Selection of cost-effective emission abatement options for early-stage ship design

A selection tool implemented for a road ferry and a workboat

I.V. van Grootheest

Master of Science Thesis

SDPO.19.038.m.

TU Delft

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to obtain the degree of Master of Science in Maritime Technology
at Delft University of Technology,

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Report number:	SDPO.19.038.m.	
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As part of the NAVAIS (New, Advanced and Value Added-Innovative Ships) project
Work package WP4, Task T4.2

Cover figure adapted from [10].

Preface

This thesis is the result of my graduation project for the completion of the Masters's program Marine Technology at the Delft University of Technology. First of all, I want to thank my daily supervisor Jeroen Pruijn. The support that I received from Jeroen contributed enormously to the structure and academic level of this thesis. I am very grateful for your extensive involvement in the graduation project in which you have given me a lot research freedom and guidance.

This thesis project has been carried out in cooperation with participants of the NAVAIS project. It was a good experience to be involved in the NAVAIS consortium and to get insights into such a maritime project. It was very interesting to speak with many people from different disciplines, whose advice all contributed to this thesis. I would like to thank Frans Hendrik Lafeber and Rudolf van Heek from MARIN, Marco Scholtens from NMT, Jorinus Kalis, Gert-Jan Meijn and Robert van Sluijs from Damen for their time. Their knowledge and experience were a valuable addition to gaining more insight into the technologies and in shaping the requirements of the selection tool. The NAVAIS deliverable 4.1 provided a good basis for this report. For the exploration of operation research techniques, I would like to thank Tom van de Beek for sharing his knowledge.

Furthermore, with regard to the technical and practical information for the case studies, I would like to thank Bastiaan Vink for sharing his knowledge on road ferries. I would also like to thank Baldassare Messina and Federico Cattaneo for their information of workboats and abatement options. Additionally, I would like to thank Koos Frouws and Mark Duinkerken for their constructive feedback. I am very grateful for the advices I received from all involved, so that I could improve this thesis.

This graduation project is in line with my interests for a broad topic of current issues and associated challenges and opportunities. This has kept me motivated in recent months to complete the graduation project. The completion of this graduation project marks the end of a challenging and exciting study in Delft where I have learned a lot. My deepest gratitude goes to my family, friends and my girlfriend who have all supported me during this study.

Ivar van Grootheest
Delft, November 2019

Summary

A ship can emit different types of maritime emissions to the environment, which can impact the climate, the eco-system or human health. It is important to reduce this environmental impact of ships due to the stricter environmental requirements set by regulators. The various maritime emissions can be reduced through a wide range of feasible emission abatement options and many combinations can be made. The identified decision problem is the selection of the optimal combination of feasible abatement options at minimum costs that at least meet the required emission regulations. The main question to be answered in this thesis is: *How to gain insight into relevant emission abatement options in early stage design at the lowest costs?* For the identified decision problem, a universal selection tool is created which allows a widespread application and supports the maritime sector in reducing its environmental impact.

First the capabilities of the selection tool were defined. The emissions considered are different exhaust emissions (NO_x, SO_x, PM, VOC and CO_2) and Underwater Radiated Noise (URN). Both upstream (WTT) exhaust emissions for fuel production and operational (TTP) exhaust emissions are considered. The emissions regulations and limits depend on the vessel characteristics, operational profile/area and energy systems. In the selection tool, energy systems such as diesel engines can be selected as the benchmark. The selection tool must find an optimal combination that is suitable for a new-build vessel from a dataset with different fuel concepts and technical abatement options. The operational measures and retrofit abatement options are not considered. The feasible abatement options must be compatible with different ship design aspects such as the vessel type and energy systems. The emission regulations may require abatement options that may have conflicting effects. Such abatement options may reduce specific emissions but can increase the fuel consumption and/or increase other types of emissions.

A suitable concept of the selection tool including a selection procedure was then defined. This has been further advanced into a coupled selection tool including datasets, a user-interface and a decision making technique. The design space of possible combinations can be significant, due to the many abatement options in the dataset. The design space is reduced by imposing the emission criteria and compatibility criteria, but this space is still substantial and therefore various decision-making techniques were explored. In this thesis, the internal (operational+investment) costs and emissions are analysed for one year. The investment costs of abatement options, that may have unequal lifetime, are evaluated on annual basis. Furthermore, a basic cost-evaluation approach is used to provide a neutral view and to reduce influential parameters such as a discount factor and the analysis period. The evaluation of the environmental (WTT+TTP) performance is based on the operational profile and on the predefined emission factors in the dataset. The reduction effects of abatement options are assumed to be constant (design condition) and their reduction effects are evaluated over the quantified benchmark emissions.

The identified decision factors were integrated into an optimisation problem. Therefore, various optimisation formulations were explored and the formulation suitable for this problem has been defined. The optimisation problem is mathematically formulated as a multi-objective optimisation problem by two objectives. The minimisation of the internal costs and the minimisation of the external costs of emissions. In addition to the strict emission regulations, the external costs of emissions is implemented to facilitate the trade-off between additional emission reductions and to reduce the overall environmental impact. Moreover, it can provide an incentive and insight into other types of cost-effective combinations located in the objective space. It may indicate combinations with a relatively large emission reduction for a small increase in internal costs. The mathematical formulated optimisation problem includes various constraints such as the emission constraints and compatibility constraints.

The total effect of multiple abatement options on the benchmark emission factor or fuel consumption can be calculated by using recurrence relations. The optimisation problem is further classified as a constrained combinatorial optimisation problem, where the decision variable is a binary. Moreover, the problem is non-linear, because of the product of the recurrence relations that both depend on the decision variable. After the optimisation problem was mathematically formulated, various optimisation algorithms were explored. It has to solve the defined optimisation problem within a reasonable calculation time and must be able to be integrated into the selection tool. A suitable optimisation solver is the NGPM solver that is an implementation of the Non-dominated Sorting Genetic Algorithm II (NSGA-II). The multi-objective formulated optimisation problem can be solved by the (NSGA) genetic algorithm. It offers the possibility to simultaneously searching through different regions of the objective space and at the same time finding a varied set of optimal solutions. The constraints violations are used for the ranking of the individuals (combination of abatement options). The initial population size (number of individuals) and number of generations were determined case-specific by 'trial and error'. The multi-objective optimisation problem gives a Pareto front with non-dominated solutions. Therefore, in the selection tool, the obtained MATLAB output is transferred back to Excel for further evaluation of the output. In this output evaluation, the performance of the resulting combinations was compared with the benchmark performance. The solutions were obtained by varying the criteria weights.

The selection tool was tested by two case studies to evaluate the performance. This thesis project is in collaboration with the project New, Advanced and Value Added-Innovative Ships (NAVAIS) and the case studies are being carried out for a (double-ended) road ferry and the workboat. The battery-electric road ferry 9819 was selected as a reference vessel. The battery mode with an assumed operational profile (Baltic sea) is evaluated as a benchmark. As there are no operational emissions, only energy-efficient options are proposed by the selection tool. In the sensitivity analysis, the price and (upstream) emission factor of green electricity were reduced. In addition, the tool has been tested to evaluate the Underwater Radiated Noise (URN) constraints. The selected reference workboat (UV) 4312 has a diesel-electric configuration with three main high-speed diesel engines. The considered configuration is an aquaculture support vessel assumed to be operating in the North Sea. This case study was conducted with a larger population size and number of generations, because there is more variability in the type of feasible abatement options. To meet the strict NO_x emission regulations, the Selective Catalytic Reduction (SCR) is implemented in every solution. Furthermore, the selection tool is tested on a scenario with stricter SO_x regulations enforcing the selection of low-sulphur fuels. This also allows the implementation of PM reducing measures such as a Diesel Particle Filter (DPF). Furthermore, a LNG engine has been evaluated as a benchmark that shows good benchmark performance and meets the (NO_x and SO_x) emission requirements.

It can be concluded that the developed selection tool serves the purpose of evaluating and selecting combinations of feasible abatement options. Different types of emissions can be reduced in order to meet the emission regulations. From the case studies that have been conducted, it is possible to conclude that the formulated optimisation problem and optimisation algorithm work well. The overall decision-problem is in practice more complex and depends on various other decision-criteria such as dimensional criteria that must also be taken into account. In addition, it may be more realistic to include the off-design reduction performance of abatement options in the analysis. Furthermore, it may be useful to optimise the energy systems and abatement options simultaneously in order to achieve a larger feasible design space. The developed selection tool can also be used to explore different abatement options (including fuels) for other ship types with different operational areas.

