relevant ship owners based on the amount of points scored according to the Green Award incentive program. These points refer to technical specifications that define the amount of emissions emitted.

Lastly, the studies and governmental documents suggest that subsidies are also necessary to create the incentive amongst ship owners (De Rijksoverheid, 2019; Nikolakaki, 2013; Shi, 2016; Zhu et al., 2017). One of the major drawbacks at the moment are the high investments costs of the sustainable alternatives. However, Port of Rotterdam is not an institution that facilitaties individual ship owners in order to make such investments feasible. Multiple academical projects are financed by Port of Rotterdam. These projects will contribute towards the body of knowledge and creates 'green' technologies considering this matter. Thus, subsidies will not be considered in the further extent of this study due to their irrelevance of the purpose of these financial incentives.

The authors have proposed a wide range of configurations and alternative energy carriers that have the potential to substantially reduce polluting and greenhouse gas emissions from conventional diesel engines. These alternatives will be used as configurations in the model if these are feasible in the short-term and have the relevant reduction effectivity.

One of these measures that has shown its effectivity in the past is the implementation of exhaust gas treatment system on conventional diesel engines. According to previous studies (Cullinane & Cullinane, 2013, 2019; Reşitoglu et al., 2015), SCR, DOC and DPF are showing the most potential. A major advantage of these technologies is that they can be used in combination with each other which makes it able to maximise their potential.

Then, De Rijksoverheid (2019) proposed the implementation of NRE. This is a development of the past couple of years and got more attention lately due to the introduction of the PMR and Stage V standards. This alternative has as major advantage that it is either ideal as a hybrid solution or can be installed directly on the drive shaft. When considering a hybrid solution these engines can be in a serial setup, with or without the relevant electrification appendices (Dedes et al., 2012; Prousalidis et al., 2005). However, this alternative is unfortunately infeasible due to the prohibitation with regards to the legal aspects. The authority concerning road- and ship engines has to legally accept this measure as a propulsion option in a marine environment.

Alternative energy carriers can replace the dependence on conventional fossil fuels. In the relevant literature multiple alternatives come forward. At the moment, LNG and hydrogen are not ready for commercial application on a general scale (Balcombe et al., 2019; Bengtsson, 2011; Cullinane & Cullinane, 2013, 2019). However, LNG is feasible and a good solution in particular situations (Balcombe et al., 2019; Bengtsson, 2011). The latter depends on the specific sailing profile and route dependent on the ship which not matches with the fleet characteristics considered within this document. The infrastructure and storage difficulties of both energy carriers are underdeveloped and insufficient (Cullinane & Cullinane, 2013, 2019). Hydrogen shows more potential in the long-term. The alternative energy carriers that are nowadays applicable in conventional diesel engines are biodiesel, methanol and GTL. These fuels are also confirmed as high potential by several authors (De Rijksoverheid, 2019; Gill et al., 2011; Xinling & Zhen, 2009). The reduction potential of these fuels can be increased when these alternatives are integrated in combination with exhaust gas treatment systems (Balcombe et al., 2019; Gill et al., 2011). Nevertheless, methanol is not developed thus far that it is applicable for commerical usage (Cullinane & Cullinane, 2019). A differentiation in these potential fuels will be taken into account when simulating and optimising amongst the alternatives.

Last, electrification of inland ships is applicably and are showing potential. Especially, an AES which could achieve an optimum in fuel efficiency and emissions. Additionally, exhaust gas treatment systems can also operate at their optimum due to constant engine loads. The latter was an incentive for Port of Rotterdam to install such a system in their latest new built vessels and in two of their existing vessels. These vessels will be completed within a short time frame. However, without the ability to store energy in a medium (Dedes et al., 2012; Prousalidis et al., 2005). As with the NRE, the layout that could be applicable for the fleet characteristics as considered in this study is using a hybrid configuration, with the relevant engines in a serial setup. The same holds for the implementation of Stage V engines that have a lower power output and thus falls in a different bandwith with relation to the emissions characteristics.

2.5 Conclusion

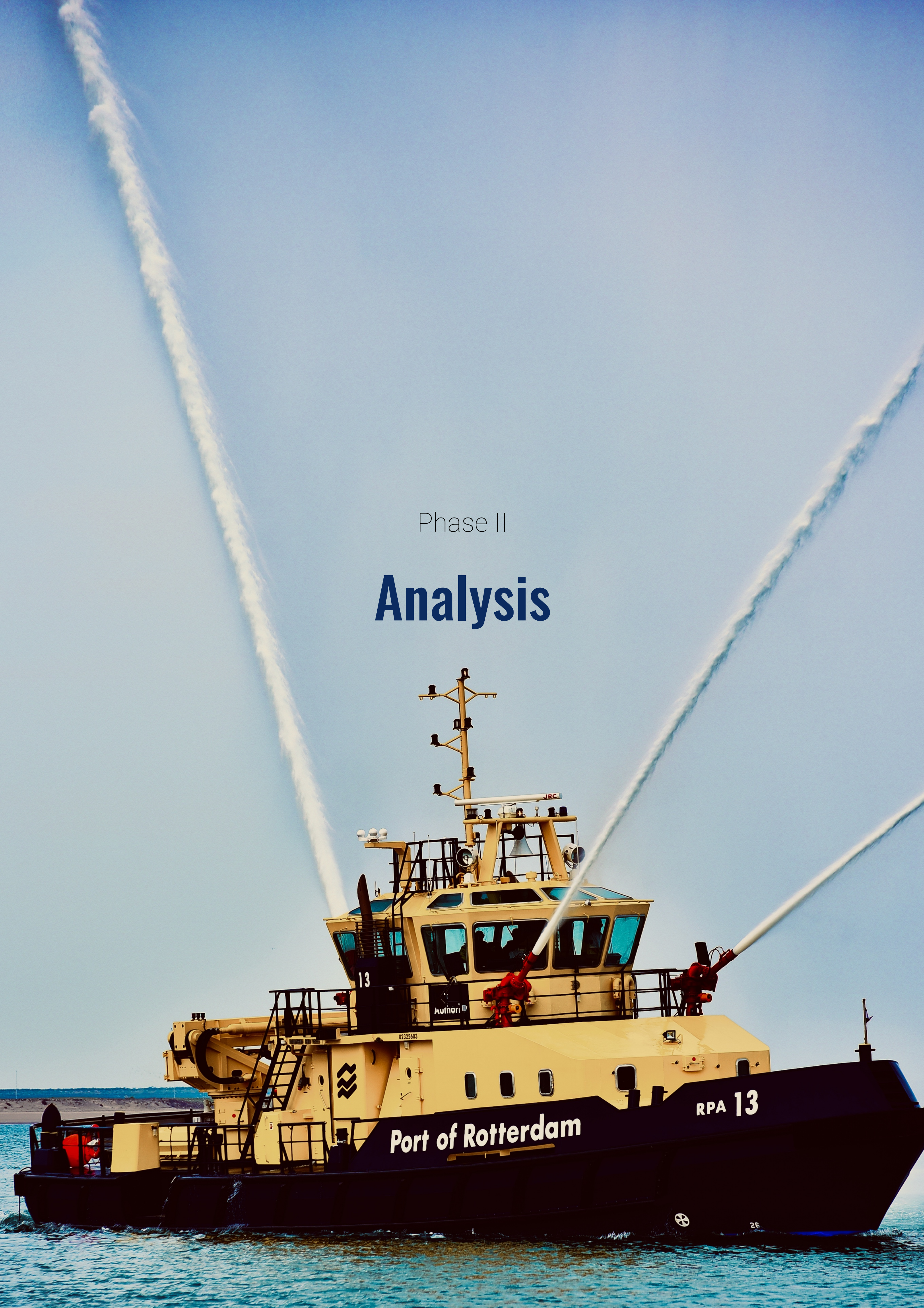
The aim of this literature study is to give an answer to SQ_1. Thus, the goal is to gather an overview of the technical, policy and subsidy measures that are available in the (scientific) literature focussing on the reduction of the emissions of ships. The literature conducted in this study contained a total of fourteen configurations (i.e. technical measures) and seven conditions (i.e. policies and subsidies) that offer the potential to reduce emissions of the (inland) ships.

The configurations were divided amongst two different categories: retrofit options and alternative energy carrier options. The literature covers a total of seven retrofit options and seven alternative energy carrier options. Amongst these retrofit options, the SCR in combinations with other exhaust gas treatment systems is offering the most potential in reducing the emissions caused by inland ships. In addition, the implementation of NRE and AES are also predicted as high potential. Unfortunetaly, NREs are not yet feasible due to legal and jurisdictional reasons. Instead the implication of multiple Stage V engines with a lower power output have the potential to achieve the same. Amongst the alternative energy carriers are biofuel and GTL showing the most potential. Both are commercially available.

Then, the conditions refer to two economic incentive instruments. Two command-and-control instruments were considered in the literature provided by the European Commission and Port of Rotterdam. These instruments were already applied in the form of a limitation on specific pollutants that are emitted by the diesel engines installed in the inland ships. The literature reviewed has covered another seven economic incentive instruments. Amongst these economic incentive instruments the ETS and environmentally differentiated port dues are identified as most effective and suitable in terms of the problem's context. They offer the most potential to reduce pollutant emissions. Especially, due to the fact that these policies incentivize the industry to invest in emission reduction technologies.

As previously described, the origin of the problem and thus the scientific relevance was characterized by the absence of sufficient scientific articles. The latter has made it difficult to gather a sufficient number of articles and publications. This problem was covered by the document published by governmental authorities and their work groups. The same issue was the case for the problem's context in terms of configurations and conditions in the inland shipping industry. Thus, was chosen for a strategy which was focusing on inland ships and sea ships considering their propulsion systems and the relevant emissions. Overall, the literature studied has given a reliable overview of all the reduction measures available, either technical or political. Moreover, an extensive insight has been proposed gained the measures and instruments that are applicable in the nowadays inland shipping vessels, considering to reduce their emissions to comply with European, Municipal and Port Authority regulations.

For the remaining part of this study several configurations and (policy) conditions will be modelled and simulated. Amongst the configurations, the exhaust gas treatment system, implementation of multiple Stage V engines and AES will be modelled and studied. Unfortunately, as previously described, not all the policy instruments as discussed in this document are available to Port of Rotterdam. Thus, the instruments available will be modelled and studied, which are emission controlled areas and differentiation in port dues. Furthermore, the resulting instruments will be implemented in the model as conditions and thus the effect can be monitored.



Phase II

Analysis

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3

System Analysis

In this chapter, the system, in which the fleet of Port of Rotterdam is the subject, is analysed to give an answer to SQ$_2$. This system is modelled using relevant software based on mixed-integer linear programming (MILP) mathematics. The software used is Linny-R, which is a tool that allows industrial processes to be optimized. This chapter will describe the linear programming problem that is modelled and elaborates upon the corresponding aspects. First, the model that is created and the relevant mathematical theory is thoroughly explained. Then, the integrity and reliability of the model are assessed with multiple verification experiments. Last, the model variations that are applied in terms of strategies and scenarios are described.

In the previous chapter, a variety of technical configurations and political instruments have been identified that could effectively reduce greenhouse gas and pollutant emissions caused by the inland shipping industry. A model is created to assess the effectiveness and feasibility of these measures in a digital environment. The model focusses on the vessels that are owned by Port of Rotterdam and are in operation in the port's area. The system in which the fleet of Port of Rotterdam operates is the central aspect of the model. The purpose of these vessels is to guide the traffic within the port's area in a safe manner, enforcement on these waters and act in case of an emergency or incident.

The goal of this model is to gain insights into the effects of individual policies and scenarios on investment decisions related to different technical configurations. The gained insights, effects and results gathered from the fleet of Port of Rotterdam allow expansion towards a more significant part of the inland shipping industry. The configurations considered have in common that they will have a beneficial result towards the climate and living environment. Thus, the purpose of this model is to create an understanding of the different measures as proposed in the studied literature. The model described in this chapter focusses on an accurate representation of the practical situation. Plus, the model is subjected to political instruments and scenarios that could occur shortly.

The type of problem that is concerned within this study is a management issue. In general, such problems fall under operation research science. Within this science, the following equation is used to structure a decision-making problem (Ackoff & Sasieni, 1968).

$$U = f(X_i , Y_j) \tag{1}$$

The U represents the utility or value of the system's performance. Furthermore, X_i represents the variables that can be controlled and Y_j the variables that are not controlled (Ackoff & Sasieni, 1968). The variables that are not controlled are called constraints. The constraints do affect the utility and the relationship between the utility function and X_i and Y_j (Ackoff & Sasieni, 1968). This function indicates that the decision-making problem consists of two types of elements: elements that can be determined by the decision-maker and elements that cannot be determined.

The objective of this kind of problems is the selection of the variables in such a way that the whole function, together with the constraints produces the best outcome, i.e. the optimum. In mathematical terms, the decision-maker has the task of finding the values of the variables X_i

that, with the given function f and the given values of the constraints Y_j produces the desired, best value of the variable U (Ackoff & Sasieni, 1968). As stated by Binnekamp (2018): 'The optimum in the problem is a combination of the values of the variables. Constraints, goals and objectives are used in the optimization process'. The function, as presented in Equation (1) can be formulated in the linear programming problem as described in Equation (2). In this equation, the utility U is replaced by the optimisation parameter Z.

$$Z = f(x_1, x_2, \ldots, x_n) \tag{2}$$

The linear programming problem that is faced in this study will be described first before elaborating the objective function and the following aspects. The model will minimise on costs, thus seeks for the optimum combination of the variables $x_1, x_2, \ldots, x_n$, that gives the lowest value for Z. Equation (3) is adopted as the standard form for the objective function within the linear programming model.

$$f(x_1, x_2, \ldots, x_n)= c_1x_1 + c_2x_2 + \ldots + c_nx_n \tag{3}$$

The mathematical model fulfils the values for the decision variables $x_1, x_2, \ldots, x_n$, which can also be called degrees of freedom, in order to optimise the utility function. In short, the values of the variables $x_1, x_2, \ldots, x_n$ are determined by the model.

The variables $c_1, c_2, \ldots, c_n$ that can be found in Equation (3) are the coefficients that are used within the model. These coefficients are imposed as fixed and represents costs within this model — for example, the fuel prices, investment costs or imposing penalties and fees. The penalties and fees will be elaborated upon further on in this chapter. Moreover, the variables used in the objective function are subjected to restrictions. These restrictions are called constraints. The general representation of these constraints is defined in Equation (4).

$$\begin{gathered} a_{11}x_1 + a_{12}x_2 + \ldots + a_{1n}x_n \leq b_1 \\ a_{21}x_1 + a_{22}x_2 + \ldots + a_{2n}x_n \leq b_2 \\ \vdots \\ a_{m1}x_1 + a_{m2}x_2 + \ldots + a_{mn}x_n \leq b_m \end{gathered} \tag{4}$$

The variables $b_1, b_2, \ldots, b_n$ found in Equation (4) represents the values of certain constraints. These constraints can be considered as fixed. As previously stated, these constraints are predefined criteria. For example, constraints can be imposed by the relevant authorities or due to regulations. Some of the constraints in this situation can be considered as negotiable because they do not relate to physical constraints. This means that when the mathematical outcome is infeasible, it can be changed to feasible due to the adaptive nature of the constraints.

The variables $a_1, a_2, \ldots, a_n$, which can also be found in Equation (4), represent the constants within the model. For example, these constants can refer characteristics relevant to the applicable variable, such as the fuel consumption rate or the emitting rate of emissions. The decision variables have to be nonnegative values, and thus the condition for $x_1, x_2, \ldots, x_n$ is described in Equation (5).

$$x_1 \geq 0, x_2 \geq 0, \ldots, x_n \geq 0 \tag{5}$$

The optimisation problem in this study makes use of integers. Therefore, the objective function will deviate from a regular linear programming objective function and makes use of the additional variables $u_1, u_2, \ldots, u_n$. The general objective function of this form is formulated in Equation (6).

$$f(x_1, x_2, \ldots, x_n) = u_1 c_1 x_1 + u_2 c_2 x_2 + \ldots + u_n c_n x_n \tag{6}$$

The integers $u_1, u_2, \ldots, u_n$ allows that the variables $x_1, x_2, \ldots, x_n$ are subjected to certain constraints, and whenever they do not meet the boundaries of the constraints, these variables are not used or shut off. The general representation of such a constraint is formulated in Equation (7).

$$u_1 b_1 \leq a_{1n} x_n \leq u_1 b_2 \tag{7}$$

The objective function presented in Equation (6) with the corresponding constraint definition in Equation (7) presents the general form of a mixed-integer linear programming (MILP) problem.

3.1 Model

This section will elaborate upon the actual model based on the relevant linear programming theory as described in the previous section. As previously mentioned, Linny-R is used to calculate and simulate the MILP problem. Linny-R makes use of time series (**t**) and can consider multiple time frames ahead to anticipate events that might or might not fire in the future. The model in this study optimizes 16-time steps. Each time step represents a full year, which means the time steps corresponds with 16 years. The period from 1st of January 2020 until 1st of January 2035 will be optimized. This timeframe is equal to the goals and ambitions as agreed upon in the Green Deal, and thus is being used as a governing benchmark (De Rijksoverheid, 2019).