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1. Introduction

First the relevance and importance of this thesis topic is explained in Section 1.1. Secondly, the context of this thesis project is given in Section 1.2. In Section 1.3, the problem definition is given, including the research questions and the scope of this research project. The research framework is given in Section 1.4 and the report structure is outlined in Section 1.5.

1.1. Problem background

Reducing the environmental impact of vessels has been gaining importance in recent years due to stricter environmental requirements in ship design and maritime transportation. A ship can emit different types of maritime emissions to the environment, which can contribute to air pollution, greenhouse gas (GHG) effect or have other negative effects on the environment. Maritime transportation contributes significantly to the global Nitrogen Oxides (NO_x) emissions [83]. NO_x emissions have several effects and can cause acidification and eutrophication (over-fertilisation) of ecosystems [31]. Sulphur Oxides (SO_x) emissions, related to the sulphur content of marine fuels, also contribute significantly to acidification with severe impact on ecosystems [31]. Above all, the most harmful maritime pollutant to humans is Particulate Matter (PM) as it penetrates into the respiratory systems and can lead to health problems and premature mortality [31]. The most important GHG emissions from shipping are Carbon Dioxide (CO_2) emissions, which have a warming effect on the climate [12]. Other GHG emissions such as methane (CH_4) emissions related to methane slip during the combustion process are also noteworthy, as they have around a 25 times higher global warming effect than CO_2 emissions [92]. CH_4 emissions are one of the aggregated Volatile Organic Compound (VOC) emissions. In addition to exhaust emissions to air, discharges to sea must also be reduced/controlled, such as Underwater Radiated Noise (URN) from ships, as this can mask communication between marine life [72].

The reduction of maritime emissions is enforced by stricter regulations or is encouraged by incentives; globally, regionally or locally. In Emission Control areas (ECAs) stricter emission regulations are imposed by the International Maritime Organisation (IMO). ECAs have been designated for NO_x emissions, SO_x and PM emissions. In the short term, there is a need in maritime shipping to reduce the SO_x, NO_x and PM emissions due to global or local regulations ([42],[43]). To stimulate the reduction of fuel consumption and the related CO_2 emissions of shipping, the IMO has introduced the Energy Efficiency Design Index (EEDI) for new ships [44]. Emissions such as methane emissions are not yet subject to strict mandatory regulations, but may also need to be reduced for the long term. This prospect of tighter limits globally and developments of stricter limits in ECAs stimulates the maritime industry to develop low-impact ship designs. A low-impact ship design is defined as a sustainable design with low emissions to the environment (and the climate) and complies with all applicable emission regulations. The emission regulations and incentives require or motivate the selection of alternative fuels, energy systems and abatement options to reduce fuel consumption and emissions. In the last decade, there has been growing interest of shipbuilders and ship operators in finding the right suite of technologies and fuels. This challenge has also received much attention in literature (e.g., [11], [25],[36]).

The various maritime emissions can be reduced and controlled by a wide range of abatement options and many feasible combinations can be made. The abatement options have various effects on the energy consumption and emissions. When combining different abatement options, interaction effects can occur. In addition, the abatement options must be compatible with each other and the energy systems. The maritime industry is characterised by fierce competition, so the abatement options must not have a major impact on the ship design, as that can lead to a ship that is no longer profitable.

All in all, cost-effective combinations of abatement options must be selected; cost-effective in the sense that the emission reductions are achieved at the lowest costs. To support the decision-makers on the selection of abatement options, different decision-making approaches (e.g., [6],[25],[86]) have been developed in the maritime industry. There is still a need for an approach which can evaluate different energy systems and select the most cost-effective combination of abatement options for various vessel types and operational regions.

The selection tool is intended for the early stage of the ship design process. At this stage, many alternative sets of systems can be assessed for their feasibility for the specific ship type and operational profile. In addition, the ship dimensions are not yet fixed and may be adjusted due to the requirements of alternative technologies and fuels. A selection tool will be developed for supporting the selection of cost-effective combinations of technical abatement options for new-build designs. The tool will be developed universally to enable a widespread application and to support the maritime sector in reducing the impact on the environment.

1.2. Background NAVAIS project

This thesis project is in collaboration with the NAVAIS project. The project name NAVAIS stands for New Advanced Value Added Innovative Ships and the context of this NAVAIS project is given in Appendix A. The NAVAIS project uses system engineering approaches for modular ship design and ship production and applies the developed methods and procedures to two product families: road ferries and workboats. One of the strategic aims of the NAVAIS project is to improve the market competitiveness of shipbuilders of ferries and workboats. These vessels are built everywhere, but Europe plays traditionally an important role in the global market for passenger ferries and workboats. A specific type of road ferry and workboat have been selected as demonstrators.

The environmental performance of the ship designs will be evaluated with simulation models and calculation tools (the specific approaches are given in Appendix A). These approaches require a significant setup time and a reasonable idea of implemented measures. In the early phase of the ship design process, a feasible ship design space of energy systems, fuels and abatement options can be identified. However, the effort can be too much to evaluate all the different combinations of energy systems and abatement options of the feasible design space at such a detailed (simulation) level. It is therefore useful to first find a feasible selection of abatement technologies before using more detailed analysis tools. A selection tool must be developed for the designer, which makes it possible to make an early selection of relevant combinations of abatement options.

The current thesis summarises the findings of earlier research (NAVAIS work package 4 deliverable 4.1 (WP4-D4.1)). This thesis continues the environmental design process by developing a selection tool. The NAVAIS project context led to the topic of this thesis. Therefore, this thesis focuses on finding a selection of cost-effective combinations of abatement options that meet restrictions such as emission regulations and compatibility constraints. The developed selection tool will mainly be tested by case studies for the NAVAIS subjects: a double-ended road ferry and an aquaculture workboat in European waters.

1.3. Research problem statement

This section formulates the problem definition in a schematised decision context, the related research questions, and the scope of the thesis project.

1.3.1. Decision context

Gaining insight into the decision context offers a clarification of the factors (alternatives and criteria) that play a role in the decision-making process. The decision context is illustrated in Figure 1.1. This decision-making process is influenced by various decision-makers such as the ship operator, the ship designer and the ship builder. The decision problem is selecting an optimal combination of miscellaneous and interacting abatement options against minimal costs that at least meet all applicable emission requirements. The input is the long list of abatement options and fuels to reduce the emissions. The requirements are complex in nature. There are compatibility constraints/criteria for the abatement options; between each other and with the ship and energy systems.

The decision problem consists of many abatement options that can be combined in different ways, whereby different decision criteria must be met. Therefore, this decision problem requires the support of a decision-making technique that facilitates the decision-making and that considers the different decision criteria. Literature will be consulted on problems with similar decision characteristics to identify suitable decision-making techniques. To make a choice of approach, it may be necessary to further identify the decision problem. This includes the types of requirements, different abatement options and their different interactions. The identified decision-making technique will be implemented in a selection tool, which will be tested for two vessels. The NAVAIS participants have defined the road ferry and the workboat as subjects. They have selected the applicable regulations and Key Performance Indicators (KPIs) [53], which are defined as minimum emissions thresholds that must at least be met.

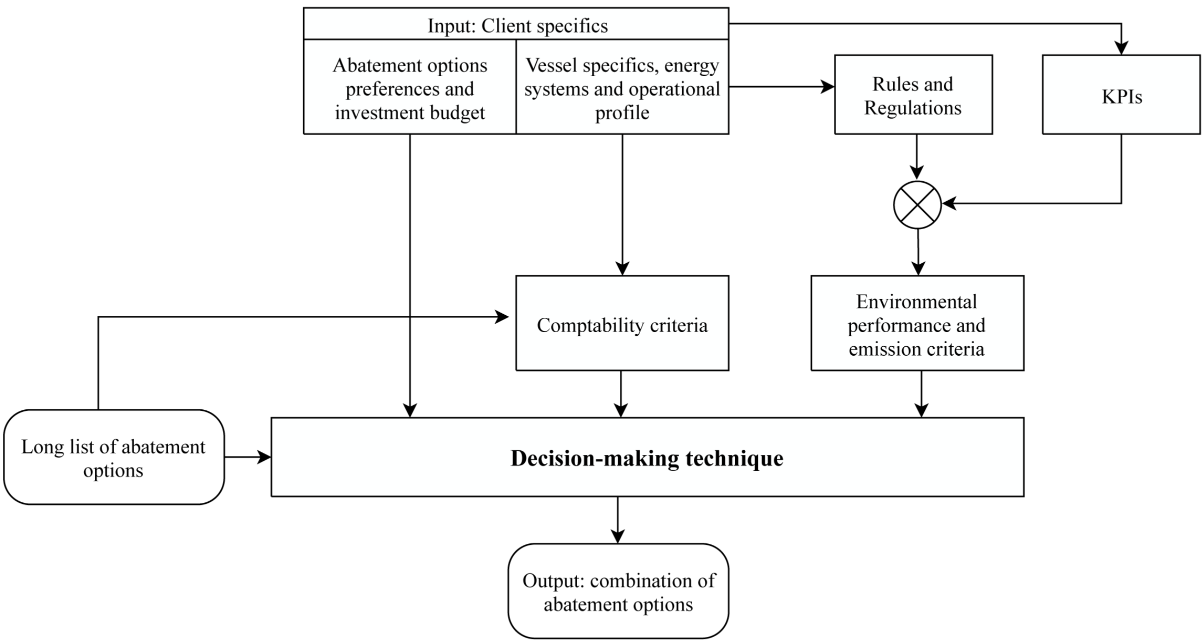


Figure 1.1: Decision context of the selection tool. Source: figure adapted from [53]

Definition of abatement option

This thesis focuses on the selection of options/measures/methods that are intended to reduce/abate exhaust emissions, also referred to as ”abatement measures/options” or ”emission controls”. Several authors ([15], [5]) have attempted to define this type of options in a more specific term based on the specific method or based on the purpose. The method to reduce emission can be either a technical (new-build and retrofit) measure or operational measure. Emission reduction can be achieved by the reduction of the specific emission (e.g. NO_x, SO_x, CO_2, or PM) or by the improvement of the energy efficiency. Although different definitions have been suggested for measures to reduce emissions, this thesis uses the definition ”(emission) abatement option”.

1.3.2. Research objective and research questions

This thesis introduces a new type of selection tool based on the given decision context. The research objective is defined as follows:

> *To reduce the environmental impact of new-build vessels by applying the most cost-effective combination of technical abatement options.*

This thesis report aims to answer the following research questions:

Main question

The central question addressed in this thesis report is as follows:

> How to gain insight into relevant emission abatement options in early stage design at the lowest costs?

Subquestions

To provide an answer to the main research question, this question is specified into four subquestions. The first subquestion addresses the alternatives, the second and third address the methodology and the fourth concerns the robustness of the methodology.

1. Which abatement options are relevant to include in the selection tool, and which specifically for the road ferry and the workboat?
2. What type of input data and boundary conditions are needed for the selection tool and how can cost-effectiveness be achieved?
3. What type of decision-making technique should be used in the selection tool?
4. To what extent is the optimal combination sensitive to the variation of input parameters?

1.3.3. Scope of thesis project

This thesis project is bounded by focusing on finding relevant abatement options for road ferries and workboats. However, the selection tool must be flexible to be used for other ships with other technical and cost requirements. The selection of abatement options is related to other installed energy systems, but the selection tool does not include the design of energy systems. Therefore, the basic design information of the energy system must be provided by the decision maker in the selection tool. The selection tool will be developed to evaluate technical abatement options, which are equipment and require physical modifications on new-build ships. Therefore, retrofit measures or operational measures are not considered. To sum up, this thesis focuses on the development of the selection tool, including choosing an appropriate decision-making technique. Technologies and fuels for ship designs are subject to numerous criteria. That is why the most relevant criteria for selecting the abatement options have been determined.

However, other decision criteria can also be decisive for the implementation of alternative technologies and fuels, such as the dimensional criteria or the adjacent infrastructure. The dimensional (weight and space) criteria are not considered, because the volume and weight limitations of the miscellaneous abatement options can be complex to define. The dimensional limits of the considered type of abatement options may be related to different spaces. For example, the dimensions of the fuel storage, the engine room, the exhaust gas system or the working deck, etc.

The abatement options are evaluated on their environmental performance including operational emissions and the upstream emissions for producing fuels. This means that the environmental analysis and assessment is bounded by excluding the potentially significant emissions caused during material production or during the demolition of the technologies. Furthermore, the tool is intended to be flexible, because the insights regarding the environmental effects of abatement options can change. For example, methane slip of LNG. Another example are open-loop scrubbers that reduce SO_x emissions, but can also pollute (acidify) waters in sheltered areas by discharging contaminated washing water [88]. With the intended flexibility, options can easily be removed or added to the selection tool.

1.4. Research approach

A research framework has been set up to gain insight into the research steps that had to be taken to answer the research questions of this thesis. The structure of the research framework is based on the System Engineering method of Kossiakoff et al. [51], because this method is useful as a guide for the development of complex systems or to develop tools for complex decision-making processes. In this report, these System Engineering phases are implemented into three clustered phases, as indicated below:

Phase I: Needs analysis
In the needs analysis phase, literature is consulted about the effects of emissions and about the measures to reduce these emissions. The relevant emissions and emission regulations identified by the project members of the NAVAIS are analysed more in detail. To answer the first subquestion, different types of technologies and fuels are explored, and relevant data is collected. The extensive needs analysis phase provides an idea of the input data, the required boundary conditions and the required capabilities of the selection tool.

Phase II: Methodology development
To provide an answer to which type of decision-making technique is suitable for the defined decision problem, different types of selection approaches are investigated. A suitable selection approach is selected based on the defined system capabilities and then defined in a concept of the selection tool. In addition, environmental and economic assessment approaches are determined for the selection tool. In the advanced development of the selection tool, the defined assessment approaches and the decision-making technique are integrated into a functional selection tool.

Phase III: Test and evaluation phase
In the test and evaluation phase, the developed selection tool is tested with case studies for the road ferry and the workboat. It was first investigated which abatement options are specifically relevant to the considered types of road ferry and workboat. To answer the fourth subquestion, a sensitivity analysis is performed to determine the behaviour of the selection tool. The sensitivity analysis supports the evaluation of whether the performance of the tool matches the expectations laid down in the proposed system.

1.5. Report structure

The report structure is analogous to the research framework and is subdivided into three parts: a needs analysis part, a methodology part and a 'test and evaluation' part.

Part I: Needs analysis part

In this part the capabilities of the selection tool are defined. The selection tool must be capable to evaluate various emissions and regulations. In addition, it must evaluate different type of technologies and fuels that are relevant for the selection tool. The relevant type of emissions and regulations are given in Chapter 2. The relevant technologies and fuels (including abatement options) are described in Chapter 3. The alternatives described in this chapter are supported by detailed descriptions in Appendix B to Appendix E. They are further provided with relevant decision parameters in Appendix F.

Part II: Methodology part

The methodology part of the report shows the conceptual development of the selection tool and its implementation in a computer model. Chapter 4 provides an exploration of selection approaches. This chapter also defines the concept of the selection tool with a suitable selection approach and describes a selection procedure. Chapter 5 refines the selection tool and describes in more detail how the technologies and fuels are assessed in environmental and economical terms. The optimisation problem of finding combinations of abatement options is defined and mathematically formulated in Chapter 6. Then the chosen optimisation algorithm for solving the optimisation problem is given in Chapter 7. This chapter also gives the background of the chosen optimisation algorithm and describes how the optimisation solver is integrated in the selection tool. It is further described how the output of the optimisation algorithm is generated and how it can be evaluated by the decision-maker. This methodology part of the report is supported by Appendix G, which provides a more detailed overview of the selection tool.

Part III: Test and evaluation part

The selection tool is tested and evaluated by case studies for the NAVAIS subjects to demonstrate the functioning of the selection tool. First the case study of the road ferry is described in Chapter 8 and secondly the case study of the workboat is described in Chapter 9. These ship types are first briefly introduced and a reference vessel is then environmentally and economically assessed, for which suitable abatement options are optimised. Both chapters contain a sensitivity analysis in which the behaviour of the tool is assessed to evaluate the functioning and the accuracy of the selection tool.

The report concludes in Chapter 10. Furthermore, recommendations are given for future research to help the maritime industry in the search for cost-effective selections of energy systems and abatement options to reduce the environmental impact of ships.

The structure of the report is schematised in Figure 1.2. This figure also shows on the left-side the followed research phases of the Systems Engineering method [51].