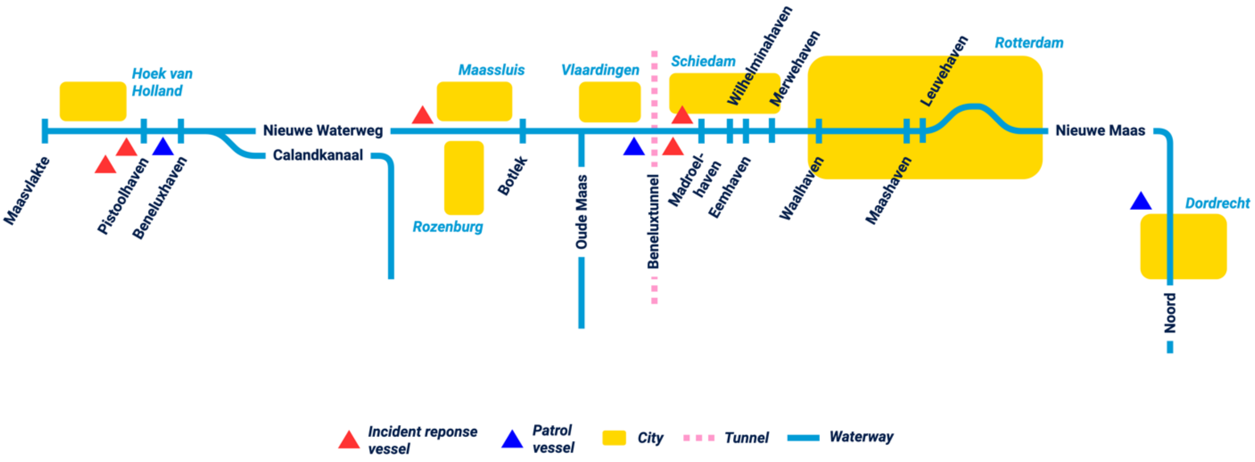

Figure 3.1
Port districts

The philosophy of the model and the corresponding system is that it has to fulfil a particular demand in every timestep taken. The demand for the relevant optimization problem is defined as the physical presence of a vessel in a certain geographical area expressed in hours. This geographical area refers to districts located within the port's area. The distribution of vessels amongst these districts is used to fulfil the required response times in case of an incident and sufficient coverage during patrol shifts. The demand for physical presence has to be fulfilled at the optimum usage of resources, which indicates the problem of fulfilling the demand at a minimum amount of costs.

The incident response vessels are deployed based on continuous shifts (24 hours), and the patrol vessels are deployed in continuous and semi-continuous shifts (16 hours). These relevant deployment hours per vessels are formulated as decision variables $x_1, x_2, \ldots, x_n$ within the MILP problem considered. The complete coverage of the port's industrial area can be fulfilled by five incident response vessels and three patrol vessels. The demand is lower than the maximum number of hours that the fleet can deliver (the supply) which leaves sufficient margin to optimise. The districts as adopted and implemented are shown in Figure 3.1. The described hours of physical presence are a fixed requirement imposed by the Port Authority and the safety region Rotterdam-Rijnmond. The hourly demand for the incident response and patrol vessels can be seen as a constraint. The remaining constraints will be further elaborated in Section 3.1.3.

3.1.1 Problem

The linear programming problem studied is complex. The problem fulfils the required hourly demand of six geographical deployment areas with a variety of eleven distinct vessels. The required propulsion for each vessel can be generated using five alternative technical configurations that could make use of three different types of fuels. Therefore, the formal problem definition is thoroughly elaborated for a single propulsion configuration for one vessel. The configuration considered is the hybrid configuration. Hence, the detailed explanation of this configuration is not relevant in this section and is elaborated in the following sections. The formulation of the linear programming problem of this hybrid configuration represents the problem and mathematics for the whole model. In short, the hybrid configuration is a modification for the relevant vessels and requires an investment, it consumes fuel, delivers hours of propulsion and emits emissions based on the specific fuels used.

The formulation of a MILP problem starts with the definition of the decision variables. The hybrid configurations have four decision variables: (1) the number of hours delivering propulsion, (2) the amount of diesel fuel used, (3) the amount of biodiesel fuel used and (4) the amount of gas-to-liquid fuel used. These decision variables are formulated as follows:

x_{11} = hours of delivering propulsion;
x_{111} = kilograms of diesel;
x_{112} = kilograms of biodiesel;
x_{113} = kilograms of gas-to-liquid;

As previously described, the problem considered is a mixed-integer linear programming problem. Therefore, variable x_{11} is multiplied by an integer variable u_{11}. This integer can either be 0 or 1. This means that the variable x_{11} can be turned on or off, depending on the decisions of the model. The variables $x_{111}, x_{112}, x_{113}$ are indirectly affected by the integer as well, but this can be found in the constraint definition and therefore do not require to be multiplied by an integer variable. The described degrees of freedom and integer variable result in the objective function as formulated in Equation (8).

$$\min Z = f(x_{11}, x_{111}, x_{112}, x_{113}) = u_{11}c_{11}x_{11} + c_{111}x_{111} + c_{112}x_{112} + c_{113}x_{113} \tag{8}$$

As previously mentioned, the objective function will be optimised in terms of costs. The variables $c_{11}, c_{111}, c_{112}, c_{113}$ are coefficients referring to the relevant costs. The integer variable u_{11}

for x_{11} allows the implementation of the investment costs of the relevant technical alternative in the model. If the model decides to choose a particular technical configuration, it incorporates the relevant investment costs of this alternative and thus compares the relevant investments costs for the variety of alternatives. The last step in the formulation of the problem is the definition of the constraints. The first constraint is relevant for the decision variable x_{11} representing the required number of hours propulsion. The relevant constraint is formulated in Equation (9).

$$u_{11}b_1 \leq x_{11} \leq u_{11}b_2 \tag{9}$$

The constant b_1 refers to the lower bound and b_2 to the upper bound of the required hours of propulsion. If the model does not select the hybrid configuration, the relevant integer variable u_{11} will be equal to 0 – and thus it shuts off. Otherwise, it will be equal to 1, then the investment for the relevant alternative is made. The next constraint is applied to the fuel mixture. The hybrid configuration requires a certain rate of fuel consumption per hour, defined as a_1, and this can be fulfilled by three types of fuel defined as $x_{111}, x_{112}, x_{113}$. The relevant constraint is defined as formulated in Equation (10).

$$x_{111} + x_{112} + x_{113} = a_{11}x_{11} \tag{10}$$

This constraint shows that a configuration is not obliged to use one particular fuel, but a blend is allowed as well. The goals of the Green Deal describe certain reductions per CO_2, NO_x and PM. These reductions are implemented as multiple constraints and are related to the amount of fuel consumed and the type of fuel. These constraints are formulated in Equation (11), (12) and (13).

$$a_{111}x_{111} + a_{112}x_{112} + a_{113}x_{113} \leq b_3 \tag{11}$$

$$a_{111}x_{111} + a_{112}x_{112} + a_{113}x_{113} \leq b_4 \tag{12}$$

$$a_{111}x_{111} + a_{112}x_{112} + a_{113}x_{113} \leq b_5 \tag{13}$$

The constraints b_3, b_4, b_5 define the upper bound of the maximum amount of emissions in CO_2, NO_x and PM as allowed. In this model, these bounds change throughout the time based on the Green Deal. The relevant constants define the factor of emitted emissions. Additionally, the ECA, as defined by the PMR, is incorporated in the model as a constraint as well. This constraint will be implemented for the relevant technical alternatives, which is not the hybrid configuration, as presented in Equation (14). The ECA is not applicable for the hybrid alternative, and thus not relevant. This constraint is applicable when $t \geq 6$.

$$x_{pq} = 0 \tag{14}$$

The other policy instruments, as defined and described in the previous chapter, are incorporated as model variations in terms of costs. These variations are described in Section 3.2. A model variation means that a distinct model is created to assess a specific policy instrument. The definition of coefficient c_{11} is presented in Equation (15).

$$c_{11} = k_{INVESTMENT} + k_{UREA} \tag{15}$$

The parameter $k_{INVESTMENT}$ refers to the required investment costs divided into costs per hour for the corresponding time frame. The parameter k_{UREA} refers to the urea costs per hour if the relevant alternative consumes urea. The coefficients c_{111}, c_{112}, c_{113} refer to the specific fuel costs k_{FUEL} per kilogram.

The above formal description represents a relatively simple MILP problem. Due to the complexity of the actual MILP problem considered in this study, and the number of decision variables, integers, coefficients, constants and constraints, is the formulation of the complete problem limited to the formulation as described above. This formulation forms the basis for every technical configuration for each vessel. The actual model and a thorough presentation of all the vessels, including their alternatives can be found in Appendix D.

The actual model, as formulated within Linny-R, and the schematic representation, are divided into a front-end and a back-end. Linny-R makes use of a graphical representation of the MILP problems solved using this software. Either the front- and back-end of the model are visualized in a full-page simplistic representation of both these partial models which can be found in Figure 3.2 and Figure 3.3. The front-end of the model, as presented in Figure 3.2, represents the variety of incident response vessels and patrol vessels fulfilling the demand per geographical location. The demand will have to be fulfilled by a total of seven incident response vessels and four patrol vessels. This fulfilment is covered within the front-end of the model. Then, the specific demand in hours per vessels has to be fulfilled by an equal number of hours in propulsion. This propulsion is delivered with a power train, and the hourly demand has to be fulfilled, selecting between a range of technical alternatives. The latter equals the back-end of the model and is presented in Figure 3.3. Keep in mind that for every vessel, a partial back-end model is created and active within the optimisation process.

During the optimization process, the model will seek the combination of decision variables and constants, which hold the lowest hourly costs that will fulfil the demand. This is called the optimum in the utility function, and thus the optimum of the objective function. The optimization process is iterative. This iterative process will be repeated every time step as defined in the model. The specific data used within the model for all the alternatives per vessel can be found in Appendix B and Appendix C. Including, the relevant fuel consumption and specific fuel emissions.

In the remainder of this study, the model will be used to study different scenarios that could be activated and what strategies apply to the situation as described in this document. To that extent, the functionality of assessing and simulating port dues and penalties is incorporated within the model. Accordingly, the taxes related to the specific greenhouse gas emissions can be simulated. An extensive elaboration upon the different scenarios studied using the model can be found in Section 3.2.

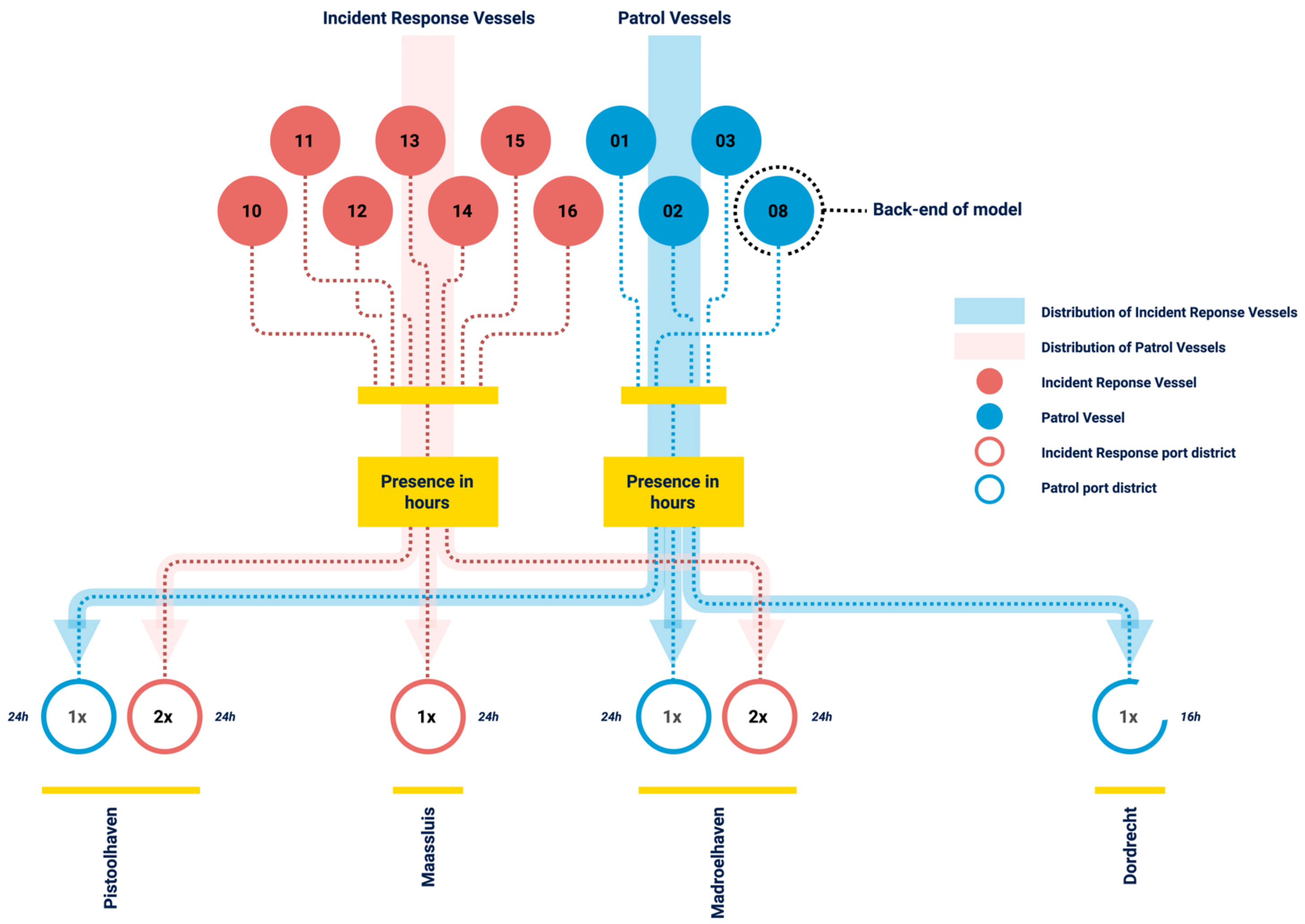

Figure 3.2
Front-end of the model

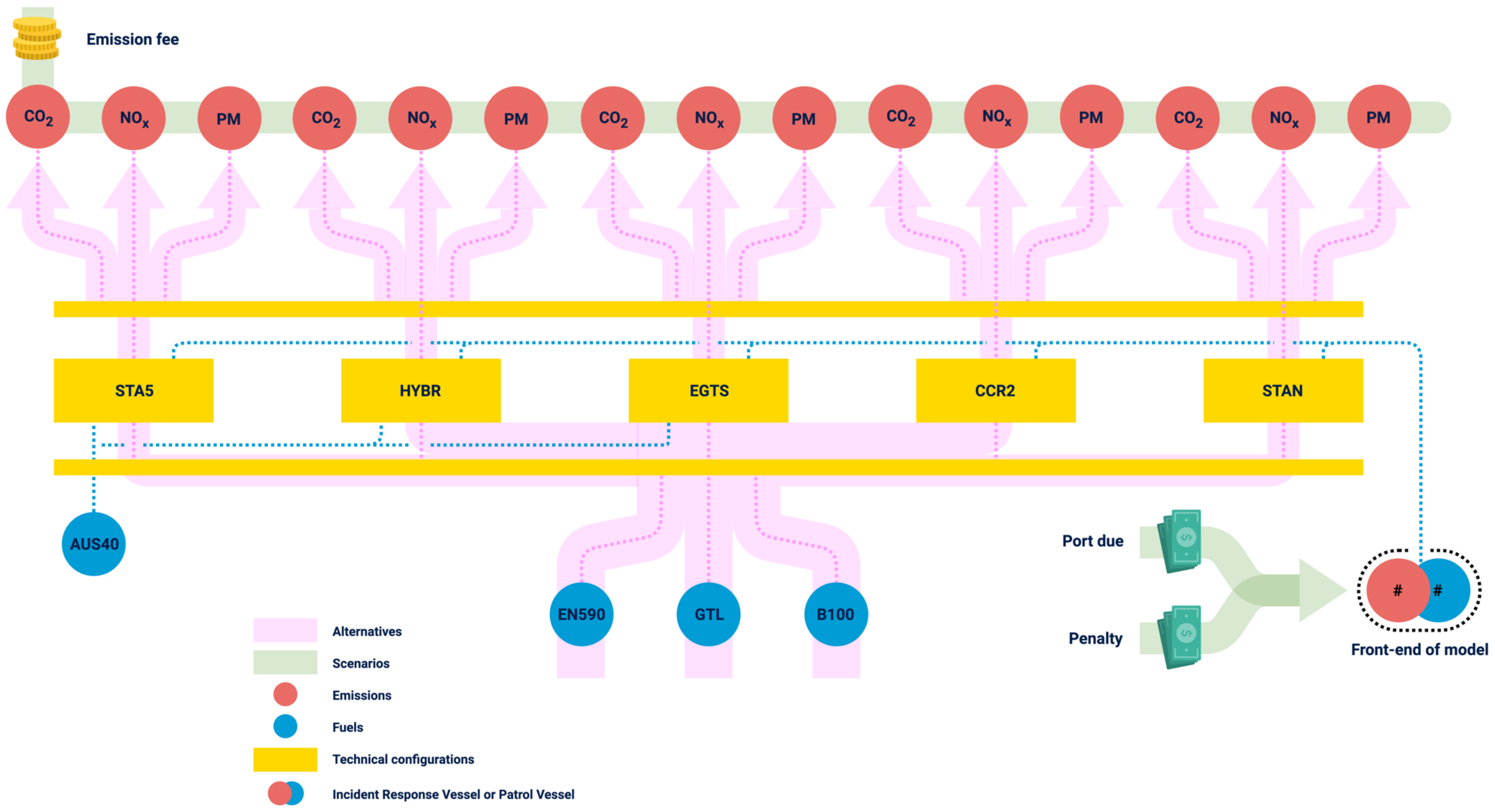

Figure 3.3
Back-end of the model

3.1.2 Decision variables

This section describes the decision variables used in the model. As previously described, the hours of presence per vessel are formulated as decision variables and are defined as $x_1, x_2, \ldots, x_p$. The remainder of the decision variables refer to the technical configurations, defined as $x_{p1}, x_{p2}, \ldots, x_{pq}$, and the alternative fuels, defined as $x_{pq1}, x_{pq2}, \ldots, x_{pqr}$. The configurations are explained to create an understanding of the content of the alternatives. Consequently, the available fuels are elaborated upon.

Five alternatives are applicable for every vessel, with some exceptions for specific vessels due to recent modifications or deviating layout. The five configurations are divided into the (current) standard configuration (STAN), CCR2 engines configuration (CCR2), the application of an exhaust gas treatment system (EGTS), a hybrid configuration (HYBR) and a hybrid Stage V engine configuration (STA5). These configurations are developed based on the insights acquired, as described in Chapter 2 and are described more thoroughly accordingly.

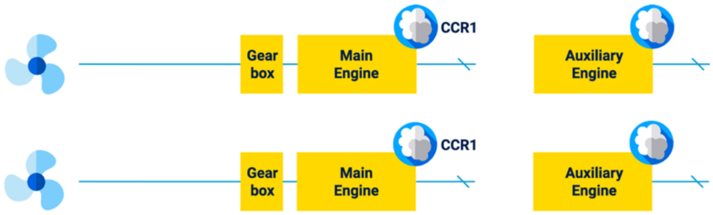

Figure 3.4
Standard configuration (STAN)

First, the standard configuration represents the configuration as it is already installed onboard. The standard configuration is the baseline, and from there on variations are introduced, the so-called retrofit options. The power output of these configurations varies from 485 kW up to 635 kW per main engine relevant to the concerned vessel. This configuration has a conventional layout. This means that the main engines directly drive a gearbox that drives the propeller shaft and the propeller itself. An additional two auxiliary engines are used to power the onboard network and other appendices. A simplified scheme of the standard configuration is shown in Figure 3.4. This configuration is compliant with the CCR1 emission requirements.

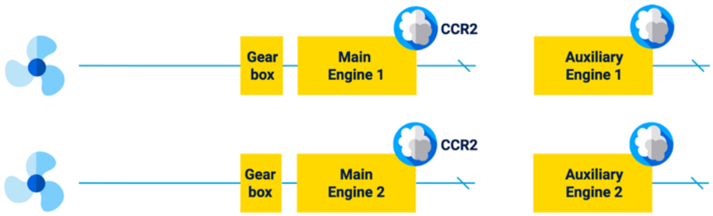

Figure 3.5
CCR2 engines configuration (CCR2)

Second, the configuration of the CCR2 engines is equal to the layout of the standard configuration. In this configuration, the two main engines are replaced by CCR2 certified engines. The main engines will have the power output as relevant to the applicable vessel.

According to Panteia (2019), a trend is ongoing that indicates that CCR2 engines are massively bought and installed amongst inland shipping owners. Therefore, this configuration is incorporated. This investment allows ship owners to comply with the latest port and European regulations. A simplified scheme of the CCR2 configuration is shown in Figure 3.5. This configuration pollutes according to the limits as specified in the CCR2 regulations.

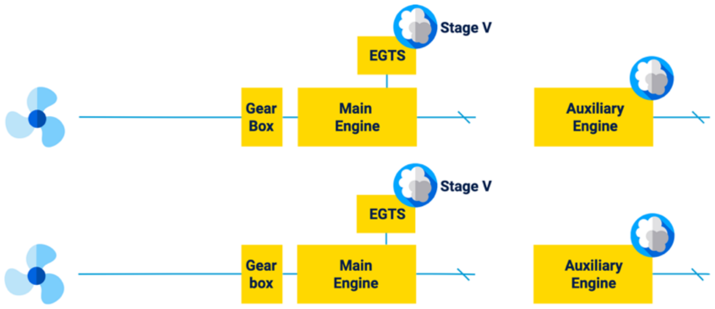

Figure 3.6
Exhaust gas treatment system configuration (EGTS)

Third, the exhaust gas treatment system is an addition to the standard configuration. This addition consists of a DPF and a SCR. The combination of these two appendices is sufficient to reduce the NO_x and PM within the latest regulatory boundaries. A thorough explanation of how these appendices work individually is described in Chapter 2. A simplified scheme of the exhaust gas treatment system configuration is shown in Figure 3.6. This configuration pollutes according to the limits as specified in the Stage V regulations.

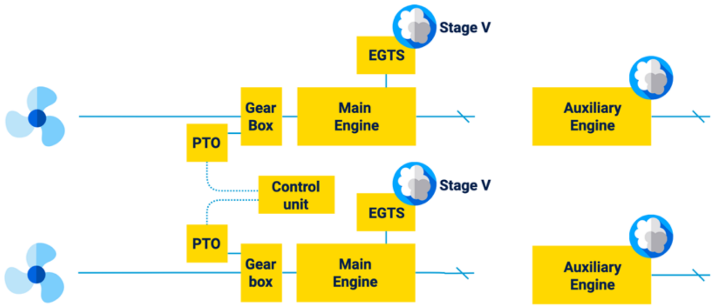

Figure 3.7
Hybrid configuration (HYBR)

Fourth, the hybrid configurations are modification to the standard configuration that has more impact. This configuration is based on the AES. As previously mentioned, the maximum potential of these engines is rarely used. Thus, this incentive has led to the development of a hybrid layout using the existing propulsion engines. The standard layout is expanded with two PTOs directly installed on the gearbox or propeller shaft. These PTOs can either generate electricity or add (additional) power on the shaft.

Additionally, a control unit is installed, which directs the generated power from the PTOs two both propellers. Hence, both main engines have also been fitted with an exhaust gas treatment system. This layout allows one engine operates most efficiently in terms of fuel efficiency and combustion temperature. Thus, a single engine can power both propellers.

In short, the hybrid configuration will result in better fuel efficiency and substantially lower emissions. It makes use of the engines that are already installed aboard. The only downside to this system is that it is not able to power the onboard network and its relevant appendices, which means that this configuration still requires a dedicated auxiliary engine. A simplified scheme of the hybrid configuration is shown in Figure 3.7. After applying this configuration, the main engines will operate and pollute equally to the Stage V standard.

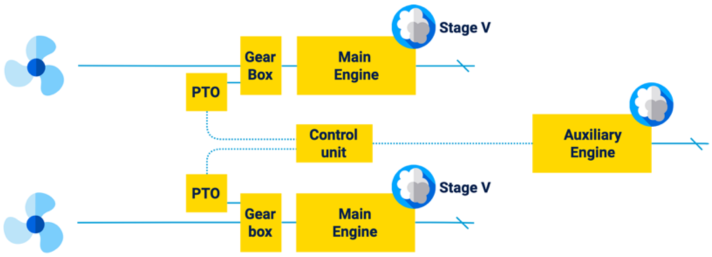

Figure 3.8

Stage V engines configuration (STA5)

Fifth, the Stage V configuration makes use of the same layout as used with the hybrid configuration. The main difference of this configuration is that it consists of three newly installed engines, which can power both the propellers, the onboard network and the relevant appendices. These engines have an individual power output of 295 kW that makes them less strict in terms of regulatory requirements. These engines can thus be Stage V certified due to the relevant power output. The reason that this configuration is incorporated as an alternative is due to the current regulatory landscape. The latest regulations are steering towards the implementation of these engines. Thus, the suitability and feasibility of these engines and their characteristics can be assessed in relation to the alternatives.

Dec. variables	Specification	Abb.
$x_1, x_2, \ldots, x_p$	Incident Response– and Patrol Vessels	-
$x_{p1}, x_{p2}, \ldots, x_{pq}$	Standard configuration	STAN
	CCR2 engines configuration	CCR2
	Exhaust gas treatment system configuration	EGTS
	Hybrid configuration	HYBR
	Stage V engines configuration	STA5
$x_{pq1}, x_{pq2}, \ldots, x_{pqr}$	Diesel	EN590
	Biodiesel	B100
	Gas-to-liquid	GTL

Table 3.1

Decision variables

The operational characteristics of this configuration are the same as for the hybrid configuration. One engine is used to power both propellers using two PTOs. A dedicated auxiliary engine is installed. When the onboard network requires power, this engine can be used, but this engine can also power both propellers. Thus, the three engines can all individually power the propellers and the onboard network. One of the main engines is, during normal conditions, powering the onboard network and the appendices. A simplified scheme of the Stage V configuration is shown in Figure 3.8. This configuration pollutes according to the limits as specified in the Stage V regulations.

The five configurations, as described, require fuel to operate. The fuels are defined as x_{pq1}, x_{pq2}, ..., x_{pqr} and present in total three different fuels. Besides conventional diesel (EN590), the model can fulfil this variable with biodiesel (HVO B100), gas-to-liquid (GTL) or a mixture of the three. The decision variables formulated in the objective function, and used in the model, are presented in Table 3.1.

3.1.3 Constants

This section describes the constants used in the model. The constants refer to specific characteristics that are relevant for the corresponding decision variables. For example, the constants a_1, a_2, ..., a_p are applicable to the decision variables x_1, x_2, ..., x_p. To be able to determine the values for these constants, a sufficient quantity of data is required. The data used to define the values for the constants are derived from the available data sources. First, the relevant data was gathered and processed in an organized and usable manner. Second, some data was used to calculate the specific emissions per hour or consumed quantity of fuel. The year of reference used is 2018 –the data acquired referring to the fuel consumption and the geographical deployment area are based on that year.

The fuel consumption data of the fleet is continuously monitored and registered in the data management system of Port of Rotterdam. This data is made available for the execution of this study. Additionally, the operating hours of all the specific engines installed onboard the vessels are also registered within this system. The combination of the fuel consumption numbers with the operating hours have been processed into the specific consumption and emissions during certain engine loads. Unfortunately, the engine loads are not monitored throughout the lifetime of the engine and are subjected to changes when the vessels are deployed in different areas of the port. A fixed pattern of engine loads, which is called a sailing profile, is adopted due to this uncertainty.

This sailing profile is partly based on the previous studies and calculations matching the specific fuel consumption. In total, two studies were available, indicating sailing profile characteristics. These studies have been used for two purposes: (1) to get an indication of the sailing profile and (2) to gather more engine specific data. The first study was focused on the difference between conventional diesel and biodiesel (TNO, 2012). The other study focusses on the electrification possibilities of certain vessels (Bureau voor Scheepsbouw, 2014). The last study confirms the assumptions that the maximum potential of the power train of the vessels are hardly ever used. More specific, almost 90% of the time the vessel is operating using 20% of the maximum available power.

The load curves and test cycles of the (main) engines installed in the vessels are available. This data refers to the specific fuel consumption per required power output. It is essential to mention that the information published in the report was based on the engines installed on a load bank and not in the real environment. Thus, an inevitable efficiency loss is not incorporated. The engine data for the alternatives containing new engines were retrieved from their manufacturers, including the relevant installation costs. The allowed emission limits as specified by the different regulatory bodies were retrieved from their authority institutions. The load curves, from the corresponding engines, used can be found in Appendix B.

Moreover, based on the type of fuel used, certain CO_2 emission factors have to be used in order to determine the footprint in terms of kilograms CO_2 per unit of combusted fuel (Lijst CO2-emissiefactoren, 2019; Shell Global, n.d.). In order to establish the costs and the costs per unit of fuel, the relevant data monitored by Port of Rotterdam has been used. Together with the fuel consumption per vessel, the related costs have also been monitored. The fuels that do not fall within the portfolio of Port of Rotterdam have been determined based on data found in literature and provided by suppliers (EIBIP, 2018; OlieDienst.nl, 2019). The costs are further elaborated in Section 3.1.6.

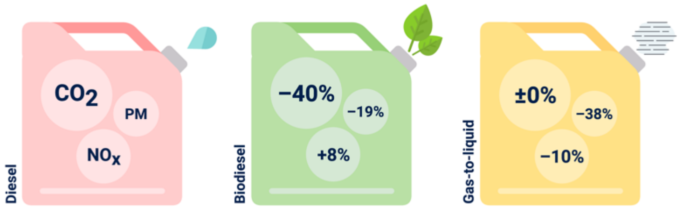

Figure 3.9
Fuel characteristics

The combination of the above-described data made it possible to calculate the specific fuel consumption for the adopted sailing profile. The adopted sailing profile refers to the profile as described within the studies. First, iteratively the fuel consumption as registered within the data management system was matched using the specific engine data. The maximum allowed error during this process was a bandwidth of 10%. Second, the combination of engine loads and fuel consumption is used to calculate the quantity of greenhouse gas and pollutant emissions per operating unit or combusted quantity of fuel. Furthermore, this process is executed for the existing configuration of the vessel, and the newly adopted alternative configurations. The full calculation and extent of the data, as described above, can be found in Appendix B.

The fuels used have specific burning characteristics. These characteristics determine the relevant emissions of the engines. The relative characteristics in terms of the CO_2, NO_x and PM are presented in Figure 3.9 in relation to diesel. These characteristics are formulated as constants within the MILP problem and are based on studies conducted by several research institutes.

Constants	Applicable to	Specification
$a_1, a_2, \ldots, a_p$	$x_1, x_2, \ldots, x_p$	Not specified, equal to 1.
$a_{p1}, a_{p2}, \ldots, a_{pq}$	$x_{p1}, x_{p2}, \ldots, x_{pq}$	Quantity of fuel consumed per hour (in kilograms).
		Quantity of urea consumed per hour (in kilograms).
$a_{pq1}, a_{pq2}, \ldots, a_{pqr}$	$x_{pq1}, x_{pq2}, \ldots, x_{pqr}$	Quantity of CO_2 emitted per kilogram of fuel (in kilograms).
		Quantity of NO_x emitted per kilogram of fuel* (in kilograms).
		Quantity of PM emitted per kilogram of fuel* (in kilograms).

**) Based on a fixed sailing profile and an average, constant quantity, of consumed fuel per hour per alternative.*

Table 3.2
Constants

The relevant studies applicable to the emission data of biodiesel were performed by specialist measurement authorities, and they published their findings based on the sailing profile and performance criteria applicable to the fleet (SGS Nederland BV, 2019; TNO, 2012). SGS Nederland BV (2019) concluded that when the ship engine was running on B100, an increase was measurable of 8% in NO_x and a reduction of 19% was measurable in PM. This measurement was based on the sailing profile of the Port of Rotterdam fleet in real-world conditions. Additionally, the studies applicable to the emission data of GTL are performed by TNO and EIBIP (EIBIP, 2018; TNO, 2014). TNO (2014) concluded that when a ship engine was running on GTL, a reduction was measurable of 8 to 13% in NO_x and 15 to 60% in PM.

The constants formulated in the MILP problem, and used in the model, are presented inTable 3.2.

3.1.4 Integers

This section describes the integers used in this model. The integers refer to whether a decision variables is shut on or off. Therefore, the decision variables that refer the vessels ($\mathbf{x_1, x_2, \dots, x_p}$) and configurations ($\mathbf{x_{p1}, x_{p2}, \dots, x_{pq}}$) are subjected to corresponding integers. These integers are defined as $\mathbf{u_1, u_2, \dots, u_p}$ and $\mathbf{u_{p1}, u_{p2}, \dots, u_{pq}}$. The integers are used to prevent the model selecting combinations of vessels and relevant alternatives at the same time. This combination is in the actual situation not possible. Thus, the selection of a particular vessel and alternative could be accuretaly be implemented using integers.

In this model, the integers have another purpose as well. The integer determines if the required and relevant investment of a specific alternative is being executed or not. It implements the investment within the cost coefficient of the relevant alternative, and considers if the required investment is feasibile or not.

3.1.5 Constraints

This section describes the constraints used in this model. The constraints refer to the demand requirements as imposed by the Port Authority, the different regional and European regulations and the goals and ambitions as agreed upon by the relevant parties. The coefficients used cover the physical characteristics of the different alternatives, the required investment costs and fuel prices. The constraints do not correspond to a specific decision variable, and are defined as $\mathbf{b_1, b_2, \dots, b_n}$.

As previously described, the demand is considered as a fixed constraint. The demand refers to a fixed required number of hours presence in a particular district by the incident response and patrol vessels. Second, a set of fixed constraints refers to the requirements as written in the PMR and the EU2016/1628. The PMR refers to the prohibition of propulsion engines lower than a CCR2 standard running in the port's area from 2025 onwards and the EU2016/1628 to the requirements of installing engines compliant with the Stage V emission requirements from 2022 onwards, taken into account a two-year transition period (Municipal Council of Rotterdam, 2010).

Third, a set of negotiable constraints refers to the goals and ambitions as agreed upon in the Green Deal. The Green Deal is a mutual agreement between a coalition of companies active within the sea shipping industry, inland shipping industry and ports in combination with societal organizations and local and national government (De Rijksoverheid, 2019).

The Green Deal was signed and published on the 11th of June (2019). One of the companies that agreed upon the content of the Green Deal is Port of Rotterdam. Furthermore, all leading parties within the inland shipping industry were involved in the creation of the Green Deal and have all agreed upon the content of the deal. Green Deal is thus ultimately the most essential constraint to which the model is optimising, due to the content and context of this deal. The downside is that the agreement is based on intentions, which means that it is not obligatory.

The year of reference used in the Green Deal is 2015, but in this study 2018 is used due to the lack of data and data quality of the corresponding year.

Constraints	**Relevant to**	**Specification**
$b_1, b_2, ..., b_n$	Areas and Ships	Required hours of presence.
	Configurations	Required hours of propulsion.
		In 2025 – Engines lower than CCR2 are prohibited.
	Emissions	In 2024 – A reduction in CO_2 of at least 20%*.
		In 2024 – A reduction in NO_x and PM of at least 10%*.
		In 2030 – A reduction in CO_2 of 40% up to 50%*.
		In 2035 – A reduction in NO_x and PM of 35% up to 50%*.

**) Compared to 2018.*

Table 3.3
Constraints

Nevertheless, this constraint does not refer to physical characteristics. In the case of an infeasible solution, the constraints can be negotiated to create a feasible solution. The constraints, as described above, are presented in Table 3.3. The hourly demand, as mentioned in Section 3.1, is excluded from this table.

3.1.6 Coefficients

This section describes the coefficients used in the model. The coefficients refer to the costs applicable to the corresponding decision variable and are formulated in the objective function. For example, the coefficients $c_1, c_2, ..., c_p$ are applicable to the decision variables $x_1, x_2, ..., x_p$. The coefficients can be divided into costs related to an individual policy instrument, investment costs of the relevant alternative and fuel prices (including urea). The costs related to policy instruments are further elaborated in Section 3.2.

Coefficients	**Applicable to**	**Specification**
$c_1, c_2, ..., c_p$	$x_1, x_2, ..., x_p$	Not specified, equal to 1.
$c_{p1}, c_{p2}, ..., c_{pq}$	$x_{p1}, x_{p2}, ..., x_{pq}$	Urea (€ 0.30 a kg)
		Investment costs (per hour – if applicable)
		Port dues or penalties (per hour – if applicable)
$c_{pq1}, c_{pq2}, ..., c_{pqr}$	$x_{pq1}, x_{pq2}, ..., x_{pqr}$	Diesel (€ 0.49 a kg)
		Biodiesel (€ 1.05 a kg)
		Gas-to-liquid (0.54 a kg)
		Emission fee (a kg – if applicable)

Table 3.4
Coefficients

The investments costs of the alternatives are based on the individual costs required for this specific alternative. In the past, multiple requests for modification of the vessels have been executed. All these requests and the related invoices are available within the data management system of Port of Rotterdam. These invoices have been used to establish the relevant investment costs for the appendices within the different configurations.