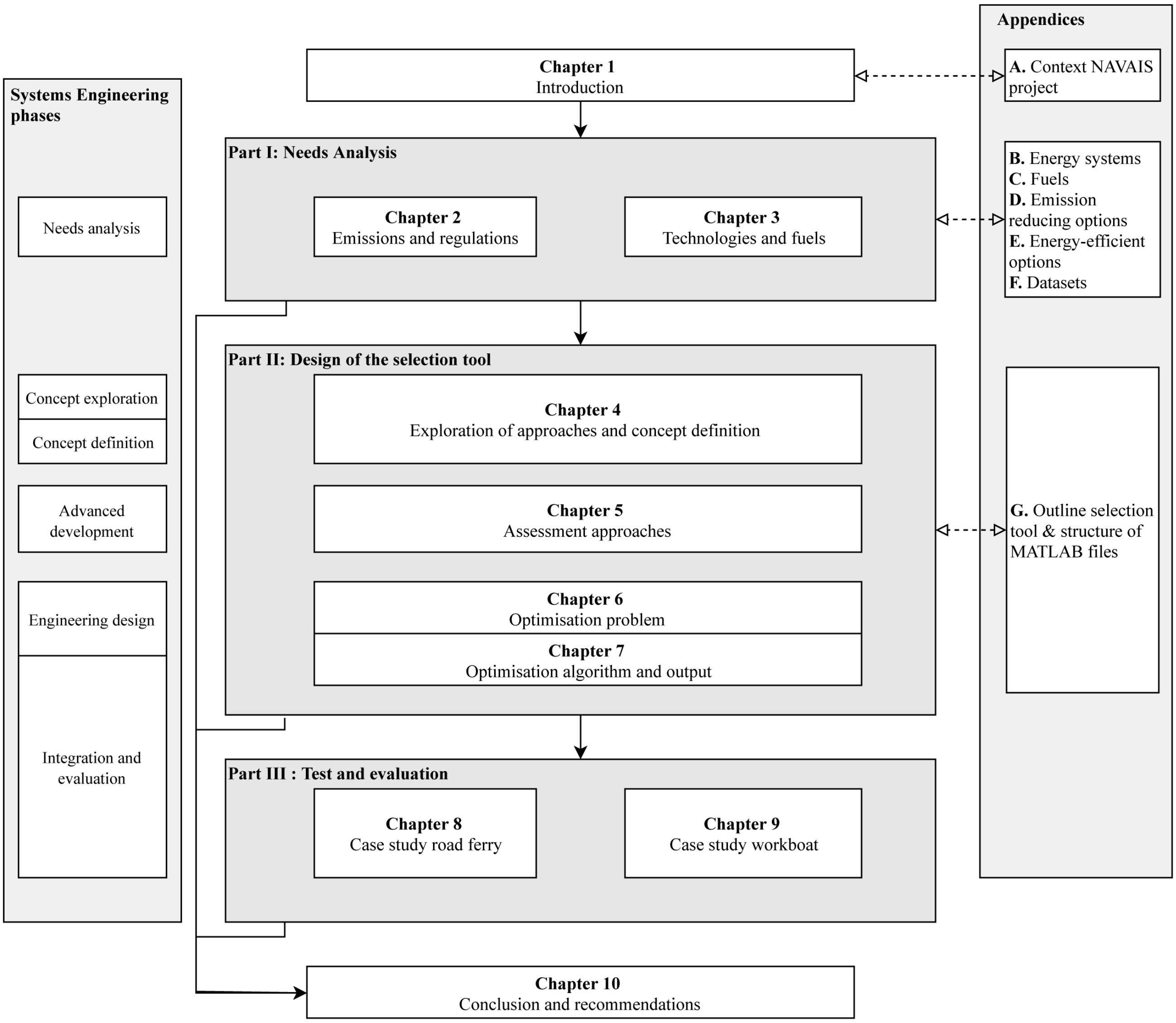


Figure 1.2: Structure of thesis report

I

Needs analysis

2. Emissions and regulations

The purpose of this chapter is to explain the necessity to reduce various emissions and why there is a shift needed in technologies and fuels. Therefore, this chapter provides an overview of maritime emissions and their various effects, sources and regulations. The scope of the environmental analysis relevant for this thesis is given in Section 2.1. Section 2.2 visualises the impacts of the exhaust emissions and gives the emission sources. The emission effects and emission sources of discharges to sea are described in Section 2.3. The emission regulations are described in Section 2.4. The external costs of exhaust emissions are described in Section 2.5. This chapter is concluded in Section 2.6, which summarises the requirements of the selection tool regarding the emissions and regulations.

2.1. Scope of environmental analysis

There are various methods to evaluate the environmental performance of a ship. For example, an extensive analysis to assess the environmental impact is full Life Cycle Assessment (LCA). The full LCA covers all phases of a product, e.g. extraction of material, transportation, production, operation and dismantling. However, such a full LCA is out of the scope for this thesis. In this thesis, the "Well To Propeller" (WTP) variant is found to be a suitable LCA stage to evaluate the exhaust emissions. The WTP can be split up in several phases as shown in Figure 2.1. The exhaust emissions emitted along the production pathway of fuels are called upstream emissions or "Well To Tank" (WTT) emissions. The exhaust emissions emitted over the operational profile of the vessel are referred to as "Tank To Propeller" (TTP) emissions [92]. The operational emissions of a ship include exhaust emissions, but also oil discharges, waste discharge, noise, ballast water, etc. These operational emissions can be classified as follows: emissions into the air and discharges into water.

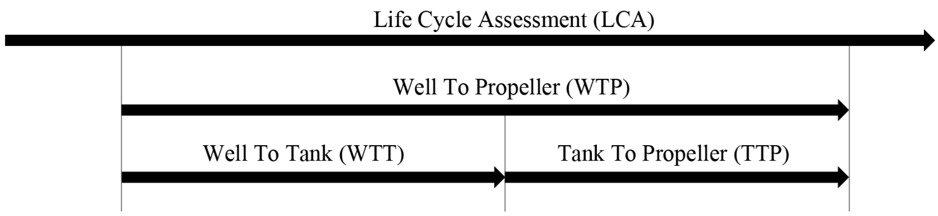


Figure 2.1: Considered emission stage (WTT and TTP)

The environmental performance in terms of (TTP) exhaust emissions can be assessed with different analysis methods, from empirical developed emission factors [87] to verification by full-scale measurements [53]. Comprehensive (inventory) assessments based on emission factors, have for example been conducted for maritime greenhouse gasses (GHG) in various studies ([12], [83]). More detailed analysis tools of the emissions in the design phase involve the equipment manufacturers during fabrication or exhaust gas analysis in approval testing and operation [53]. The testing consists of tests in the factory (Factory Acceptance Test) and testing at the quay. Furthermore, the engines are tested during shipboard trials to verify compatibility with the power and propulsion system.

NAVAIS participants have documented the emissions that are relevant for the selection tool and the articles of relevant regulations in earlier research (work package 4 deliverable 4.1 (WP4-D4.1)). The discharges to sea, oil and sewage are suitable for compliance Key Performance Indicator (KPI). However, oil and sewage are not taken into account in the selection tool, because they play less of a role in the trade-off between the other different types of emissions that are considered.

Five exhaust emissions (NO_x, SO_x, PM, VOC and CO_2) are suitable for quantitative KPIs. The discharge to sea, Underwater Radiated Noise (URN) will be evaluated in the NAVAIS project [53]. Table 2.1 provides the considered relevant emissions and the types of KPI targets. The other identified emissions are described in Appendix A.

Table 2.1: Relevant emissions. Source: obtained from deliverable WP4-D4.1 by Lafeber et al. [53]

Emission	Relevant	Type of KPI	In selection tool
Oil	yes	Compliance y/n	no
Sewage	yes	Compliance y/n	no
Nitrogen Oxides (NO_x)	yes	Quantitative	yes
Sulphur Oxides (SO_x)	yes	Quantitative	yes
Particulate Matter (PM)	yes	Quantitative	yes
Volatile Organic Compounds (VOC)	yes	Quantitative	yes
Carbon Dioxide (CO_2)	yes	Quantitative	yes
Underwater radiated noise (URN)	yes	Quantitative	yes

2.2. Effects and sources of exhaust emissions

The following subsections offer insights into the emission effects and the sources of exhaust emissions.

2.2.1. Effects of exhaust emissions

Figure 2.2 shows the links between the air pollutant (exhaust) emissions and their effects on air quality and their resulting impacts on climate, eco-system and human health. The exhaust emissions NO_x, SO_x, PM, VOC are shown in this figure. This figure only shows air pollutants. Therefore, it doesn't include greenhouse gas (GHG) emissions such as CO_2 emissions. Particulate Matter (PM) refers both to the emission and the air quality effect.

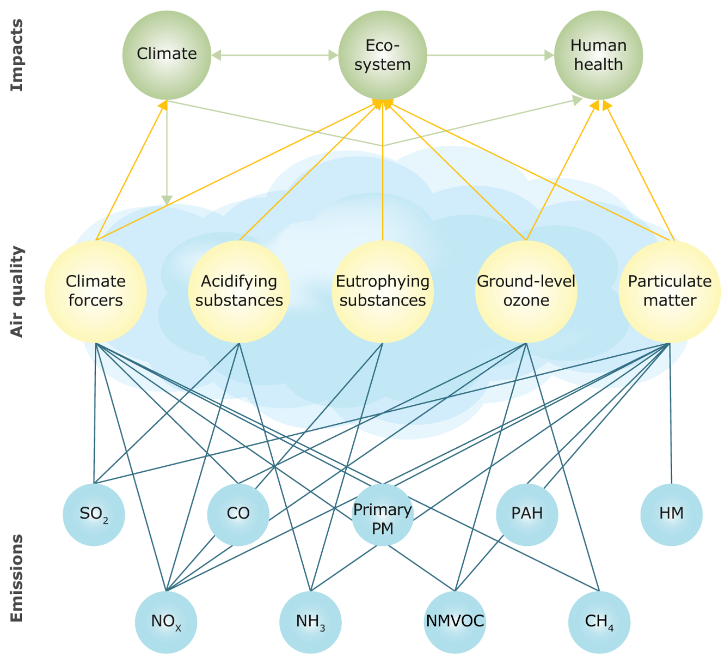


Figure 2.2: Various effects of air pollutants clustered according to impacts (Climate forcer: pollutants that interfere with Earth's energy balance [31]. Source: figure obtained from [31]

The links may need to be clarified, therefore their multiple effects are also presented in Table 2.2. This table also shows the effects of greenhouse gas (GHG) emissions, such as Carbon Dioxide (CO_2) and Nitrous Oxides (N_2O). An increase of GHG emissions in the atmosphere causes global warming [4], due to absorption of infrared radiation that is reflected and emitted by the earth [85]. Methane (CH_4) is both a GHG emission and an air pollutant emission. It can be deduced from Table 2.2 that NO_x emissions have various effects on air quality and have an acidification and eutrophication impact on the eco system and human health.

Table 2.2: Various effects of air pollutants clustered according to impacts. (Climate forcer: pollutants that interfere with Earth's energy balance [31]). Source: table adapted from [31]

	PM	SO_2	NO_x	NMVOC	NH_3	CO_2	NO_4	N_2O
Health impacts:								
Particle pollution (Health impact)	1	1	1	1	1			
O_3-ozone (Premature mortality)			1	1			1	
Ecosystem impacts:								
O_3-ozone (fluxes)			1	1			1	
Acidification (Excess of critical loads)		1	1		1			
Eutrophication (excess of critical loads)			1		1			
Climate impacts:								
Long-term forcing (GWP)						1	1	1

Note on Particulate Matter

The PM emission is a mix of non-volatile and semi-volatile compounds and can therefore not be referred to as a gaseous emission. PM can also be classified as fine particles ($PM_{2.5}$) or coarse particles (PM_{10}), which refers to the diameter of PM and relates to how severe the PM's effect is on human health [45]. Due to increasing awareness of the consequences and technological advancements in measurements methods, smaller $PM_{2.5}$ such as particles (soot) has gained increasing attention. Another serious emission is Black carbon (BC) (a component of fine particles) that absorb sunlight and thereby contribute to heating of the atmosphere [52].

Note on Volatile Organic Compounds (VOC)

The Volatile Organic Compound (VOC) emission is an aggregated emission consisting of Methane (CH_4) and Non Methane Volatile Organic Compounds (NMVOC). The methane (CH_4) emissions are the result from incomplete combustion of marine distillates and incomplete combustion of LNG [83], also referred to as 'methane slip'. As reported by Smith et al. [83] the methane forms 2% of the total VOC emissions. Methane emission are considered, because using LNG can contribute to methane emissions and this methane slip has severe impact on global warming.

2.2.2. Sources of exhaust emissions

The considered exhaust emission can be divided into fuel-related emissions and into (diesel) combustion related emissions [85].

Fuel-related emissions

The fuel-related emissions are exhaust emissions from complete combustion. The considered exhaust emissions that are fuel-related emissions are given below.

- Carbon Dioxide (CO_2) from carbon (C)-based fuels;
- Sulphur Oxide (SO_x) from sulphur (S)-containing fuels;
- Nitrogen Oxide (NO) from fuel-bound nitrogen (N).

Combustion process related emissions
The combustion-process related emissions are emissions that can be caused by incomplete combustion in the engine process [85]. The amount of these machinery-technology related emissions is dependent on the machinery type, specified tier level, engine mode and load factor of the engine. The considered emissions that are combustion-related emissions are given below.

- Particulate Matter (PM), also related to sulphur content of the fuel;
- Volatile Organic Compounds (VOC).

Nitrogen oxides (NO_x)
The NO_x emission is an aggregated emission and nitrogen oxides can be viewed as unintended combustion from nitrogen contained in the air [85]. The amount of NO_x is mainly dependent on the temperature, air to fuel ratio and the (in) completeness of the combustion [45]. The largest amount of produced NO_x is thermal NO_x, mainly reaction products from diatomic nitrogen (N_2) and oxygen (O_2) in the air under high peak temperature [85]. The fuel-related Nitrogen Oxide (NO) largely originates from the fuel-bound nitrogen [85]. Furthermore, the aggregated emissions contains Nitrogen oxide (NO), Nitrogen dioxide (NO_2) and Nitrous Oxide (N_2O).

Trade-off between NO_x and PM
The trade-off for diesel engines between NO_x and PM emissions is visualised in Figure 2.3. This trade-off is often referred to as the Diesel Dilemma or the Diesel paradox. The changes of NO_x and PM are typically inversely related, due to their formation as function engine temperature and fuel to air ratio [45]. On the one hand an engine can be designed with a more efficient combustion, but due to the higher temperature it has higher NO_x emissions. At the other hand, an engine with a lower peak temperature has lower NO_x emissions, but is less efficient and has therefore higher fuel consumption and fuel related emissions such as CO_2 and PM emissions. Therefore an optimum must be found for a diesel engine. Figure 2.3 also shows different measures for reduction of NO_x and PM emissions.

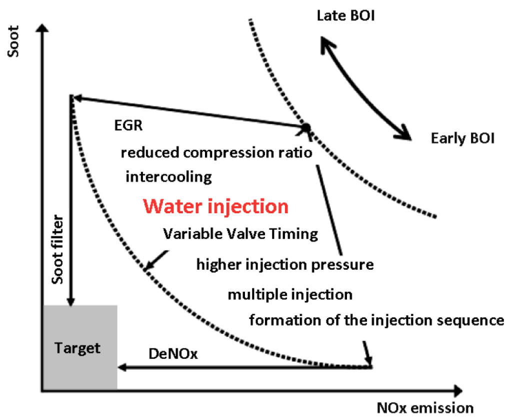


Figure 2.3: Trade-off for diesel engines between NO_x and PM emissions. Source: figure obtained from [49]

2.3. Effects and sources of Underwater Radiated Noise

Underwater Radiated Noise (URN) is a discharge to sea. The marine life is vulnerable to Underwater Radiated Noise from vessels, because fishes and marine mammals are dependent on the sound for communication. The sound originates from anthropogenic (caused by humans) sources can mask the communication between marine life [72] as shown in Figure 2.4. URN sources can be categorised as impulsive sound sources or continuous (ambient noise) sound sources [72]. For example, an impulsive sound source is offshore pile driving and a continuous source is shipping [72].

Shipping noise falls in the (low-frequency) band range between the frequencies 10 Hz and 1 kHz, the frequency band which is audible for different species of marine animals falls in this range [84]. These low-frequency noise can travel long distances underwater. For some vessels such as fishing vessels, it can be important to minimise the URN signature, because it can cause fish avoidance. However, it also becomes more important for other commercial vessels to reduce the environmental impact to sea life. Significant sources of URN can be cavitating propellers or onboard machinery [53].

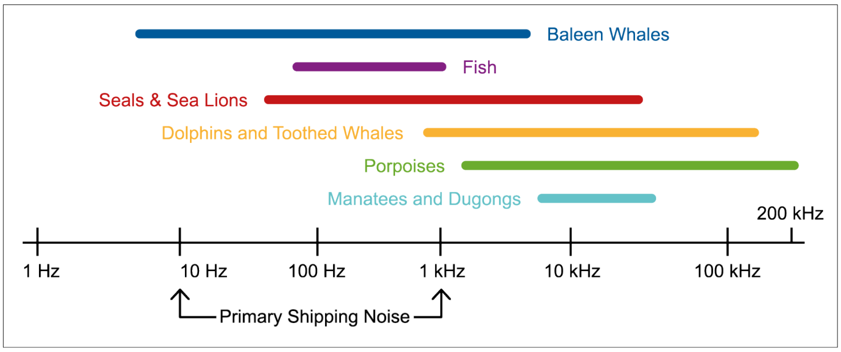


Figure 2.4: Audible range of hearing for marine life and shipping noise. Source: figure obtained from [62]

2.4. Emission regulations

This section provides a background of regulatory bodies and ECAs. Thereafter it describes the applicable regulations for the considered exhaust emissions and Underwater Radiated Noise.