The remainder of the coefficients is related to fuel costs. In total, four prices have been established. The prices of EN590 and B100 are based on the bunker history data provided by Port of Rotterdam. The prices for GTL and Urea have been established based on the data found in literature and provided by suppliers (EIBIP, 2018; OlieDienst.nl, 2019). The prices are implemented as fixed coefficients in the model.

An overview of the coefficients that have been used can be found in Table 3.4. The extensive data for the specific investments costs per alternative can be found in Appendix C.

3.1.7 Verification

The integrity of a model and the reliability of the insights and results are of major importance. In order to confirm a certain level of integrity and reliability, a verification process should be followed (ProModel Corp., 2011). The verification process of this model is executed and described accordingly within this section. Verification can be done according to two different processes and refers to demonstrating that a model works as it was intended to and the degree to which the model corresponds with the real system. The latter refers to the actual representation of the real-world system. Both processes indicate if a model is sufficiently accurately representing the actual situation (ProModel Corp., 2011).

In total, four verification experiments have been conducted to affirm the integrity and accurate representation of the model. The first three verification experiments are based upon the calculation of extremes. Using extremes is useful in order to determine the integrity and trivial solutions. The fourth experiment is based upon the current regulatory landscape and used to determine the predictiveness of the model, which allows determining the actual representation of the model of the real world.

The first verification experiments consider the fuel price. If the model is subjected to an artificially high price for the coefficient corresponding to the diesel fuel decision variable (i.e. €100), it is expected that the alternative fuels are considered and chosen. This is in-line with the optimization process within the model. It will seek the lowest costs to fulfil demand. The model succeeds in this experiment. The second experiment considers the costs of a specific alternative. This alternative is focused on the hybrid configuration. This configuration is efficient in terms of fuel consumption and produces the lowest environmental emissions. If the investment cost coefficient for this alternative are set artificially low (i.e. €1), the model is expected to choose for this alternative. The latter is in-line with the optimization process within the model and is optimum to comply with the emission constraints. The model succeeds in this experiment. The third experiment considers the demand for the model. The model is focused on complying with the emission constraints and fulfilling the required demand. To reduce the emissions, the most trivial thought is not to use the vessels at all, and thus there are no greenhouse gas and polluting emissions. It is expected that when the constraints corresponding to the hourly demand of the model is removed, the vessels are not used according to the characteristics and the method the model is built upon. The model succeeds in this experiment.

The fourth verification experiment that is conducted is focussed on the implementation and governance of the PMR in combination with the latest European Commission regulations. As previously described, the PMR prohibits entrance towards the port's area with engines less than the CCR2 standard from 2025 forwards. The current market statistics and trends observed by different authorities (i.e. Port of Rotterdam, EICB and VIV) are indicating that ship owners are investing in CCR2 engines to comply with the latest European Commission regulations and still have access to the port's area (Panteia, 2019). It is expected that when this political landscape is implemented in the model, the model will choose for the CCR2 configuration to comply with the demand. The political landscape is implemented as follows: a limitation of the CCR1 process from 2025 onwards plus a limitation to of the CCR2 process from 2022 onwards. The model failed this experiment due to the investment cost coefficients. The investment costs for an exhaust gas treatment system are lower than the costs for CCR2 engines, which made the model decide for the exhaust gas treatment system alternative. To successfully verify the model, and still execute this experiment, the investment costs for the exhaust gas treatment system were increased to a level that the CCR2 engines were cheaper. Consequently, the experiment succeeded, and the model was verified, requiring two-steps.

Method	**Experiment**
Verification experiment using extremes.	Increased coefficient (c_{pqr}) for fuel (x_{pqr}).
Verification experiment using extremes.	Decreased coefficient (c_{pq}) for configuration (x_{pq}).
Verification experiment using extremes.	Removing constraints (b_n).
Verification experiment based on predictiveness.	Combination of constraints (b_n) and coefficients (c_{pq}).

Table 3.5

Verification experiments

The above described failed experiment increased the integrity of the model due to the understanding and insights of the decisions the model took. Based on this experiment, certain conclusions could be drawn in relation to the investment decisions the ship owners are currently taking. This conclusion is dependent on the investment coefficients that are being used. An overview of the four verification experiments executed are summarised in Table 3.5.

3.1.8 Simplifications

The integrity of the results and insights acquired according to the model depend on an accurate representation of the real-world situation. To achieve this, the model has to be verified. This process is described in Section 3.1.7.

Deviations in interfaces between the model environment, the software and the real-world led to the implementation of simplifications. The latter could also be entitled as model limitations. The following summary shows the simplifications applied in the model. Furthermore, the summary of simplifications is followed by uncertainties that are present within the model.

1. A specific alternative requires some time to be installed in the vessel and become operational. This time could increase to a couple of months. Additionally, the (remaining) lifetime of the alternatives and vessels itself is not incorporated. Both these limitations are applied due to software limitations and their irrelevance to the goal and purpose of the model.
2. Port Authority demands a required amount of extinguishing volumes at a specific location within a maximum timeframe. Sailing times do not lend themselves for implementation in a model, because they are profoundly affected by location and moment of an incident. Instead, a more simplified demand is implemented; districts. The district division, which is also used by the Port Authority to schedule the employment of the vessels, is used as a reference for the requirements as described above.
3. The model represents a specific timeframe and incorporates alternatives and developments that are available to the market at this moment in time. In the near future, many developments and alternatives will become available to the market due

to the current ongoing energy transition. These developments and alternatives have not been implemented in the model because they are unknown.

4. A fixed sailing profile is used to simulate the behaviour of the fleet. The sailing profile of a specific vessel is subjected to variations and depends on different criteria. For example; currents, winds, user, deployment area, type of operation, etc. Due to these uncertainties, a fixed sailing profile was adopted. This profile is widely accepted as a profile that represents the usage of the vessels in general.

The model is subjected to certain factors that are applied based on assumptions or real-world information. It is not sure that these factors will hold throughout the timeframe of the model. It is uncertain what the future holds, and if the relevant variables, coefficients or constraints are still applicable in the relevant timeframe. These uncertainties are identified as follows.

1. Fuel prices are regularly subjected to price fluctuations. Fixed fuel prices are used based on a two-year average. The incorporation of price deviations is irrelevant to the goal and purpose of the model but could influence certain decisions that the model suggests. Due to the latter, this is considered as an uncertainty.
2. Investment costs of the alternatives are based on invoices gathered by Port of Rotterdam in the past. These invoices are dependent on the time of application, specific techniques and the relevant supplier. These dependencies are relevant to the price given at that moment in time. A possible price deviation is not considered within the model and can be seen as an uncertainty.
3. In the past, the requirements imposed by Port Authority were subjected to regular modifications. A fixed hourly demand for the vessels is adopted in the model. The relevant requirements could be changed in the future due to shifts in responsibilities. Thus, this is considered as an uncertainty.
4. The regulatory landscape is nowadays subjected to quite some changes. If specific climate and living environment goals are not met shortly, hard measurements will be introduced by the government. Such measurements could have a substantial impact on investment decisions and fuel prices. The insecurity of the regulatory landscape is not incorporated and is considered as an uncertainty.
5. Port dues have been incorporated in the model as a variable. In general, vessels owned by Port of Rotterdam are not required to fulfil these dues but to uphold the interface with the inland shipping industry, this variable is incorporated. The costs related to the port dues have been fixed to a sum that is equal to the highest amount that a ‘similar’ vessel should pay and not to the specific characteristics of the vessel (i.e. € 0.10 per hour based on a yearly fee of €876 – Passenger Ships and Tugs’, as defined in Annex 1, Paragraph 4, Table 1, Column (c), of the General Terms and Conditions regarding Port Dues (Port of Rotterdam, 2013, p. 32). Thus, the 'real' port due for an individual vessel could deviate from the due that is adopted in the model and is thus an uncertainty. On the other hand, the port due differentiation based on the engine standards (bonus/malus arrangement) is incorporated.

3.2 Strategies and scenarios

This section will elaborate upon the strategies and scenarios that have been simulated using the model. These strategies and scenarios are established based on the insights gathered during the literature study and study of public authority related documents (e.g. Green Deal). In total, two strategies and two scenarios have been simulated. The first scenario considers the actual situation, without any interventions from public or port authorities. The second scenario simulates a possible intervention by the public authorities when the goals and ambitions of the Green Deal will not be met based on the polluter-pays principle. The two strategies simulate the policy instruments that are available to Port of Rotterdam. The first scenario is used as a basis for the implementation of the remaining scenario and two strategies. Thus, in total, four distinct models have been created based on the model formulated for the first scenario.

3.2.1 Scenarios

The first scenario reflects the current situation and is entitled as the political landscape scenario. The fleet of Port of Rotterdam is subjected to the new port regulations (PMR) and regulations imposed by the European Commission (EU2016/1628). Additionally, Port of Rotterdam is one of the parties that has agreed upon the goals and ambitions as written in the Green Deal. As described in Section 3.1.1, these regulations and goals are implemented in the model as constraints as formulated in Equation (11), (12) and (13). The purpose of this scenario is to acquire insights on the decisions the model makes depending on the decision variables. Taking into the demand and simultaneously considering the constraints.

Additionally, this scenario is also important in terms of identifying the solution space. If no results are presented, this will mean that there is no solution space available, and thus the constraints have to be negotiated. In short, the simulation process of this scenario considers different alternatives amongst all vessels. The combination of alternatives per vessel has met the relevant constraints, and an optimum was found. The model selects the different alternatives over time, in combination with alternative fuels, in order to meet the PMR, EU 2016/1628 and the Green Deal. An alternative is sought due to the limitation on CCR1 engines that are in operation, the limitations for the installation of CCR2 engines and the goals and ambitions have to be met. The latter is found in a combination of fuel-efficient and less pollutant alternatives. Altogether, climate and living environment goals have been met.

The second scenario considers the implementation of an environmental fee. This scenario is originating from the relevant indications stated in the Green Deal. The Green Deal indicates that an intervention will take place when the required transition towards 'green' technologies is not met, such an intervention could relate to the environmental fees as assessed within this scenario (De Rijksoverheid, 2019). An environmental fee is a charging alternative that falls under the economic incentive instruments and assumes the polluter-pays principle (Nikolakaki, 2013). In the case of this charging alternative, participants are imposed with a charge linked to a particular emission. The environmental fee, applicable to the emitted amount of CO_2, applies to the fuel costs. Therefore, a model variation is applied, and an additional constant in the cost coefficient of the relevant fuel is implemented. These costs are implemented in the variables $c_{pq1}, c_{pq2}, \dots, c_{pqr}$ due to the relation between the amount of emitted CO_2 and the amount of consumed fuel. The definition of $c_{pq1}, c_{pq2}, \dots, c_{pqr}$ incorporate these costs as k_{CO_2} and is formulated in Equation (16).

$$c_{pqr} = k_{FUEL} + k_{CO_2} \tag{16}$$

The purpose of this scenario is to acquire an understanding of the effects of environmental fees. Due to the structure of the model, this environmental fee is imposed per kilogram of relevant emission. No specific limit is implemented; thus, all 'users' within the port's area are subjected to this environmental fee. As stated above, the purpose is to acquire an understanding, and the practical form of such a fee can be further developed in the future. A sensitivity analysis has been conducted in order to identify their relevant tipping points. The analysis is executed by increasing k_{CO_2} with marginal steps, until deviations in the results are observed. The relevant tipping points have been identified according to the lower and upper bounds as specified by the Green Deal goals and ambitions. The purpose of this scenario is to acquire insights in the height of these environmental fees that will effectively incentivize a shipowner.

3.2.2 Strategies

The first strategy considers the implication of environmentally differentiated port dues. The port due program is a policy instrument that the Port of Rotterdam holds in order to incentivize the inland shipping industry to invest in 'green' technologies. The purpose of this scenario is to assess the current effectiveness of the port due differentiation program. Also, the effects of this instrument are further assessed, and a sensitivity analysis is conducted. The current port due difference program is based on the certificates issued by the Green Award institute. These certificates refer to a specific emission requirement and based on these, the port dues are determined. A bonus or addition is applied to the standard port due factor. The environmentally differentiated port dues are incorporated as a model variation in the form of an additional constant within the coefficient definition of propulsion costs for a specific alternative. The environmentally differentiated port dues, defined as $k_{PORT\ DUE}$, are implemented as costs per hour within the coefficients $c_{p1}, c_{p2}, \ldots, c_{pq}$ corresponding to the relevant decision variables $x_{p1}, x_{p2}, \ldots, x_{pq}$. The port due indexation as currently applied by Port of Rotterdam is implemented in the coefficients. The definition for the coefficients becomes then, incorporating the policy, as formulated in Equation (17).

$$c_{pq} = k_{INVESTMENT} + k_{UREA} + k_{PORT\ DUE} \tag{17}$$

In short, no measurable effect was noticed due to the implementation of the port dues in the model. That concluded a sensitivity analysis was conducted. The analysis is executed by increasing $k_{PORT\ DUE}$ with marginal steps, until deviations in the results are observed. This analysis is performed in order to determine the tipping points in the magnitude of the port dues. The premises remain the differentiation percentages as governed. The relevant tipping points have been identified according to the lower and upper bounds as specified by the Green Deal goals and ambitions.

The second strategy considers the introduction of a penalty when a vessel does not comply with the emission-controlled area (ECA) as imposed by the PMR. This ECA refers to the limitation on propulsion engines with an emission characteristic relevant to CCR1 or lower. The penalties are incorporated as a model variation in the form of an additional constant within the coefficient definition of propulsion costs for a specific alternative. The penalty, defined as $k_{PENALTY}$, are implemented within the coefficients $c_{p1}, c_{p2}, \ldots, c_{pq}$ corresponding to the relevant decision variables $x_{p1}, x_{p2}, \ldots, x_{pq}$. The penalty is solely applicable to the standard configuration, and thus only incorporated in that relevant cost coefficient. The definition for the coefficients becomes then, incorporating the policy, as formulated in Equation (18).

$$c_{pq} = k_{INVESTMENT} + k_{UREA} + k_{PENALTY} \tag{18}$$

Due to the absence of such a measure, the current effectiveness cannot be assessed. According to the structure of the model and the software characteristics, an hourly penalty fee is introduced. A sensitivity analysis has been conducted to identify the tipping points of the height of this fee. The analysis is executed by increasing $k_{PENALTY}$ with marginal steps, until deviations in the results are observed. The relevant tipping points have been identified according to the lower and upper bounds as specified by the Green Deal goals and ambitions.

The purpose of this scenario is to acquire insights in the height of such a penalty that will effectively incentivize a shipowner.

Type	Model variation	Context
Scenario	Constraints on emissions (b_n).	Political landscape
Scenario	Increased coefficient (c_{pqr}) for fuel (x_{pqr}).	Environmental fee
Strategy	Increased coefficient (c_{pq}) for vessels (x_{pq}).	Environmentally differentiated port dues
Strategy	Increased coefficient (c_{pq}) for vessels (x_{pq}).	Penalising

Table 3.6
Strategies and scenarios

A thorough elaboration and representation of the results of both the scenarios and the strategies can be found in Chapter 4. An overview of the scenarios and strategies calculated using the model can be found in Table 3.6.

3.3 Conclusion

The aim of this system analysis and creation of the model is to give an answer to SQ_2. Thus, the goal was to represent the actual situation as accurately as possible in a mathematical model. Besides, an understanding of the concerned system and the relevant insights was created. The latter refers to the identification of critical variables, constraints and scenarios active within the system.

The system analysed was transformed into a mathematical model using linear programming mathematics and the Linny-R software package. The demand characteristics of the Port Authority are incorporated, and the model covers eleven vessels (both incident response and patrol vessels) from the fleet of Port of Rotterdam. A variety of alternatives has been implemented to the extent of five technical alternatives complemented with three relevant fuel alternatives. Furthermore, the most recent regulations have been implemented. In total, four verification experiments were conducted in order to assess the integrity of the model. Additionally, the accurate representation of the actual situation could be confirmed. In order to assess the effects of the latest regulations, the policy instruments and the implications of the polluter-pay principle, a total of two scenarios and two strategies have been simulated.

It can be concluded that the model accurately represents the actual situation for the extent of its purpose.

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Phase III

Results

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4

Results

The system analysis in the form of a model description has been described in the previous chapter. This chapter will subsequently describe the results from this model. The results will be presented using a variety of graphs. The presentation is visualized in such a way that the percentage reductions, relevant investments, relevant fuel costs and accomplishing the different goals from the relevant regulations are directly clear. Thus, the purpose of this chapter is to visualize and present the results from the different strategies and scenarios as described. The goal of this chapter is that the results can be interpreted and a conclusion can be drawn in the consequent chapters. Furthermore, this chapter, and thus, the combination of the results will also give an answer to SQ_3.

As previously described, two scenarios and two strategies have been assessed. First, the results of the two scenarios will be presented. Then, the scenarios are followed by the presentation of the two strategies. The year of reference used is 2018. The software makes use of user defined solver settings. The solver settings determine how the linear programming problem is solved within the model. The model simulates in total 16 time steps ($t = 1 \ldots 16$), which is equal to the period from 2020 up to 2035. The solver settings have been set to solve the problem one-step at the time or one-year. Including a look-ahead of two-years. In short, this means that an investment decision will be anticipated every year using all the information available from that year and two-years ahead, thus in total three-years.

The goals mentioned throughout this chapter will refer to the goals as described in the Green Deal. The investment costs mentioned in this chapter refer to the initial costs of the relevant modification. Not taking into account depreciation, additional maintenance costs or renewal costs.