2.4.1. Regulatory bodies and emission control areas

Maritime transportation is subject to regulations of the International Maritime Organisation (IMO). For monitoring and control of the marine environment, the IMO has established the Marine Environment Protection Committee (MEPC). This MEPC recommends the International Convention for the Prevention of Pollution From Ships (MARPOL). The regulations to prevent pollution are provided in the annexes according the type of emissions. The MARPOL regulations are also incorporated into national regulations of countries for territorial water or local limits. The IMO designates ECAs to areas which are sensitive with respect to maritime transportation and their environmental impacts. The ECAs have stricter limits for exhaust emissions than non-ECAs, mainly NO_x and SO_x (PM) emissions.

2.4.2. Regulations for exhaust emissions

The release of exhaust emissions can be regulated by the MARPOL and other local regulations. The applicable regulation for the respective exhaust emissions are described below.

Regulations for Nitrogen Oxides (NO_x)

The NO_x emissions are regulated through MARPOL Annex VI, Reg. 13 [42]. This regulation apply to ships with an installed marine diesel engine of over 130 kW output power other than those used for emergency [42]. The limits are divided in three tiers. Ships that are sailing in NO_x-ECAs must comply with the strictest limits (Tier III) and ships sailing outside NO_x -ECAs must comply with the Tier II limits (expressed by the weighted cycle value). The total weighted cycle means that the engines must be tested for different load factors, which are then combined in one weighted limit. Manufacturers need to do tests for marine diesel engines to demonstrate compliance with NO_x emission limits [42]. If the NO_x emissions are in compliance, an Engine International Air Pollution Prevention (EIAPP) certificate is issued [42].

The weighted cycle NO_x limit depends on the engine's rated speed (n) as shown in Table 2.3.

Table 2.3: NO_x total weighted cycle emission limit. (n=engine's rated speed [rpm]) Source: obtained from [42]

Tier	Ship construction date on or after	Total weighted cycle emission limit [g/kWh]		
		n <130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17	$45 \cdot n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	$9 \cdot n^{(-0.2)}$ e.g., 720 rpm – 2.4	2

Regulations for Sulphur Oxides (SO_x) and Particulate Matters (PM)
The SO_x emissions are regulated via MARPOL Annex VI, Reg. 14 [43]. Indirectly the PM emissions are also covered in this regulation. The regulations for SO_x are defined as the maximum sulphur content in the fuel, which must be below 0.5% (5000 ppm) for all ships sailing outside an ECA and less than 0.1% (1000 ppm) for vessels sailing inside an ECA. The introduction of the global cap for the sulphur limit (0.5 % m/m) in 2020 is stated in Table 2.4.

Table 2.4: SO_x and PM emission limit. Source: obtained from [43]

Outside an ECA to limit SO_x and PM	Inside an ECA to limit SO_x and PM
4.50% m/m prior to 1 January 2012	1.50% m/m prior to 1 July 2010
3.50% m/m on and after 1 January 2012	1.00% m/m on and after 1 July 2010
0.50% m/m on and after 1 January 2020*	0.10% m/m on and after 1 January 2015

Regulations for carbon dioxide (CO_2)
The CO_2 emissions are regulated through the MARPOL Annex VI, Ch4. The MEPC aims to minimise the CO_2 emissions from international shipping through the implementation of the mandatory Energy Efficiency Design Index (EEDI) for newbuilds and the Ship Energy Efficiency Management Plan (SEEMP) for current sailing vessels. The SEEMP however is an operational measure and is therefore not taken into account in the selection tool. The EEDI motivates to improve the ship's energy efficiency by installing more energy efficient technologies. According to Ch4, reg. 19 the EEDI applies to ships with gross tonnage of more than 400 and that sail in international waters. Furthermore, the EEDI is only suitable for diesel-mechanic and diesel-electric system architectures, but less suitable for hybrid energy systems [44]. The EEDI reflects the CO_2 emissions per ship's capacity mile, or the amount of emissions divided by the cargo capacity of the ship as shown in Equation 2.1 [44]. A higher attained EEDI means that the vessel is less energy efficient and vice versa. The attained EEDI should be equal or less than the required EEDI value. In which the required EEDI is based on the (ship-specific and implementation phase dependent) reduction factor and the (ship-specific) reference EEDI.

$$\text{Attained EEDI} = \frac{CO_2 \text{ emissions}}{\text{Transport work}} \tag{2.1}$$

Regulations for Volatile Organic Compounds (VOC)
The regulations of MARPOL Annex VI regarding to VOC caused from venting of cargo vapours are not taken into consideration. However, the emission of VOC is taken into account, because the severe effects of methane (CH_4) slip as described on page 13. In the selection tool methane slip is taken into account by using the external costs of VOC.

2.4.3. Regulations for Underwater Radiated Noise

There are no definitive regulations from IMO that include noise limits, but the reduction of URN has received much attention by various initiatives [41]. Classification societies have introduced noise-related notations for different ship types and some norms are based on the response of fishes to URN [53]. The KPI used in the NAVAIS project is set to maximum noise levels (covering a frequency range) for different operational conditions.

2.5. External costs of exhaust emissions

This section describes the external costs of exhaust emissions. First, the background and the reasons are given why the external costs can be used in the decision-making. The literature source and the determination of external cost factors are then described. This section ends with a description of how the external costs of upstream emissions are taken into account in the selection tool

2.5.1. External costs in decision-making

The emission regulations may require the implementation of an abatement option that may have a conflicting emission effect (with a higher impact). The emission impact can be converted into external costs (also expressed as societal costs or abbreviated CTS (Costs to Society)). External costs mean economically that not the buyer or seller of a technology is incurred by the costs or benefits, but the costs are incurred by an external party [3]. For example, society, therefore the state can introduce a green tax to internalise the external costs [89]. External costs can be applied in the decision making (e.g., [9], [3] [89]). Moreover, external costs can be used to serve as a balancing approach between technologies to stimulate the reduction of the (overall) environmental impact beyond the emission regulatory limits [9]. The same monetary unit also makes it possible to facilitate the trade-off between internal (investment+operational) costs versus the external costs of emissions. In addition, if there are no operational emissions, but only upstream emissions (e.g., battery-electric vessel), the external costs can be used to stimulate the selection of energy efficient technologies or other fuels.

2.5.2. Determination of external cost factors

The emissions can have impacts on different impact categories (climate, ecosystem and human health as shown in Figure 2.2) and these impacts can be converted to external costs to the society. The approaches for evaluating the external costs differ for air pollutant emissions and Greenhouse Gas (GHG) emissions. In this thesis, the external cost factors as derived by NAVAIS participants [53] are used. They are based on the two different assessment approaches as described below.

The external cost factors of air pollutants (air pollution damage costs) are based on a handbook of external costs reported to the European Commission [2]. It provides the external costs for the main air pollutant emissions (NO_x, SO_x, PM, VOC) for maritime transport in the North Sea. They are evaluated by the EcoSense model [2], which is a dispersion and exposure assessment model. This EcoSense model evaluates the spread of air pollution and assess the extent of the population and ecosystem which are exposed by the emissions [2]. The impacts on ecosystem and/or human health can be expressed by impacts such as the number of premature deaths, illness, lost crop production or damages to buildings. These impacts can be transformed into external costs [2].

The CO_2 (GHG) emissions contribute to global warming and can therefore impact ecosystems and human health [31]. The external cost are linked to an increase of CO_2 emissions in a certain year [2]. The used external cost of CO_2 emissions are derived by assessments models which use a damage cost approach [2]. The increase of atmospheric concentrations of CO_2 emissions are translated to changes in radiative forcing, which in turn affects the earth temperature [2]. As a result, it can lead to changes in sea level, biodiversity, etc, which can also be converted to external costs [2].

Table 2.5 shows the used external cost factors in which the factors are projected for 2030 (when the NAVAIS vessels are assumed to be operational) by using an inflation correction. The external cost factor for the exhaust emission VOC is based on an indicator of NMVOC emission [2]. It is important to note that these derived external cost factors are based on estimation methods that involve much uncertainty and assumptions about causality. For example, the pathway of some air pollutant emissions can be complex and difficult to evaluate [2]. Moreover, the external costs are based on valuation studies [2] in which certain damages are converted to reasonable costs. In this thesis, these external cost factors are seen as given information and will not be varied in the sensitivity analysis. However, the external cost factors used are also compared with other sources (e.g.,[3], [9], [89], [92]) that show a similar order and distribution.