4.1 Political landscape

In this section the results of the political landscape, as assessed using the model, are presented using graphs. The political landscape scenario refers to the PMR and the goals as agreed upon in the Green Deal. In total four different situations have been assessed using the political landscape. The political landscape scenario is modelled using constraints which are applicable to the relevant decision variables. An explanation of the latter is described within the corresponding sections. First, the influence of solely the PMR, solely the CO_2 emission goals and solely NO_x and PM goals will be presented. Then, the combination of the PMR and goals will be presented. This division has been made in order to assess the different conditions and the consequences of these specific conditions.

The figures presented in this section, present the years in which a reduction or decision is observable. The relative percentages reduction achieved within that year, due to a certain decision, are presented in the graphs located in the upper part of the figure. The reductions are presented using a bar graph which is divided into CO_2, NO_x and PM. Furthermore, the red lines, that are intersecting the bars of the graph, are indicating wether the goals have been accomplished. The fuel mixture percentages, due to the decisions made by the model, are presented in the piecharts located in the lower part of the figure. This mixture has its influence on the percentages reduction wether it is CO_2, NO_x or PM, depending on the type of fuel used.

Moreover, within the piecharts the amount of investment costs or the increase in percentages fuel costs are presented as well. In general, all the related parameters due to certain decisions are presented in these figures. The origin of the additional investment costs or increased fuel costs are elaborated accordingly.

4.1.1 Port Management Regulations

In total four distinct calculations have been executed, in order to observe and analyse the effects of the PMR and goals from the Green Deal. In the figure below, Figure 4.1, the impact of the PMR is presented and described accordingly.

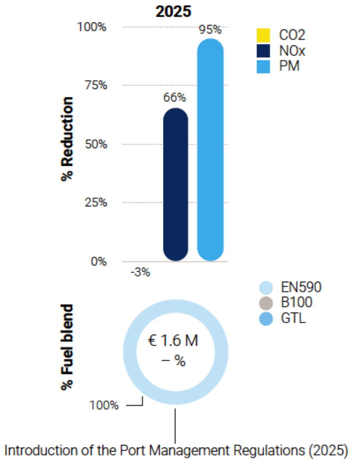

Figure 4.1
Results of PMR

The PMR requires the whole (operational) fleet to comply with the ECA in order to continue their daily operations. The PMR is modelled using constraints which are applicable to the relevant decision varaibles that represent the configurations containing CCR1 engines. These constraints are equal to $\mathbf{0}$ when $\mathbf{t \geq 6}$, representing 2025 and onwards. An investment of €1.6 million is required to comply with these regulations, as observed from the results. These investments cover the implementation of five exhaust gas treatment configurations over five different vessels. The fuel mixture has been left unchanged, due to the absence of CO_2 reduction requirements. The modifications achieved a reduction of 66% in NO_x and 95% in PM.

A beneficial outcome of commiting to the requirements of the PMR is accomplishing the NOx and PM goals in the long-term, i.e. the goals set in 2035. Nevertheless, it has no effect on the goals relating to the reduction of CO_2. Hence, there is even a slight increase in CO_2 observable due to the worser fuel efficiency characteristics of exhaust gas treatment systems.

4.1.2 Green Deal

The goals as described in the Green Deal are divided into a greenhouse gas part (CO_2) and a pollutants part (NO_x and PM) when it comes down the type of emissions. Both parts require a different approach and different type of technical alternatives to reduce the relevant emissions. Therefore, both parts have been calculated separately. The Green Deal is modelled using constraints as well. These constraints are applied to the decision variables of the corresponding fuels. The constraints are equal to the goals over time, as described in the

Green Deal. The percentages reductions are applied to the fleet performances, in terms of emissions, in 2018. In Figure 4.2 the effects of the NO_x and PM emission goals have been presented and in Figure 4.3 the effects of the CO_2 emissions goals. The same representation of the results within these figures is used as used in the first section.

The first goal can solely be met by using a partition of GTL in the fleet's fuel consumption. A reduction of 10% in NO_x and 29% in PM can be achieved using a fuel blend which consists of 40% GTL. This mixture results in a 5% increase in fuel costs. The second goal is, relatevily seen, more strict. This leads to compulsory modifications instead of an addition to the fuel mixture. A total of €0.6 million has to be invested in the implementation of two exhaust gas treatment configurations amongst two vessels. The model applies these investments over two years, resulting in the required reductions as prescribed by the goals. More specifically, a reduction of 35% in NO_x and 49% in PM has been achieved by the year 2035.

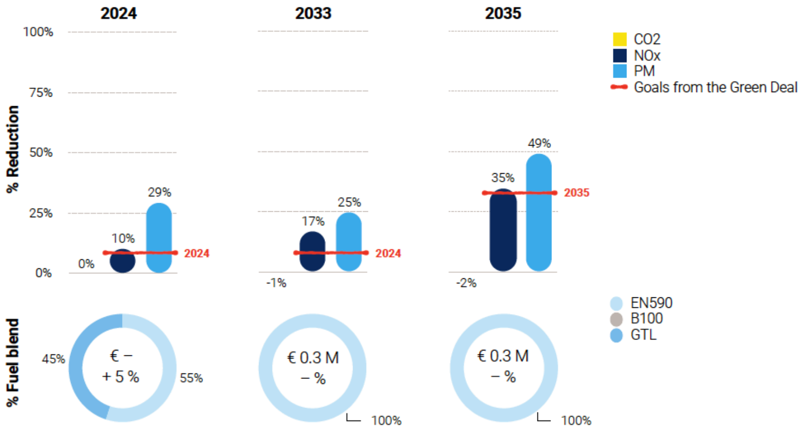

Figure 4.2
Green Deal (NO_x and PM)

The observations, acquired during the calculations as presented in Figure 4.2, allow to state that it is relatively easy to comply with these goals until 2035. With relatively easy is meant that only an addition in the fuel mixture, which leads to a marginal increase in fuel costs, is sufficient to comply with the goals. Then, the goals in 2035 forces the model to do more substantial investments, but relatively seen still the lowest thus far, to comply with those goals. Unfortunately, this result has no effect on compliance with the PMR or is beneficial for the goals regarding CO_2. The observations made during this calculation can be an opportunity to reduce the effects on CO_2 elsewhere, and comply with the goals with relatively low investment costs.

Consequently, the results of the calculations referring to the CO_2 goals are presented in Figure 4.3. The first goal can be achieved using an investment in alternative configurations and fuels. Surprisingly, a total of three investments in a hybrid alternative are required to achieve the first goal. In addition to these investments, a fuel mixture that consists of 20% biodiesel has been adopted. The investment costs for these alternatives are €1.8 million spread across three vessels. The substantial increase of fuel costs, relevant to biodiesel, made the model decide to invest in an alternative configuration over time, i.e. more cost effective. The additional biodiesel results in an increase of 23% in fuel costs.

The second goal can be met, continuining on the investments made on the hybrid alternatives, by increasing the partition of biodiesel up to 77%. Consequently, this will result in an increase in fuel costs of 88% compared to the basecase.

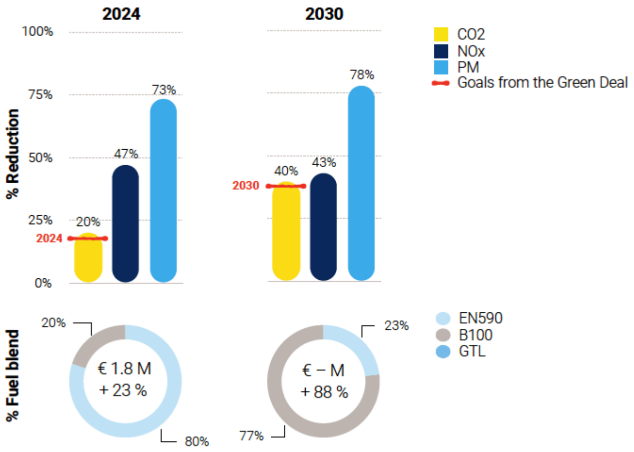

Figure 4.3

Green Deal (CO_2)

Observing these results, it can be stated that accomplishing the CO_2 goals will also result in accomplishing the NO_x and PM due to the investments made in hybrid configurations. Nevertheless, compliance with the PMR from 2025 onwards is not achieved, thus not all vessels have a minimum polluting behaviour of the CCR2 emission standard installed onboard.

4.1.3 Port Management Regulations and Green Deal

In Figure 4.4 the results of the PMR and the goals as agreed upon in the Green Deal are presented. The constraints as discussed in Section 4.1.1 and Section 4.1.2 are both implemented. The observations based on this figure are elaborated below. The same representation of the results within one figure is used as used in the previous sections.

To start with, the first CO_2, NO_x and PM goals are set in 2024. These goals have been met due to multiple investments in alternative configurations and an additional biodiesel component in the fuel mixture. More specifically, these first investments are focussed on the implementation of the hybrid configuration for in total three ships. The total costs of these modifications are €1.8 million spread out over two years. The fuel costs are increased with 25% due to a biodiesel component of 20%. Due to these decisions a total reduction was observed of 20% in CO_2, 47% in NO_x and 73% in PM in the year 2024. This means that the goals in NO_x and PM as set are abundantly achieved.

Furthermore, the second event that led to more investments is the implementation of the PMR in 2025. An additional investment of €0.7 million is required to implement two exhaust gas treatment installations, due to the prohibition of CCR1 engines in the port's area from this year onwards. This means that the vessels from the fleet that are in operation need to comply with the regulations as written in the PMR. A slight increase in biodiesel is measurable due to the reduced fuel efficiency effects of such an exhaust gas treatment system. Last, the reduction in NO_x has increased to 61% and PM to 94% due to the implementation of these two configurations.

The second goal, dedicated to solely reduction of CO_2, is set in 2030. A fleetwide reduction of 40% has to be achieved in order to comply with these goals. The fuel mixture has to be increased to an addition of 79% biodiesel. This will result in an intentioned CO_2 rduction of 40%. The last goals set, a reduction in NO_x and PM, are set in 2035. No additional modifications are required to comply with these goals due to the modifications as implemented in the previous years.

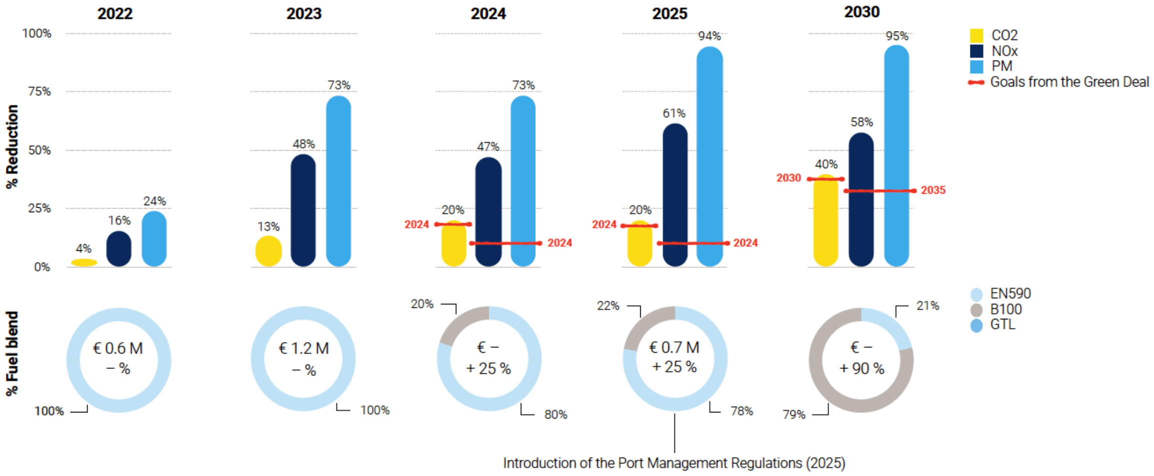

Figure 4.4

Results of PMR and the goals of the Green Deal (CO_2, NO_x and PM)

As a result, after simulating the full time-frame, the set of constraints and conditions have been met. In linear programming terms, an optimum was found and a solution was available. A total investment of €2.5 million is required in order to achieve a reduction of 40% in CO_2, 58% in NO_x and 95% in PM across the fleet. Additionally, the fuel mixture has to be adapted to 79% biodiesel which results in an increase of 90% in fuel costs.

4.2 Environmental fee

The other scenario calculated within the model is the implementation of an environmental fee. An environmental fee could be implemented in the near future, due to possible ineffectiveness of the port due differentiation and penalties on CO_2 and lack of sufficient reduction towards the goals set. An environmental fee is calculated considering a fee per kilogram of emitted CO_2. This scenario is incorporated in the model applying an additional constant within several cost coefficients. The relevant cost coefficient is applicable to the decision variables of the corresponding fuels. The type of fuel determines the amount of emitted CO_2. A sensitivity analysis is executed to indicate the tipping points and identify what height of fee would effectively reduce the emission towards accomplishing the goals. The analysis is executed by increasing the constant $\mathbf{k}_{CO_2}$ with marginal steps.

The results are presented in Figure 4.5 which indicates the effectiveness of the CO_2 tax using a bar chart. The bar chart has two directions on the horizontal axis. The negative direction of this axis shows the height of the tax in euros (pink). Keep in mind, that this axis does not show negative values. The taxes have been calculated as a fee per kilogram emitted CO_2. The positive axis show the relative reductions of CO_2 (light blue), NO_x (yellow) and PM (dark blue) in percentages. Additionally, the red line, that is intersecting the bars of the graph, is indicating if the goals regarding CO_2 have been accomplished.

The first reduction in either CO_2, NO_x and PM is observed at a tax height of €0.51 per kilogram emitted CO_2. At this point, the model shows that it is more cost effective to invest in a hybrid configuration for three vessels within the fleet. This decision is made due to the more beneficial fuel consumption numbers, which therefore result in a reduction of emitted CO_2. The total investment costs are €1.8 million and results in a reduction of 13% in CO_2, 48% in NO_x and 73% in PM. Simultenously, the goals referring to the reduction in NO_x and PM are met in the long-term, i.e. 2035. Increasing the tax with a marginal €0.01 resulted in evenmore reduction. This slight increase, results in making it more cost effective to add 34% of biodiesel amongst the fleet. At this height, the combination of the investments in the hybrid configuration together with the bio component in the fuel mixture result in accomplishing the CO_2 goals for 2024 as well.

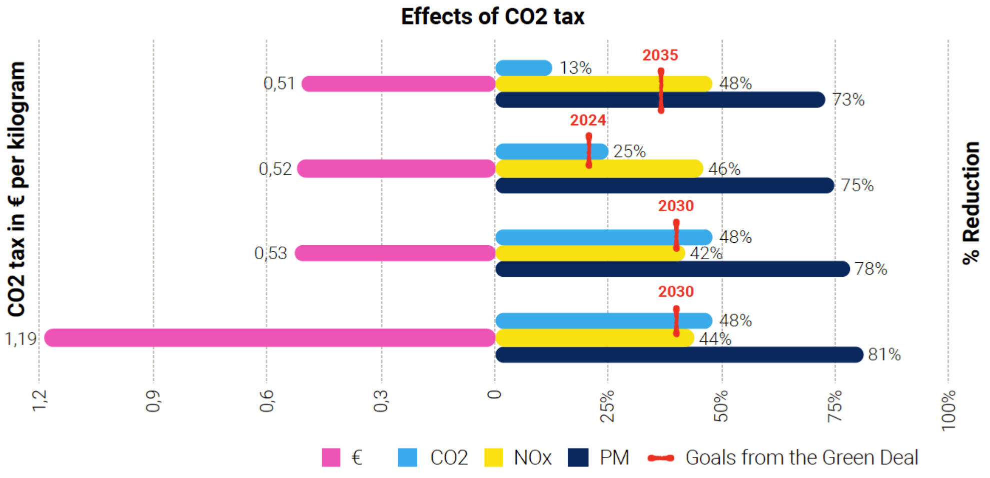

Figure 4.5

Sensitivity analysis environmental fee considering carbon dioxide (CO_2)

At €0.53 per kilogram of CO_2 the reduction increases to 48% in CO_2, 42% in NO_x and 78% in PM. At this height the whole fleet will sail dedicately on biodiesel, with no conventional diesel component within the 'mixture'. The goals of the Green Deal for greenhouse gas emissions and pollutant emissions are met in the short- and long-term (i.e. 2024, 2030 and 2035). The maximum reduction in emissions is achieved at €1.19 per kilogram of emitted CO_2 due to the selection of a different vessel. At this height a reduction of 48% is achieved in CO_2, 44% in NO_x and 81% in PM. Nevertheless, the goals were already met due to the decisions the model makes at €0.53 per kilogram emitted CO_2.

The introduction of an environmental fee per kilogram of emitted CO_2 could result in achieving all the goals set in the Green Deal, when the required investments will be done by the ship owners. At €0.53 per kilogram of CO_2, which equals €530 per ton, all the goals are met in the short- and long-term, either in terms of CO_2 as for NO_x and PM. The height of the tax leads to three investments in hybrid configurations which leads to better fuel and cost efficiency, simultaneously with the investment of running fully (100%) on biodiesel. Unfortunately, if all these goals have been met, it will still not meet the requirements as set by the PMR.

4.3 Environmentally differentiated port dues

The port due differentiation program is one of the two policy instruments that are available in order to incentivize ship owners to invest in 'green' technologies. The model is used to assess the effectiveness of this program and additionally assesses the effects of higher port dues. This strategy is incorporated in the model applying an additional constant within several cost coefficients. The relevant cost coefficients are applicable to the decision variables corresponding to the alternative configurations. The indexation of the port due is applied as constants a_{pq} to the constants $k_{PORT\ DUE}$ of the cost coefficients c_{pq}. The tipping points have been identified according the decisions made and the relevant reductions observed. The analysis is executed by increasing the constant $k_{PORT\ DUE}$ with marginal steps.