Table 2.5: External cost factors for maritime exhaust emissions in the North-Sea. Source: External cost factors obtained from [53], projected for 2030 and based on inflation correction of the values of [2]

Emissions	External cost factor [€/ton]
NO_x	7,557
SO_x	9,652
PM	32,766
VOC	2,667
CO_2	54

2.5.3. Evaluation of external costs in the selection tool

The IMO emission requirements apply to the operational (TTP) emissions, but the upstream emissions are not regulated by the IMO. For the operational phase all emission types (as shown in Table 2.5) are evaluated. In the tool both upstream (WTT) emissions and operational (TTP) exhaust emissions are considered, because some alternative fuels can have zero TTP emissions, but can have significant WTT emissions. In the selection tool, the upstream emissions are evaluated on the basis of CO_2 equivalent emission factors. The upstream emissions of other emission types (NO_x, SO_x etc.) are also reported for some fuels [100]. The SO_x upstream emissions can be significant due to desulphurization [100]. The aggregated CO_2-equivalent indicator can be used to evaluate the amount of GHG emissions, this indicator is also known as the Global Warming Potential (GWP). The aggregated CO_2-equivalent indicator is made up of the three main weighted GHG emissions: CO_2 multiplied by 1, methane (CH_4) multiplied by a factor of 25 and Nitrous Oxide (N_2O) emissions multiplied by a factor of 298 [92]. The aggregated CO_2-equivalent [gCO_2-eq/kWh] indicator is specified for the fuels in the dataset.

2.6. Conclusion

The selection tool is needs-driven, because there is a need to reduce various types of maritime emissions. The exhaust emissions (NO_x, SO_x, PM, VOC and CO_2) and Underwater Radiated Noise are evaluated in the selection tool. This chapter also stressed the importance of reducing exhaust emissions by presenting the effects on air quality and the impacts on the climate, eco-system or human health. For the reduction effects of alternative fuels, the energy system in which the fuel will be used must be taken into account. The emission requirements do not apply to any single vessel, but there is an environmental need to reduce the emissions across the maritime sector. In addition, to the potential absence of applicable emission requirements, some emission regulations may require the installation of abatement options with conflicting effects. The external costs can be considered as a balancing approach of the emission effects. Thereby they can be used in the trade-off between abatement options which may have conflicting effects or fuels with significant upstream emissions. The following chapter describes energy systems and the abatement options to reduce the emissions described.

3. Technologies and fuels

This chapter describes the state-of-the-art alternatives that are considered relevant for the selection tool. The analysis structure of the alternatives is explained in Section 3.1. The energy systems are described in Section 3.2 and the fuels are given in Section 3.3. The abatement options are described in two sections, Section 3.4 describes the emission-reducing options and Section 3.5 describes the energy-efficient options. The requirements of the selection tool with regard to the technologies and fuels are described in Section 3.6. This chapter is concluded in Section 3.7.

3.1. Analysis structure of alternatives

The alternatives are grouped into four categories: energy systems, fuels, emission-reducing options and energy-efficient options. These alternatives are summarised briefly in this chapter by stating their advantages and disadvantages. The alternatives are described in more detail in the appendices: Appendix B, Appendix C, Appendix D and Appendix E. The description is done in a uniform way to make a fair comparison and to clarify the differences between the alternatives. The appendices also describe whether the considered alternative applies to the road ferry and/or the workboat. The decision parameters for the selection tool are tabulated in the Excel datasets as shown in Appendix F. Excel was chosen, because it offers a clear overview of all the technology parameters to the user. In addition, new systems and updated parameters can easily be added to the datasets in the selection tool.

TRL-scale

The availability level of an alternative (energy system, fuel or abatement option) can be defined by the Technology Readiness Level (TRL). The Technology Readiness Level (TRL) method is a unified scale developed by NASA [30]. It is also used in the NAVAIS project and by the Horizon 2020 programme from the European Commission (EC) [30]. The TRL scale is broadly as follows: ready-to-use alternatives have a TRL of 9, alternatives that may be available in the near future may have a TRL of 6 and scientific methods or ideas have a TRL of 1 (lowest TRL). The TRL can be an influential parameter in the decision-making process, for example decisions regarding reliability and safety aspects of the alternatives. The relevant alternatives for the case studies have a TRL between 6 and 9.

Consideration of costs and reduction potentials

The investment costs may change over time due to technology progress or inflation. In view of the exploration phase, it may be sufficient to estimate the costs of technologies based on data from literature, because the input parameters and decisions made in this phase can change a lot. As the decisions become clearer, the costs in the datasets can be replaced by more accurate cost data from manufacturers. The fuel costs are based on fixed fuel costs factors. However, fuel costs vary over time due to various factors and the fuel price can play an important factor as it contributes significantly to the internal costs. The reported reduction potentials of the abatement options are dependent on many factors, such as vessel-specifics, operational profiles, engine loads, ship power configurations, etc. [45]. These reduction potentials should therefore be evaluated on a case-by-case basis. Most values are given for design-conditions. They are considered constant in the selection tool, also because the information about part-load conditions is often not available in the early design stage. To evaluate the overall (including off-design) performance in more detail, more complex tools such as the simulation-based approach SEECAT by Bureau Veritas [80] can be used.

3.2. Energy systems

In this thesis, the energy systems are defined as the subsystems of the power and propulsion system. The described energy systems are Internal Combustion (IC) engines, Energy Storage Systems (ESS) such as batteries and fuel cells. The pros and cons are summarised at the end of this section.

Internal Combustion Engines

Diesel engines in combination with diesel fuel are often used in maritime transportation, because these engines have relatively high efficiency and high specific power compared with other energy systems. In addition, IC engines can operate on a range of different marine fuels. However, they have high NO_x emissions. Due to Tier III (NO_x) emission requirements there is a required shift in engine technologies and abatement options such as Selective Catalytic Reduction (SCR) [26]. The engines are continuously being developed, e.g. due to the introduction of emission requirements and the introduction of alternative fuels such as Liquefied Natural gas (LNG). The main types of engines that can operate on LNG are dual fuel (DF) engines and pure gas (spark ignition) engines [93].

Energy Storage Systems

The last decades, battery technology such as Lithium-Ion batteries has been rapidly developed [73]. Lithium-Ion batteries have high specific energy density and high specific power compared to other batteries. However, batteries have a low specific power and specific energy compared with diesel engines running on diesel fuels [73]. Batteries offer the possibility for engines to work on the optimal load point for a larger portion of time [24]. During peak loads, the additional power can be obtained from the batteries and the engines can charge the batteries when the power demand of the engine is low. Other types of ESS are ultracapacitors, which have a higher specific power and can be charged and discharged faster than batteries [73]. Flywheels also have specific energy and power, but the design of a flywheel is relatively complex and additional safety cautions must be taken [71].

Fuel cell

The difference between a fuel cell and batteries is that the reactants are stored externally, the fuel cell can be supplied with a fuel and oxygen. There are various types of fuel cells such as Solid oxide Fuel cells (SOFC) that can operate on various types of fuels. However, fuel cells generally have lower specific power and higher investment costs than conventional diesel engines [91]. The defined type of fuel cell in the selection tool is a hydrogen Proton Exchange Membrane Fuel Cell (PEMFC), which emits no operational emissions and has low machinery noise.

Summary of energy systems

The advantages and disadvantages of the energy systems are given in Table 3.1. The detailed descriptions of the energy systems are provided in Appendix B.

Table 3.1: Overview of advantages and disadvantages of energy systems

Alternatives	Advantages	Disadvantages/issues
Diesel engine	High specific power	Noise and high NO_x emissions
Gas engine	High specific power and lower NO_x	Noise and CH_4 emissions
Batteries	No emissions and noise	Low specific power and energy
Ultracapacitor	High specific power and no emissions	Low specific energy
Flywheel	High specific power and no emissions	Complex design
Hydrogen fuel cell	No emissions and low noise	Low specific power

3.3. Fuels

The described fuels vary from conventional fuels, transitional fuels to alternative fuels with a long-term potential. For fuels, the upstream emissions for producing the fuels ar also taken into account.

Conventional fuels

Fossil-based fuels (e.g. HFO, MDO, MGO) have been used for decades in maritime transportation. Due to stricter SO_x requirements, there has been a shift in the types of marine fuels to low-sulphur fuels (e.g. LSMGO). However, engines operating on low-sulphur fuels still have high NO_x and PM emissions. Furthermore, conventional fuels have a high carbon content and therefore lead to high CO_2 emissions [26].