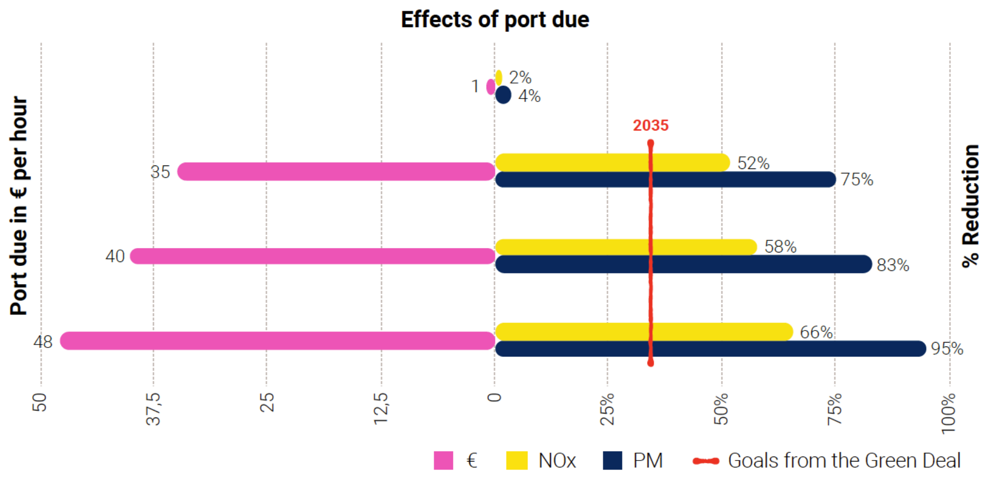

Figure 4.6

Sensitivity analysis port due differentiation

Figure 4.6 shows the effectiveness of the environmentally differentiated port dues program using a bar chart. The same bar chart is used as in the previous section. The port dues have been calculated as costs per hour as a result of the model, i.e. the hours present in the port's area. The positive axis shows the relative reductions of NO_x (yellow) and PM (blue) in percentages. The reduction of CO_2 is not implemented in this figure, because it has no effect on this matter, and thus remains unchanged.

The current program, when projected on the fleet, results in a due of €0.10 per hour. The port due has been calculated based on an operational window of 365 days a year with 24 hours a day attendance in the port's area, using the most conservative numbers. The latter equals the area of the vessels times the port due coefficient as determined for 'Passenger Ships and Tugs', as defined in Annex 1, Paragraph 4, Table 1, Column (c), of the General Terms and Conditions regarding Port Dues (Port of Rotterdam, 2013, p. 32).

Figure 4.6 illustrates that the current port due differentiation program is ineffective in terms of achieving a reduction in emissions due to investments in alternative configurations or fuels for being more cost effective, and thus incentivize ship owners. A slight reduction is observed of 2% in NO_x and 4% in PM, due to the selection of an alternative vessels within the fleet which produces marginally more emissions. These results have led to the sensitivity analysis, as additionally presented in Figure 4.6. The sensitivity analysis increased the port due amount step-by-step and recalculated the model per increase. During the sensitivity analysis, changes in the reduction percentages and investment decisions were observed when the port due amount was set on € 35, € 40 and € 48 per hour. Between these values only marginal differences were observable, and no investments took place.

First, at a port due of €35 per hour a reduction of 52% in NO_x and 75% in PM was achieved. At this amount, the model decided to invest in three exhaust gas treatment systems for three vessels because it was more cost efficient. This reduction equals a total investment of €0.9 million. Therefore, the goals for NO_x and PM in the long-term, i.e. 2035, were met. A marginal increase in CO_2 emissions was observed due to the negative effects on the fuel consumption of exhaust gast treatment systems.

Second, at a port due of € 40 per hour a reduction of 58% in NO_x and 83% in PM was achieved. At this amount, another two investments were made by the model for exhaust gas treatment systems. Holding a total investment of €0.7 million. Finally, at a port due of € 48 per hour the maximum reduction was observed, which is a reduction of 66% in NO_x and 95% in PM. This reduction was the result of the last investment in an exhaust gas treatment system for one vessel. This last investment equals €0.3 million.

The results of the environmentally differentiated port dues program led to the conclusion that the current program is ineffective when it comes to incentivizing ship owners. Furthermore, the sensitivity analysis led to the insights that the program has no beneficial effect on reducing CO_2 emissions. Hence, due to a slight increase in fuel consumption the amount of CO_2 emissions is increased. As previously written, at €35 the long-term goals of the Green Deal regarding pollutants are met, when the required investments are made. Thus, a reduction of at least 35% in NO_x and PM emissions was achieved. Additionally, at €48 the whole fleet even complies with the PMR.

4.4 Penalising

The other instrument refers to the introduction of a penalty when a vessel does not comply with the ECA as imposed by the PMR. At the moment, it is unclear how this ECA will be governed, but a penalty is one of the options. The application of such a penalty is assessed using the model, and the results are presented and discussed accordingly. The relevant tipping points have been identified due to the decisions made and the relevant reductions observed. The penalty applies for vessels that have an engine installed with worse emission characteristics than the CCR2 standard. The penalty is applied as an hourly fee which equals the hours attendance in the port's area. This strategy is incorporated in the model applying an additional constant with several cost coefficients. The relevant cost coefficients are applicable to the decision variables corresponding to the configurations containing CCR1 engines. In formal terms, the penalty is formulated as a constant $\mathbf{k_{PENALTY}}$ of the cost coefficients $\mathbf{c_{pq}}$. The analysis is executed by increasing the constant $\mathbf{k_{PENALTY}}$ with marginal steps.

The results are presented using the same figure as described in the previous section. The results of penalizing ship owners that do not comply with the ECA are presented in Figure 4.7 below. At €2 per hour a slight reduction of 2% in NO_x and 4% in PM is observed due to the selection of an alternative vessel within the model. The first major reduction is observed at a penalty of €14 per hour. At this height the model has calculated that it is more cost effective to invest in three exhaust gas treatment system for three vessels at a total cost of €0.9 million. Simultanously, due to the investment decisions, the long-term goals (i.e. 2035) of NO_x and PM are accomplished.

Even a higher reduction is observed when the penalty is put at €21 per hour. At this height, an additional investment for one vessel is more cost efficient. Again, this investment can be allocated to the exhaust gas treatment systems and holds €0.3 million costs. Then, the maximum reduction is observed at €23 per hour. An additional two investments are made of €0.6 million, allocated to the exhaust gas treatment systems. At this maximum amount, it is more cost effective to invest in exhaust gas reduction systems for all vessels.

Observing Figure 4.6 and Figure 4.7, it can be stated that the there are a lot of simelarities in investments and reductions. The differences are situated in the quantity of investments relevant to the height of the fee or penalty. Nevertheless, both instruments correlates in terms of incentising relevant alternatives and reductions.

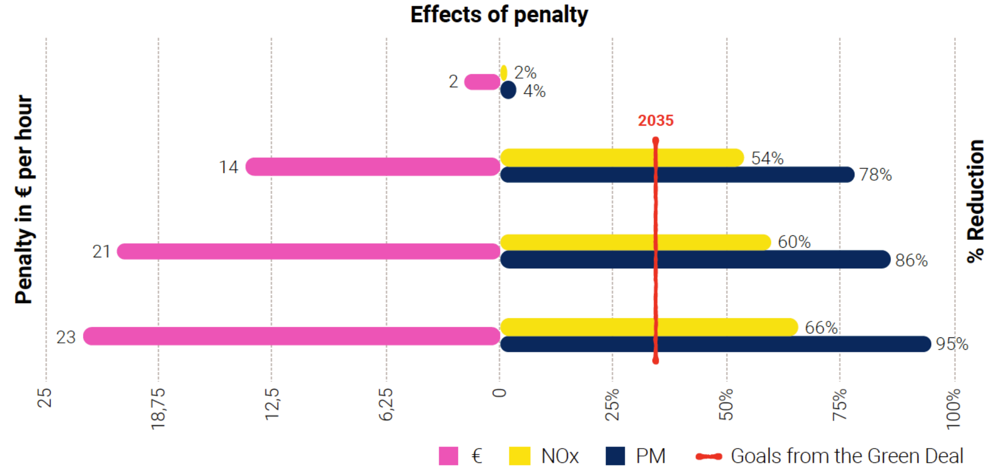

Figure 4.7

Sensitivity analysis penalties

It can be concluded that introducing a penalization measure for violators that are not compliant with the PMR is ineffective towards reducing CO_2 emissions. Furthermore, the model indicates that the goals in the long-term (i.e. 2035) referring to reducing NO_x and PM can already be achieved at an hourly fee of €14. Keep in mind, this holds when the ship owners will invest in 'green' alternatives, as the model does.

4.5 Validation

The method and relevant results have been assessed by experts. The method refers to the creation of the model, data acquiring and processing and assumptions that have been made. In total, three experts have been interviewed using the semi-structured interviewing method. The roles and organisations of these experts can be found in Table 4.1.

Participant	Role	Organisation
Expert 1	Managing Director	Expertise en Innovatie Centrum Binnenvaart (EICB)
Expert 2	Technical Consultant	Maritiem Adviesbureau (MAVRED)
Expert 3	Project Leader	Port of Rotterdam

Table 4.1

Panel of experts

The three experts are working in three different types of organisations and hold various positions. The purpose of these interviews is to retract their knowledge in order to determine how they would execute this study and what they expect the result would be. Thereafter, the executed method and results of the model have been explained to the experts. The goal of holding interviews with experts is to validate the method.

The method and results will be validated when the result of the interviews comply with two requirements that have been set. First, the experts have to think in the same direction as the actual method executed. Second, when the experts agree upon the applied method, the relevant results do also have to meet their expectations. When not, a substantiated argument was retrieved, or an in-depth discussion was held. The latter prevent that no surprisingly or inevitable wrong results came out of the model.

As previously mentioned, the interviews have been executed using the semi-structured interviewing method. This means that most of the questions are predefined. The expert is informed in advance how the interview will be held and what the content of the interview is using an interview protocol. The interviews were divided into two parts. These parts refer to the same parts that have been mentioned in the previous paragraph: validate the method and validate the results. This section will describe the key findings that were acquired during the interviews. The order in which the questions were asked towards the experts is also used in this section. The interesting observations and key findings have been described within this section. The most important key findings are presented in Table 4.2, summing up the most important quotes from the experts.

The relevant protocol and the questions as asked during the actual interview can be found in Appendix F. Additionally, the full transcription of the three distinct interviews can also be found in this appendix.

4.5.1 Method

Then, the method was assessed. The experts acknowledged the fact that there are three possibilities in order to reduce the emissions: alternative fuels, modifying elements within the engine and apply appendices focusing on the exhaust. Furthermore, electrification is also mentioned as an alternative, if the sailing profile of the vessels allows such a modification remainds the question. Additionally, all three experts see electrification as the alternative that is future proof and will be implemented on all vessels in the short- and long-term because the propulsion system is fully modular. A modular propulsion system allows the part that generates the power to be interchangeable and prepares vessels for alternative power sources, such as hydrogen fuel cells. Two out of three experts would have added LNG and batteries as a supplement to the alternatives that are considered within the model. Hence, they acknowledge the fact that both these alternatives come with drastic modifications and relatively high costs. Thus, not relevant in the comparison made in this study.

The experts do unanimously agree with the calculation approach used to determine fuel consumption and relevant emissions. One of the experts state that the density of the different fuels is different, but this difference is only marginal. Keep in mind that the engines can respond differently in terms of power output on those fuels. Furthermore, all the experts acknowledge the use of emission factors as a requirement. Hence, more research and studies are required in order to make those factor more realistic and reliable. One of the experts states that a measurement campaign would be most realistic in order to determine the sailing profile and fuel consumption.

Furthermore, the situations (i.e. strategies and scenarios) simulated using the model are agreed upon by all the experts. Nevertheless, one of the experts sees more in applying subsidies instead of using policy instruments that result in financial measures. Additionally, penalising ship owners could have some practical issues based on how to govern this instrument. Hence, it could result in market share loss within the port of Rotterdam. Last, an environmental fee is seen by one expert as the main scenario which allows business cases to become positive, and would substantially increase the reduction of emissions due to ship owners making their ships more sustainable.

4.5.2 Results

The results have been discussed with the experts. Starting with the scenario implementing the PMR and Green Deal. All the experts expected the configurations to be in the direction of exhaust gas treatment system or hybrid configurations with the addition of biodiesel component in the fuel. One of the experts expected CCR2 engines in order to comply with the PMR, but not in terms of complying with the goals of the Green Deal. The other expects that a hybrid configuration will increase the greenhouse gas emissions due to worse fuel consumptions performance and that this will have to be compensated using biodiesel. All of the experts agreed upon the results. When assessing the scenario in which only the PMR was simulated, the experts expected that the model would choose for the CCR2 engines. This is also something that is a current market trend, due to the new European regulations, i.e. Stage V. According to the experts, the result is surprising. The investment decisions are based on rational thinking of the shipowners; the model proves then wrong.

Two out of three experts agree with the results considering the CO_2 goals from the Green Deal. However, both add that smaller engines are required in order to reduce even more CO_2. Additionally, the experts state that alternative fuels still have some logistical problems and that the demand for these fuels has to increase in order to make it more attractive for a larger group of customers. Hence, related to the addition of GTL in order to accomplish the short-term NO_x and PM goals, it has to be stated that adding GTL to the fuel mixture will not always result in more favourable emissions, that has to be studied.

All the experts unanimously state that the current environmentally differentiated port due program is ineffective. The effect of the port dues is too low in relation to the required investments. Two of the experts state that this instrument will be one for the future, in order to incentivise ship owners and allow ship owners to show that they are sufficiently sustainable. One expert even states that this instrument has to be expanded towards a national and even international scale. Although, still one of the experts disagrees with this instrument and sees it as a risk for the port of Rotterdam, and expects a loss of market share if this instrument will be used to reduce emissions.

The experts have a variety of opinions considering the penalties based on the PMR. One states that penalising the polluters based on the PMR is only realistic, when it is measurable. The other two do not see this as a realistic instrument, and state that this penalty is already implemented in the port dues. This instrument has the same risk as the one mentioned at the environmentally differentiated port due program.

All the experts are enthusiastic with regards to the environmental fee on emitted CO_2. One states that it is crucial to keep in mind that Rotterdam may fall under the Act of Mannheim. The Act of Mannheim states that it is not allowed to collect taxes from fuels, and a CO_2 tax may be an indirect collection of taxes. Nevertheless, they see many advantages within this tax. Although, one doubts if this is not another economic instrument in order to generate more money, instead of reducing the problem. Even though it is not an instrument that can be executed by Port of Rotterdam, it is for sure a scenario in which they can express their influence up to the Central Government and lobby for such an instrument.

4.5.3 Discussion

In general, all the experts agreed upon the method used in this study, although comments have been placed to certain aspects. Furthermore, the most surprising result experienced by the experts was that the model showed that exhaust gas treatment systems were more cost-effective than new CCR2 engines in order to comply with the PMR. All the experts expected the opposite, but the model illustrated otherwise. The latter confirms the rumours that are ongoing in the industry that the PMR is hampering the emission reduction process in the industry.

The experts think that a bonus and penalising system, such as the environmentally differentiated port due program, is one of the most effective policy instruments that will eventually incentivise ship owners. Additionally, a form of subsidy is expected to be required in order to make investments feasible. The bonus and penalising system has to be based on the requirement that shipowners can show their degree of sustainability using some certificate. The latter will increase the success ratio of that specific policy.

Expert	Quote
1	There are three categories in terms of (retrofit) solutions – alternative fuels, modify the internal parts and/or management of the engine and locate an append in the exhaust system behind the engine.
1	Electrification is a step forward and towards the future. The modular characteristics are beneficial for further developments within the ongoing energy transition.
1	Another alternative is the implementation of Euro VI and Non-Road Engines, after marinising them.
1	Adding GTL to your fuel mixture will not always result in a reduction of pollutant emissions.
1, 2 and 3	The current port due differentiation program is ineffective. The marginal costs are too low in relation to the required investments.
2 and 3	The proven alternatives, that are also commercially available on the market, have been assessed within this study.
2	It is important to establish a (measurement) method that defines the extent of how polluting or sustainable a vessel is, in order to apply specific policy instruments.
2	Emission fees have multiple benefits. One of them is that business case calculation can become positive, and investments can be justified.
3	Insufficient sustainable alternatives are available in combination with a regulatory landscape that is too uncertain in the future.

Table 4.2

Summary of the key-findings from panel of experts

In terms of technical development in the short- and long-term, the experts think a substantial gain is feasible using alternative fuels. A mixture of conventional diesel with other parts is a transition solution. In the long-term, this mixture will be replaced with hydrogen or another synthetical fuel. Another step in the right direction is the hybrid configuration, which facilitates the implementation of hydrogen fuel cells in the future. Concluding, based on the interviews held, the content that was discussed, it can be stated that the method used and the results created were validated by these experts.

4.6 Conclusion

This chapter aimed to give an answer to SQ_3. The goal was to identify the critical variables, constraints and scenarios by interpreting the results. Critical refers to the amount of influence on a decision that the model makes of that specific variable, constraint and scenario. These critical variables refer to the fuel consumption rates of the alternatives, the constraints to the PMR and the scenario to the environmental fee scenario.

In total, seven distinct results have been presented based on two scenarios and two strategies. The results have shown that there is a solution space within the model, which means that there is an optimum considering the variables, constraints and coefficients. More thoroughly, the model showed that the current political landscape (i.e. regulations) together with the goals and ambitions (i.e. Green Deal) could be met when the owners of the vessels are prepared to make the required investments.

First, the fuel costs and therefore also the fuel consumption are of significant influence on the alternative configurations within the model. The financial viability of an investment decision is based on fuel consumption due to its relation to the operational costs. Investments can be justified when a certain degree of fuel efficiency can be established. Second, in terms of constraints, the results show that the PMR is hampering the energy transition towards more 'green' technologies onboard vessels. It requires a substantial amount of additional resources in order to comply with these regulations, which not per definition result in a step in the right direction to reduce a significant amount of emission throughout the years. Third, based on the results established when applying an environmental fee per kilogram emitted CO_2, it can be stated that this scenario is substantial beneficial for the energy transition. Moreover, these goals refer to either the CO_2 emissions and NO_x and PM emissions. Hence, the environmental fee instrument, in this study, is incentivizing ship owners to invest in hybrid alternatives that are characterized by their modular composition and can result in additional emission reduction in the long-term.

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5

Discussion

The results of this study are described and presented in the previous chapter. The current chapter discusses the acquired insights, the relevant key findings and their implications. A certain level of abstraction is adopted, and links are made. Moreover, the generalisation of this model towards the whole shipping industry is further elaborated. This generalisation assesses the application of the model towards the industry. In the end, the limitations of this study are described.

The purpose of this chapter is to review the findings and discuss the outcomes. The outcomes must be placed in their relevant context. Therefore, a certain level of abstraction is adopted in order to retract statements and conclusions for this study. However, the additional purpose is to assess if the approach executed in this study applies to a more substantial part of the inland shipping industry. Therefore, the goal of this chapter is to discuss the findings and outcomes and, additionally, project them on the inland shipping industry. The content of the projection on the inland shipping industry will give an answer to SQ_4, which is a goal of this chapter. This chapter consists of four parts. First, the findings are reviewed and described, followed by a discussion of the outcomes and relevant stakes claimed. Second, a further analysis of the outcomes is described and explanations are given. The connection towards the literature is made. Based on these two aspects, specific implications are made. Third, the generalisation of the model is elaborated. Finally, the limitations of this study are discussed.

5.1 Scenarios

The Green Deal within this study is of significant importance. This deal consists of the required performance in terms of reductions. The whole industry has agreed upon the content of this deal. In total, three instruments have been defined within the literature as a successful climate protection instrument. These three instruments have been assessed within this study. These instruments refer to the environmental fee, environmentally differentiated port dues and a penalisation fee based on an ECA. In this and the following section, the effectiveness of these instruments will be elaborated. As described in Chapter 2, Miola et al. (2011) and Koesler et al. (2015) state that economic incentive instruments are preferable over command-and-control instruments. Effectiveness will relate to the cost-effectiveness and degree of pollution control. Therefore, this study contributes to the current knowledge by assessing both types of instruments. The instruments have been assessed within a model environment.

5.1.1 Political landscape

The political landscape scenario led to an optimum that complies with the regulations (i.e. PMR) and goals (i.e. Green Deal). In other words, there is a solution, and this solution consists of a variety of investments in alternative configurations and increased fuel costs due to alternative fuels. The political landscape scenario consists of three aspects: the CO_2 goals, the NO_x and PM goals and the contents of the PMR. These distinct aspects are discussed separately.

First, the most significant amount of costs is required to comply with the CO_2 requirements. An investment of €1.8 million is spent on hybrid alternatives in combination with 88% increased fuel costs. The additional advantage of these hybrid alternatives is that these investments will lead to compliance with the NO_x and PM requirements in the long-term amongst the fleet. A significant advantage of the hybrid configurations is that the propulsion is electrical, which allows that the power source is interchangeable. Second, the lowest amount of costs are required to comply with the NO_x and PM requirements. Therefore, an investment of €0.6 million is required with temporarily increased fuel costs of 5%. The investments are spent on exhaust gas treatment systems, which is a relatively easy modification with a significant amount of reduction. Third, to solely comply with the ECA, as specified by the PMR, multiple investments are required. These investments vary between €0.6 million up to €0.9 million and are spent on exhaust gas treatment systems. The PMR requires substantially more investments, and these investments do not contribute towards the goals. In other words, the investments spent on compliance with the PMR should be allocated somewhere else and would be more beneficial in the energy transition. In short, the optimum requires an investment of €2.5 million spent on hybrid configurations and exhaust gas treatment systems in combination with an increase in fuel costs of 90%.

These results show that indeed a significant investment is required to comply with the regulations. Therefore, these results suggest that insufficient financial room is available for ship owners to invest in sustainable techniques, as previously stated by Hopman (2017). However, a previous study (De Rijksoverheid, 2019) indicated that a large-scale transition towards, the cheaper, CCR2 engines is a result of the contents of the PMR. The results found in this study contradicts with this claim. In order to comply with the PMR, the model chooses for exhaust gas treatment systems. However, these investments have no additional benefit to the reduction of emissions, due to the introduction of the Green Deal. These investments result in more modifications and even an increase in CO_2 emissions. Even though it achieves substantially more reductions in NO_x and PM in the short-term, it has no beneficial effect in the long-term. In short, it does not prepare the layout of the vessels for future innovations. Therefore, it can be stated that the PMR should be repealed and the goals of the Green Deal should be solely governing, in order to create more certainty surrounding current and upcoming regulations. Based on the relevant claims in the studied literature (De Rijksoverheid, 2019; Hopman, 2017; Panteia, 2019), this will incentivise ship owners to make more sustainable investments instead of solely focussing on business cases and costs.

5.1.2 Environmental fee

The second scenario, the implication of an environmental fee focussed on CO_2, led to new insights. This scenario is a policy instrument that steers on the amount of CO_2 emitted by applying a fee per kilogram emitted. The amount of fuel consumed directly refers to the amount of emitted CO_2. This fee indirectly increases the price of the relevant fuels. The first reduction was observed at €0.51 due per hour based on a variety of investments in hybrid configurations. These investments led to already accomplishing the NO_x and PM requirements in the long-term. Marginal increases in the fee led to a larger partition biodiesel in the fuel mixture and eventually led to 100% biodiesel operational within the fleet. At €0.53 due per hour, the goals considering CO_2, NO_x and PM are met in the long-term, based on the investments made.

The results of the model show that the environmental fee instrument is effective. It steers the degree of emitted CO_2 and, within the model, it also affects the NO_x and PM emissions. Previous studies (Nikolakaki, 2013) claim that such an instrument incentivises to increase fuel efficiency and to seek alternative technical measures. The results of this study confirm these statements and incentives to invest in hybrid configurations, which additionally creates a modular foundation for future innovations. Furthermore, Harrison et al. (2004) and Cullinane & Cullinane (2013) state that this instrument reduces the demand for fuel. The results do show a reduction in fuel consumption, and incentivise to acquire fuels with a low carbon degree. Therefore, these statements are confirmed by the results.

This instrument shows its effectiveness within previous studies (Cullinane & Cullinane, 2013; Harrison et al., 2004; Nikolakaki, 2013) and the current study. The results show that this instrument achieves a reduction in NOx and PM emissions, besides CO2 emissions, as well. Therefore, this study provides the current body of knowledge with additional insights. Alternative configurations and alternative fuels have the ability to, besides the reduction of CO_2, to reduce the NO_x and PM emissions. Keep in mind that a reduction in fuel consumption can also be achieved within the operational aspect, which is not part of this study but is also suggested by several studies (Shi, 2016). Finally, alternative synthetic fuels are more favourable due to the less impact on the climate, which will lead to lower costs – the 'green' gold paradigm (Cullinane & Cullinane, 2013). The potential of synthetic fuels is not yet fully utilised. When these fuels can compete with the low price of conventional diesel, it can achieve its full potential.

It is favourable, in order to control the amount of pollution, that this instrument, when applied, is actively steered. For example, the fuel price and the acquired reduction have to be levied in order to guarantee the effectivity — the latter results in an increase in effectiveness that is acknowledged by Nikolakaki (2013). The revenue created by the application of this instrument has to be widely invested into more 'green' technologies, subsidies or other applications that have a beneficial contribution to the problem faced in this study. Another application for the revenue would include the redistribution in order to rewards operators who consume or emit less (Nikolakaki, 2013).

There are two points of attention regarding environmental fees. First, the policymakers have to acknowledge and use the instrument as it was intentioned, in order to prevent the introduction of another economic instrument that generates more revenue than being beneficial towards in terms of reducing emissions. Second, an environmental fee could conflict with the contents of the Act of Mannheim. Therefore, the content of the Act of Mannheim should be thoroughly assessed in order to determine if the instrument is executable. Last, this instrument is not an instrument that could be imposed by the Port of Rotterdam. Hence, Port of Rotterdam has to apply mighty lobbying power towards the Municipal Council of Rotterdam and the Central Government and should use this if it is convinced from the success of this instrument. Therefore, this instrument could be a crucial measure if the goals as described in the Green Deal are not met within the timeframe set. It should be applied not only nationally but throughout Europe due to the international characteristics of the inland shipping industry and the global nature of the problem. Altogether, the environmental fee shows signs of a promising instrument.

5.2 Strategies

The two policy instruments, entitled as strategies in this study, are discussed. The environmentally differentiated port due program is an instrument that is currently governed within the port's industrial area. This program is adopted in order to incentivise ship owners to invest in emission reducing technologies that are more beneficial for the living environment. The second instrument is a penalisation fee based on the ECA as prescribed by the PMR.

5.2.1 Environmentally differentiated port dues

The current environmentally differentiated port due program is connected to the existing port due program, which applies to all inland shipping users within the port's area. A reduction in port dues can be achieved based on the environmental performance of the users. Thus, participating in the program is voluntary. The results of the model have shown that the current environmentally differentiated port due program is ineffective. The program is too marginal in order to affect investment decisions. Neither an alternative nor fuel becomes cost-effective due to the content of this program. The ineffectiveness of the current program can be assigned towards the current indexation that is based on outdated emission standards.

Therefore, a sensitivity analysis was executed, at a substantial increase (€35) in the current port due the first reductions were observed. Thus, it becomes then more cost-effective to invest in exhaust gas treatment systems for some individual vessels. At a more significant increase (€48), an investment in such systems became more cost-effective for all vessels. A significant disadvantage that the results show is that it has no beneficial effect on the reduction of CO_2 emissions. Hence, even an increase was observed due to the fuel consumption characteristics of exhaust gas treatment systems. The results show that this instrument strongly correlates with the results of the ECA as described in the PMR. The latter is discussed more thoroughly in the subsequent section.

According to Zhu et al. (2017), this instrument has two significant advantages. It will incentivise the adoption of reduction technologies and will give insights to the government to monitor the shipping industry. There are several examples in the Port of Vancouver and Swedish ports that show the success of this program (Nikolakaki, 2013). This study shows that this instrument incentivies the industry to adopt emission reducing technologies, and based on the indexation of the port due program, the government acquires the relevant pollution data. Therefore, the statements made by multiple scholars (Harrison et al., 2004; Nikolakaki, 2013; Zhu et al., 2017) corresponding to the effectivity of this instrument are valid. Harrison et al. (2004) state that CO_2 emission objectives should be incorporated as well. The results of this study show that this is highly preferred for two reasons. The program should be more structured in-line with the goals from the Green Deal, and if CO_2 emission objectives are incorporated, the program also incentivises a variety of different, climate beneficial, alternatives. The lack of climate protection goals within the program is a significant shortcoming of these type of programs – the geographically limited nature of the application, as stated by Nikolakaki (2013) and acknowledged in this study.

The results of this study suggest that expanding the program with a malus scheme on carbon holding fuels would stimulate emission-reducing technologies and adopt the polluter pays principle. The latter is recommended by multiple scholars (Nikolakaki, 2013; STC Nestra & Rebel Group, 2015) as well. The current program allows for significant pollution control due to the monitoring characteristics of this program. Besides, the instrument is cost-effective; the polluters pay for the benefits of the 'cleaner' ships. A CO_2 emissions monitoring system should be introduced as a mandatory requirement for certification and therefore provides an economic incentive for ship operators about climate protection (Nikolakaki, 2013). Multiple scholars (Nikolakaki, 2013; Zhu et al., 2017) state that environmentally differentiated port dues has a lot of potential. This study has not been focusing on expansions in terms of different price reductions on services, financial profits or market preferences insisted by the clients. Market preferences refer to quality and environmentally friendly cargo. Even though the results of this study and relevant acquired insights do insist and encourage these statements made by Zhu et al. (2017) and Nikolakaki (2013). Governments could consider these program and relevant certificates as a benchmark when providing subsidies and preferential tax treatments (Nikolakaki, 2013; Zhu et al., 2017).

The practical implications, which are not discussed by the relevant authors, is that this instrument could result in loss of market share. This scenario should be taken into account as a serious threat. The experts who participated in the interview agree with the statements above and confirm that the current program is ineffective. The model shows that just increasing the fee is an infeasible measure. This conclusion is unfortunate due to the beneficial characteristics of such an instrument. An indexation should be adopted that is in-line with the transition path as described in the Green Deal and based on the latest emission standards. This instrument could be expanded using periodic monitoring (Harrison et al., 2004). This periodic monitoring could be coupled to an onboard monitoring device. The experts see this onboard monitoring as the basis for all regulations within the port's area. Both instrument objectives can then be met. An instrument that is cost-effective and gives maximum pollution control.

The program should also be expanded towards a national level, in order to prevent loss of market share. The latter comes with another problem; expansion of the program is not within the jurisdiction of Port of Rotterdam. Therefore, it should, again, use their mighty lobbying power to incentivise other ports within the country or even within Europe.

5.2.2 Penalising

The penalisation fee is based on the geographical perimeter as imposed by the Municipal Council of Rotterdam. An ECA is incorporated in the PMR and will be governed from 2025 onwards. Compliance and enforcement measures are not yet determined (Municipal Council of Rotterdam, 2010). Enforcement will most likely result in a financial penalty. The latter is based on the measures that are taken in other transportation modalities – for example, the ECAs in city centres. The implication of an ECA falls under command-and-control instruments as defined by the literature. The penalisation fee that would 'punish' the violators is, according to the literature, and economic incentive instrument and falls under the charging alternatives. The environmentally differentiated port dues fall under this division as well. The penalties assessed are imposed as an hourly fee.

At the first reduction, the instrument incentivised to invest in exhaust gas treatment systems for three vessels. The maximum reduction was realised due to incentivising the investments in exhaust gas treatment systems for all vessels, which means that at this height, it is more cost-effective to invest in these systems. The latter resulted in compliance for the whole fleet with the PMR, as the objective is for this instrument. Unfortunately, this instrument does not contribute to any CO_2 reductions whatsoever. At a fee of €14 per hour, it is already sufficient for an investment decision to the NO_x and PM goals in the long-term.

The presented results are correlating with the results from environmentally differentiated port dues. Both instruments incentivise the adoption of exhaust gas treatment systems and show similar reductions. The main differences between these instruments are the structure and applied indexation. The results show that the implementation of the current ECA will hamper the transition towards emission reducing technologies. That can be assigned to the absence of CO_2 requirements and using a regulation that is based on outdated emission standards. Therefore, ship owners are required to invest substantially more in order to comply with these regulations and the investment are spent on techniques that show gains in the short-term. Therefore, vessels are not prepared for long-term technical innovations and will eventually hamper the transition. The panel of eperts that due to the rational thinking of the ship owners, a substantial number will invest in CCR2 engines, which will eventually hamper the transition even more.

Governing such an ECA will encounter difficulties in practice. Where lies the responsibility of verifying the compliance with the ECA; will this be with the ship owners or the enforcing entity. The violators will have to be identified by the enforcing entity. The ECA focusses on particular emission limits which can only be identified with physical measurement. The absence of regulations that obligate ship owners to demonstrate their emissions makes this infeasible to assess in practice. It can be stated that the current PMR, and therefore the ECA, is hampering the ongoing transition and is based on outdated emission standards. The contents of the PMR should incentivize ship owners to commit to the goals as described in the Green Deal. Therefore, this instrument should be combined with the environmentally differentiated port dues program, as discussed previously, to steer towards long-term technical alternatives.

5.3 Policy instruments and a mixed-integer linear programming model

In total, three different policy instruments are assessed within this study. These three instruments refer to economic incentive instruments. One environmental fee, or emission charge, and two charging alternatives as defined by the relevant literature. Unfortunately, multiple parties (Hopman, 2017; Panteia, 2019; TNO, 2015) state that it is unlikely that CO_2 reduction in the short-term will take place. The results from this study contradict with these claims. It is relatively easy to achieve CO_2 reduction with an alternative, low carbon, fuel. The environmental fee is an instrument that is recommended by Hopman (2017). The results of this study show encouriging signs. Therefore, it can be stated that taxation policies are potentially required to increase the cost affordability of alternatives. This statement is in-line with the claims made by Zhu, Li, Shi, & Lam (2017). Also, they state that the effects of emission-reducing policies have to be considered.

This study has shown that MILP models are effective in terms of assessing instruments but also shape policies. The studies (Hahn & Stavins, 1992; Koesler et al., 2015; Miola et al., 2011; Nikolakaki, 2013; Shi, 2016) conducted within the relevant literature are based on practical implications, experiences and case studies. Therefore, the application of MILP techniques for this particular problem and purpose contributes to the current body of knowledge. This study assesses a variety of policy instruments using MILP. The application of MILP allows us to approach the practical situation as closely as possible and simulate the effect of different alternatives. Either new policies or active policies can be assessed or actively steered using these types of models. Besides, the problem faced considers if certain investments will be feasible or if specific techniques will be incentivised as a result of a policy. These investments are formulated using the integers as formulated in the MILP problem definition. The application of integers in terms of investment decisions is a type of model variation that is unique within the MILP modelling techniques. Concluding, this study shows new applications for MILP and unique applications of the model characteristics referring to the integers.

Previous studies (Cullinane & Cullinane, 2013; Shi, 2016; STC Nestra & Rebel Group, 2015) have come to a mutual conclusion – a combination of regulations and technological innovations are required to reduce the environmental impact of the inland shipping industry dramatically. This study shows that indeed a combination of the two will result in a dramatical reduction of emissions in either CO_2 and NO_x and PM emissions. The environmental fee and environmentally differentiated port due instrument show that policies will incentivise ship owners to invest in emission-reducing technologies. Therefore, the market has shown that with either modifications or fuels, it is possible to meet the goals as defined by the Green Deal, and thus short- but also long-term reduction is feasible.

This study suggests that the claims from Miola et al. (2011) that command-and-control instruments are outperformed by economic incentives are, to some extent, true. The current market characteristics still show an insufficient transition towards emission reducing technologies, and this market is characterised by command-and-control instruments. Therefore, the instruments assessed with the relevant show that economic incentive instruments have the potential, and when they are applied effectively, the industry would be provided with sufficient incentives.

The bottleneck of the current market is the lack of economic motives and finance characteristics, as stated by several authors. The results of this study show that the economic incentive instruments will create sufficient economic motives and depletes the current financial gap in the business cases. The adoption of solely technical measures is not sufficient to incentivise the shipowners, which is agreed upon by Shi (2016).

5.4 Towards the inland shipping industry

The study executed and the results generated are based on the fleet owned by Port of Rotterdam. The effectivity of technical configurations and policy instruments has been assessed using the model. The fleet used is a small partition of the total number of vessels active in the port's industrial area. Therefore, this section illustrates the applicability of the used model, the generated results and contents of the measures assessed towards the inland shipping industry. Thus, this section gives an answer to SQ_4.

The current model and study are based on eleven vessels. These vessels have more or less the same characteristics as other service vessels, passenger vessels, workboats and tugs within the port's area. In 2018, a total of 382 of these individual vessels had been recorded operational within the port's area. Thus, it can be stated that the results of this model can be applied to this partition. To put this number in context – in 2018, a total of 5,042 individual inland ships have been recorded within the port's area (excluding unidentified towed/pushed objects). The following (possible) adaptions to this study could result in applicability towards this whole fleet. The inland shipping statistics used from 2018 can be found in Appendix G, and have been provided by 'Bureau Havengelden', which is a department of Port of Rotterdam

The relevant data from the inland shipping industry has to be gathered. This data refers to installed power output, the number of operating hours and the relevant sailing profile. The fleet assessed in this study and the inland shipping industry will deviate in the installed power output and sailing profile. The sailing profile is of significant influence for what technical alternatives are feasible, and the performance in terms of emissions of these alternatives.

Besides, another point of attention is the scale. In this study, a fleet of eleven vessels is assessed. It is unrealistic to use the same model structure projected on the whole industry, as used within this study. Thus, the structure of the model should be adapted to the new particular 'sample' size. It is not recommended to make a model from the whole industry, and incorporate every individual vessel, but identify a representative 'sample'. The latter could be done using two methods. First, make an indexation based on the type of vessel. The type of vessel usually indicates the operating hours, sailing profile and installed power output. Another indexation possible is one based on the type of engine. Marine engines are categorised according to the number of operating hours and relevant power output. Both methods are suitable, and the following step is to create the model structure that calculates the amount of fuel used and the relative amount of generated emissions.

The model needs to fulfil a particular demand. The demand used in this study is the available hours attending the port's area. That was the criterion imposed by the Harbour Master due based on the public safety requirements of the fleet. This demand function is not suitable to apply for the whole inland shipping industry. Relevant demand criterion could be the number of operating hours. Thus, the number of hours the propulsion system is operational on a monthly or yearly basis. Besides, these numbers are usually the numbers that are used to determine the sailing profile and the type of suitable engines. Other demand functions could be useful, as well — besides, a vast difference between the service vessels and general cargo vessels in the relevant business case. In order to generalise this model, the business case for a shipowner should be implemented as well. A shipowner depends on a certain quantity of cargo, income and revenue. His or her activities should cover the relevant investment.

Lastly, the model used in this study was created to assess if there was a solution available and whether policy instruments were effective. If a model is created for the whole industry, that objective still holds – is there a solution available in terms of meeting the goals and demands as described in the Green Deal. Consequently, the model should be used to determine and shape a particular policy instrument or instruments in order to achieve the intended goals. Further on, the model could also be used to adapt the implemented policy instruments actively.

Concluding, the most significant challenges and deviations between the two situations, when this study will be expanded towards the whole inland shipping industry, is the relevant scale, the demand criteria and the purpose of the model. Therefore, SQ_4 can be answered summing up the above insights. The structure of the model should be adapted to the vast difference in scale. Besides, the demand criterion should be adapted towards the criterion of required operating hours or similar criteria. Lastly, the purpose of the model studied should be expanded with another objective. When the whole shipping industry is covered, it is still essential to assess a possible solution. Besides that, the model can be used to structure the policy instruments. There, the model can act as a steering tool that allows reaching the goals as intended. Also, the model can be used to steer the instrument based on the interim results actively.

The results found based on the current model characteristics can be used towards the inland shipping industry. The model has shown that ship owners facing the implications of the PMR have to make investment decisions if they do not comply with the requirements. The model has shown that an exhaust gas treatment system is more cost-effective and beneficial in terms of NO_x and PM reduction than CCR2 engines. Moreover, the model has shown that not only radical modifications result in a reduction of CO_2, NO_x and PM emissions. Adding an alternative synthetic fuel to the fleet's consumption can lead to a substantial reduction in these emissions. More synthetic fuels that are commercially competitive in terms of price will be introduced more and more in the short-term. These so-called drop-in fuels could have a substantial contribution towards the general emission reductions within the port of Rotterdam and the whole industry.

5.5 Limitations

This section elaborates upon the limitations of this study. The limitations refer to the shortcomings of this study. Acknowledging the limitations define the transparency and fields of improvements.

1. In this study, the fleet of Port of Rotterdam is used. In the previous sections, it has been described how this study could be generalised. A limitation of this study is that this study is focused on a small partition of the industry. Therefore, this study could draw the wrong image of the whole industry. The latter could question the applicability to other vessels or other partitions within the industry.
2. In total, three policy instruments has been assessed within this study, due to the jurisdictional limitations of Port of Rotterdam. In the literature, more policy instruments have been identified as possible effects in terms of incentives towards emission reduction technologies. Thus, not the whole spectrum of available tools is assessed.

3. The reductions used in the model are based on average reductions from studies executed in the past. These studies define a bandwidth of reductions based on alternative fuels used in their particular studied engine(s). Therefore, the forecasted reduction could in practice not been met by the vessels operating within the fleet studied.
4. In total, four alternative configurations, and thus technologies, have been assessed within this study. The configurations used were showing either small improvements or relative significant improvements in their emission reduction characteristics. Therefore, more configurations with more fragmented degrees of reduction could give a more nuanced result.
5. In this study, the acquired and monitored data of one vessel is used as input for the whole fleet. The fleet consists of eleven vessels with their engine configurations and different geographical deployment area. Therefore, the adopted sailing profile could deviate for every vessel. The properties in terms of fuel consumption, power output and relevant emissions could deviate from the numbers used in this study.

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Conclusion

As previously described, the inland shipping industry is not sufficiently incentivised to invest in sustainable technologies in order to reduce their emissions. Therefore, the main objective of this study is to gain insights into the relationship between policy instruments and incentivising technical alternatives. A variety of emission-reducing strategies, i.e. policy instruments, are assessed using a MILP model. The model is based on the fleet owned by Port of Rotterdam and subjected to a variety of scenarios and strategies. This chapter will give an answer to the main research question and proposes several recommendations.

The conducted literature study has shown that either technical measures or political measures could reduce emissions from the inland shipping industry. A variety of technical measures and policy instruments have been assessed within the model environment, and the model environment accurately represents the actual situation – representing the fleet owned by Port of Rotterdam. Consequently, this representation led to the identification of critical variables, constraints and scenarios located within the system. The model, representing the system, shows that the fuel costs and therefore, the fuel consumption variables are of substantial influence on the feasibility of alternative configurations and policy implications. Additionally, based on the results, it can be stated that the implication of the PMR has shown that it has a hampering effect instead of incentivisation effect. The environmental fee, instead of an obliged PMR, has shown more potential and has led to the conclusion that it substantially benefits the ongoing energy transition. In order to apply the model created towards a partition or the whole inland shipping industry, several modifications should be taken into account. The vast difference in sample size and demand criterion differs between the case study and the industry. If the model is applied towards the shipping industry possibilities are somewhat endless. Therefore, the purpose of this model should be expanded from assessing instruments to actively steering and the design of instruments.

The combinations of answers to the sub-questions, as listed above, has led to an answer to the (main) research question – 'Which strategies could effectively reduce the emissions in the port of Rotterdam caused by the inland shipping industry?'. Effective refers to the degree of cost-effectiveness and pollution control of this particular strategy. It can be concluded that this study has identified two effective strategies. These two strategies are elaborated accordingly.

The first effective strategy is the implication of environmentally differentiated port dues. It can be stated that this instruments' effectivity can be allocated to the degree of pollution control based on the results of this study. In linear programming terms; the port dues are formulated as additional constants in the cost coefficients of the decision variables reffering to the alternative configurations. The current program, as executed by Port of Rotterdam, has shown to be ineffective. The indexation is based on outdated emission standards, and it is too marginal. Therefore, the application of the current instrument should be adapted in several aspects. The instrument should be expanded with greenhouse gas emission reduction goals and is based on the contents of the Green Deal. This instrument should be expanded nationally or even across Europe. In order to utilise the biggest shortcoming of this instrument; the geographically limited application and prevent unfair competition between ports. This instrument will incentivise the adoption of reduction technologies and will give insights to the government to monitor the inland shipping industry. The several successful applications of this instrument in ports around the world are confirmed within this study.

The second effective strategy is the introduction of an environmental fee. In linear programming terms; the environmental fees are formulated as additional constants in the cost coefficients of the decision variables reffering to the variety of fuels. This study has shown the positive results of the implications of such a policy and has led to either greenhouse gas emissions and pollutant emissions reductions. The degree of pollution control is relatively less compared with the environmentally differentiated port dues. The model shows that this instrument accomplishes a reduction in NO_x and PM emissions as well, which is not mentioned in previous studies. The amount of CO_2 can be monitored precisely, based on the amount of fuel bunkered. However, the amount of NO_x and PM is not monitored based on this instrument. This instrument increases the degree of fuel efficiency, reduces the demand for conventional diesel and incentivises to seek for alternative techniques. Alternative synthetic fuels become favourable due to the lesser impact on the climate, which will lead to lower costs.

This study has shown that the implication of policy instruments, and the relative effectiveness, can be assessed using MILP modelling techniques. These models allow to define the problem, identify critical parameters and assess the effects of specific policies. The application of integers that can consider financial investments and assess the feasibility of the relevant alternatives based on a particular applied policy instrument is unique, and therefore a valuable contribution to the current body of knowledge. This study has led to insights that show the potential of MILP modelling techniques within the types of problems as faced.

The results of the PMR shows that sustainable growth is hampering. Not due to the implementation of CCR2 engines but using short-term solutions such as exhaust gas treatment systems – no fundamental improvement. The current political landscape shapes uncertainties, due to the steering effects towards different technical measures. The uncertainties regarding regulations are appointed as one of the lacking parameters for sustainable investments. The PMR should be repealed, and the contents of the Green Deal should be used as the governing criterion.

This study has shown that a sufficient incentive could be created and that the policies have the potential to reduce greenhouse gas and pollutant emissions. The combination of policies and available technical alternatives could result in sufficient financial room for ship owners. The combination of incentivising policies and technical alternatives will result in a dramatical reduction of the environmental impact. The instruments have the potential to create sufficient financial room and reduce emissions in the short-term. Therefore, the results of this study contradict with the common reasoning that short-term greenhouse gas reduction is unlikely. The combination of effective instruments and sufficient financial room proves the opposite.

6.1 Recommendations

This section elaborates upon the recommendations that can be made. The limitations are partially the input for these recommendations. A distinction is made between recommendations for Port of Rotterdam and further research.

6.1.1 Port of Rotterdam

Port of Rotterdam has two separate interests in this study. First, which configurations or alternative fuels would reduce the emissions from their vessels. Second, what instruments are effective in terms of incentivising ship owners to invest in sustainable, emission-reducing technologies.

1. A variety of new fuels are continuously introduced on the market. These fuels have emission-reducing characteristics, either for CO_2 and for NO_x and PM. Port of Rotterdam has conformed itself to the goals as described in the Green Deal and has their own corporate goals in terms of emissions. Therefore, these goals should be used to determine the fuel blend. The fuel blend used yearly can be accurately controlled, and therefore the number of emissions as well.
2. The configurations studied in this study can be divided into two categories: short-term and long-term configurations. The vessels owned should be categorised in terms of remaining life. Based on the emission goals adopted, the vessels with a short remaining life should be modified using the short-term alternatives, and the vessels with a long remaining life should be modified using the long-term alternatives. The exhaust gas treatment systems are effective in the short-term when it reaches its end-of-life; it has to be replaced. The hybrid configuration is effective in the long-term as well. The electrification aspects of this configuration prepare a vessel for future innovations and developments. In terms of costs, the exhaust gas treatment systems are half as expensive as the HYBR configuration.
3. The available data from Port of Rotterdam is insufficient. The data referring to the usage of the vessels (i.e. sailing profile) and the number of emissions is unavailable. The only data were available in the engine data provided by the engine producers and from outdated reports indicating fuel tests from the past. Therefore, the Port of Rotterdam should increase their data quality. The individual vessels should be monitored on the aspects of sailing profile and amount of emissions emitted. Then, more accurate calculations can be conducted, and more precise alternatives can be proposed in terms of fuels or modifications. An additional advantage is the possibility to conduct predictive maintenance.
4. The results show that the PMR requires a significant amount of additional investments to comply with content. The results show a contradictory phenomenon. On the one hand, Port of Rotterdam wants to govern and commit themselves to the PMR. On the other hand, they are the initiating party and parties which commit themselves to the goals of the Green Deal. Two different regulations, which require different behaviour and investments. Also, the results show that these additional modifications, and substantial investments, do not contribute in a significant and required better emission performance. Interpreting the contents of the PMR, the fleet of Port of Rotterdam is is not obliged to comply with these regulations. On the other hand, Port of Rotterdam is the authorising party and should lead the way for the industry. Hence, this could be a difficult discussion. Adapt your fleet to comply with the regulations, to avoid bad publicity and be subjected to damaging your image. Or, do the required investments that lead to substantially more costs and abolish the beneficial effects of the premium fuels used within your fleet.

6.1.2 Further research

This study is the first in its field. Therefore, many limitations have been identified. This section will propose several recommendations that can be improved within future research.

1. A particular division of vessels within the inland shipping industry is assessed within this study. In subsequent studies, a different section or a more extensive section should be studied. The results of this study can be used to validate future research, or future research could show that this study has drawn partially wrong conclusions or results.
2. The fleet used in this study is not subjected to any business case thus far. The business case, in this sense, refers to the required amount of cargo shipped

throughout the year in order to cover individual costs. The vessels studied are service vessels owned by a semi-public organisation. Future research should include more variables in terms of relevant costs, relevant revenues and adopt a more realistic approach for the 'general' shipowner/user. Alternative configurations will result in better emission performance, but these investments have to be covered within the business case of the shipowner.

3. A few policy instruments and a handful of technical alternatives have been assessed within this study. The market is continuously developing, and throughout this study, already new alternative fuels and distinct configurations have been introduced. Therefore, in future research, more policy instruments should be included in this study and a more extensive variety of technical alternatives — for example, the implementation of Euro VI and NRE engines. Additionally, the alternatives assessed should also be more fragmented. In this study, only extremes in terms of reduction performances have been used (i.e. minimal and maximal reduction within the bandwidth).

7

Reflection

This graduation research was an extensive process to achieve my ultimate personal goal – become a Master of Science. This process has led to all types of emotions, doubt and has put my dedication to the test. Therefore, this chapter is a part in which I can reflect on the process and look back to this period. The process can be divided into four parts.

Before this study even started, I had experienced already a setback. I had a difficult period in which I had to choose a subject and to form my graduation commission. The content of my topic has been changed three times, and therefore I wrote three different proposals before I could finally start my study. Also, the formation of my graduation commission was far from a straightforward process. Several supervisors from the university were to busy to be involved within my graduation project. The study started, after successfully completing my kick-off meeting, with a literature study.

During this literature study, I experienced my second setback. I had chosen a subject in which a lack of scientific literature was available. It was quite exceptional to study strategies for a large port that wants to be part of the energy transition. This organisation had to fulfil a public task, does not wish too loose market share, and is dependent on those customers for their revenue. I had difficulties in identifying the research gap I wanted to fill. After an extensive literature study, I achieved to identify this specific gap. Unfortunately, regarding this gap, still, some scientific literature was absent. Luckily, I was able to identify multiple technical alternatives that could successfully reduce emissions, but therefore require some intervention by public authorities or, in this case, a port. Consequently, I had also identified multiple policy instruments, that could incentivise the implementation of these technical alternatives, and together this had formed a solid basis for this study. The literature study was completed.

During the second phase, I wanted to create a linear programming model to be able to analyse the current system. I was very enthusiastic about the mathematics involved and was keen to deliver a well structured and most of all, useful model. It was a bit of a risk I took, due to the lack of any experience with creating a model or the mathematics involved with linear programming. During this period, I was facing a challenge, but simultaneously I gained a lot of satisfaction from this process. I really enjoyed myself creating the model because I was able to put a lot of effort into the creation process. The hardest part of the process was to acquire and process all the relevant data. Even more, when I was close to completion, I discovered that there were crucial mistakes in the data I had received. It took me some stressful evenings to rectify these errors. In the end, I had created a model that was able to assess the technical alternatives based on the political landscape and policy instrument the model was subjected to. There was not a lot of time to enjoy this moment, because the next phase was around the corner.

In this last phase, I had to present the results from the model and validate my methods and model based on interviews. Creating a model is one, presenting the results is an entirely different task. The model allows me to offer all the results I want to. Thus, I first had to really dig into the essence of what I wanted to present, and how I wanted to show it, for the purpose of my study. I tried to present graphs that were able to inform the reader as good as possible, preventing to create figures that were some kind of puzzles. Second, I had to conduct interviews, which I had never done before. Therefore, after I had created a semi-structured interview, I decided to practice my interview with a colleague. This was the right decision because I knew which questions could be misinterpreted, and I knew how long the interview lasts. I had no real drawbacks during the interviews, something that a lot of students have, and everything went fluently. I think I had everything under control due to a proper preparation. The last part I had to face was the discussion. In the discussion, I really wanted to take a step back from my results and my own model world. Therefore, I tried to gain a certain level of abstraction and really draw up links that were not directly clear from the results.

Additionally, I wanted to not mince my words during statements that can be found in the discussion. The latter is based on the fact that during the whole process, you develop a personal verdict for the problem that you are studying. Therefore, I really wanted to stay rational and make objective statements and let everything be driven based on the results generated by the model. Personally, I think I achieved both.

Looking back at my graduation project, I can state that I have successfully managed this project. I enjoyed my time at Port of Rotterdam and met a lot of new people. Port of Rotterdam allowed me to learn from their successful organisation and handed me the tools to fulfil my personal objective. Throughout the process, I discovered that a policy or just an emission reduction technique is intertwined in a lot of systems. Current regimes and present working methods are tough to intercept. Besides, I have increased by scientific writing and reading skills. And do not forget, I have acquired the scientific research methodology skills.

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Appendix

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If you are interested in the contents of this appendix, please contact the author.

A few pages to take

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