Transitional fuels

Transitional fuels are fuels that can be expected to arise in the short term and medium term, e.g. from 2020 towards 2050. Due to the stricter SO_x and NO_x requirements, the use of Natural Gas is increasing. Natural gas can be stored compressed, liquefied or absorbed in other media. Natural gas is a hydrocarbon fuel with the lowest carbon content and therefore the CO_2 emissions are reduced [26]. The challenges with natural gas are the storage requirements. When LNG is used in a gas engine, the NO_x emissions are further reduced. However, natural gas can be seen as a transitional fuel, because it still contributes to CO_2 emissions and can lead to methane (CH_4) slip. Liquefied Petroleum Gas (LPG) has good storage requirements and contains no sulphur and the combustion results in lower CO_2 emissions than diesel fuels. Second and third generation biofuels show the potential to become an alternative fuel [16]. Some biofuels can be used as a drop-in fuel and can be mixed with diesel fuels. Biofuels typically have lower CO_2 emissions, but they have lower energy content.

Alternative fuels with a potential for the medium and long term

Methanol is an alcohol fuel and can be produced from various sources. Methanol has a low carbon content and reduces the amount of CO_2 and PM emissions. Methanol has similar fuel storage requirements as conventional fuels. However, methanol has a relatively low calorific value and therefore has a higher specific fuel consumption [36]. Hydrogen has no (e.g. CO_2) emissions and can be produced by electrolysis or by steam reforming of various sources (e.g. methane). Hydrogen can be stored liquefied (at - 253°C), pressurised or stored in metal hydrides [91]. The volumetric storage density of hydrogen compared with diesel fuels is relatively low [26]. Ammonia contains no carbon and has no CO_2 emissions. However, ammonia has relatively low volumetric energy density and is furthermore toxic.

Summary of fuels

An overview is given in Table 3.2 and the detailed descriptions are provided in Appendix C.

Table 3.2: Overview of advantages and disadvantages of fuels (FC:Fuel consumption)

Alternatives	Advantages	Disadvantages/issues
Diesel fuels (high S)	High energy density; low fuel cost	SO_x, CO_2
Diesel fuels (low S)	High energy density, low SO_x	Fuel costs, CO_2
Natural gas	Low SO_x; lower CO_2, PM and NO_x	Dimensions and costs, CH_4 slip
Biofuels	Lower CO_2; drop-in fuels	Increase of FC, affects (fuel) system
LPG	Low SO_x; lower CO_2, PM and NO_x	Safety, LPG slip
Methanol	Reduction of CO_2, NO_x and PM	Corrosive, low energy density
Ammonia	No CO_2	Low energy density, NH_3 slip
Hydrogen	No emissions in fuel cell	Low energy storage density

3.4. Abatement options: emission-reducing options

The emission-reducing options are grouped by the three main strategies as recognised by CIMAC Exhaust Emission Control [85] to reduce and control the exhaust emissions. Furthermore, there are various measures to reduce Underwater Radiated Noise (URN), they are described in Appendix D.

Primary methods

The primary methods vary from modification of combustion, modification of air intake conditions, water injection methods to Exhaust Gas Recirculation (EGR) systems. There are various methods for introducing water in the combustion process: by means of water vapour (Humid Air Motor (HAM)), Direct Water Injection (DWI) or Fuel Water Emulsification (FWE) [77]. In Fuel Water Emulsion (FWE), the fuel is mixed with fresh water prior to injection into the combustion chamber. This makes it possible to reduce NO_x and PM emissions [99]. The EGR makes it possible to reduce the cylinder temperature and the related amount of NO_x emissions. A side effect of these water-addition methods and the EGR is that the engine runs less efficient, which can increase the fuel consumption (FC) and fuel-related emissions.

Secondary methods

Selective Catalytic Reduction (SCR) is a secondary ('end-of-pipe') method. The SCR uses a catalyst to convert NO_x emissions into nitrogen (N_2) and water (H_2O) by injecting an additive, which can be ammonia (NH_3) or urea ($CO(NH_2)_2$) [77]. Significant space is required for storage tanks for the additives and catalyst elements. The lifetime of catalyst elements of a SCR depends on the sulphur content of the fuel [55]. Another type of aftertreatment methods are the Diesel Oxidation Catalyst (DOC) and Diesel Particulate Filter (DPF). The DPF collects soot (PM) from the exhaust system [52]. These aftertreatment methods are most efficient when the fuel sulphur content is less than 0.05% [77]. A SO_x scrubber scrubs the exhaust gas by exposing it to a medium, either water (with or without additives) or a dry chemical [56]. However, scrubbers require significant space and have relatively high costs.

Summary of emission-reducing options

The advantages and disadvantages of the emission-reducing options are given in Table 3.3. The detailed descriptions of the emission-reducing options are provided in Appendix D.

Table 3.3: Overview of advantages and disadvantages of emission-reducing options (FC:Fuel consumption)

Alternatives	Advantage	Disadvantages/issues
Humid Air Motor (HAM)	Reduction of NO_x	Increase FC
Fuel Water Emulsion (FWE)	Reduction of NO_x and PM	Increase FC, corrosive
Direct Water Injection (DWI)	Reduction of NO_x	Increase of FC
Exhaust Gas Recirculation (EGR)	Reduction of NO_x (and CH_4)	Increase of FC and PM
Selective Catalytic Reduction (SCR)	Reduction of NO_x and PM	Increase of FC
Diesel Particulate Filter (DPF)	Reduction of PM	Increase of FC, sulphur
Diesel Oxidation Catalyst (DOC)	Reduction of PM	Sulphur in fuel
Exhaust gas scrubber	Reduction of SO_x and PM	Dimensions, increase FC

3.5. Abatement options: energy-efficient options

The selection tool also contains various types of energy-efficient options. However, only technical measures are taken into account, so operational measures and retrofit measures are not considered. Operational measures, such as speed reduction can reduce the fuel consumption significantly, because the fuel consumption increases as cubic function of vessel speed [24]. There are various other operational and maintenance measures to reduce fuel consumption such as hull cleaning, propeller polishing, green Dynamic Positioning (DP) and weather routing.

Ship design

Lightweight material (e.g. aluminium) can be used for the construction of the hull or the superstructure. A lighter displacement contributes to a reduction in the frictional resistance and thus to a reduction in fuel consumption [1]. The hull form can also be hydro-dynamically evaluated and optimised by doing Computational Fluid Dynamic (CFD) assessments. The superstructure can be aerodynamically evaluated by doing CFD calculations, and can be optimised to reduce wind resistance. The hull can be treated with a hull coating that reduces corrosion and fouling on the hull and thereby reduces frictional resistance and fuel consumption. A positive side-effect is that reduction of fouling improves the water flow and reduces turbulence-related URN [41]. Other technical measures are measures such as energy-efficient lightning that can be applied to reduce the (auxiliary) energy consumption.

Power and propulsion system and alternative energy sources

A Waste Heat Recovery (WHR) system recovers the thermal heat energy (of exhaust gases). The recovered energy can be converted into useful electrical or mechanical energy and therefore reduces fuel consumption. Propulsion Improving Devices (PIDs) can be used to improve the wake inflow to the propeller or to utilise the rotational energy behind the propeller. They can reduce cavitation (and URN) and/or improve the propeller efficiency [25]. The propeller can be optimised to reduce cavitation and/or efficiency for off-design conditions and/or design speed [47]. Wind energy recovery systems, such as Flettner Rotors can be used to increase ship's speed or to reduce the fuel consumption. However, the supply of wind energy is variable and the operating envelope of the ship is often limited [1]. Solar panels convert solar energy directly into electricity also have to deal with the variability of the energy source. Moreover, solar panels have a low energy density and are therefore more suitable for supplementing auxiliary power.

Summary of energy-efficient options

The advantages and disadvantages of the energy-efficient options are given in Table 3.4. The detailed descriptions of the energy-efficient options are provided in Appendix E.

Table 3.4: Overview of advantages and disadvantages of energy-efficient options (FC:Fuel consumption)

Alternatives	Advantage	Disadvantages/issues
Lightweight construction	Reduction of FC	High investment costs
CFD	Reduction of FC	High investment costs
Hull coating	Reduction FC and URN	-
Air cavity lubrication	Reduction of FC	Less effective off-design
Waste Heat Recovery (WHR)	Reduction of FC	High costs and efficiency
Propeller optimisation/PID	Reduction of URN and/or FC	Trade-off URN and efficiency
Wind recovery systems	Free energy and reduction of FC	Operational envelope and space
Solar panels	Free energy and reduction FC	Low and variable energy yield
Energy-efficient lighting	Reduction of FC	-

3.6. Requirements for the selection tool

It may be necessary to implement multiple different abatement options, because usually no single abatement option can reduce the various exhaust emissions to meet the applicable emission regulations. These various abatement options can interact with each other, might be incompatible or may have significant costs.

3.6.1. Compatibility relations and interaction effects

The abatement options must be technically feasible and compatible. Several studies ([5], [11], [99]) address the importance and different types of compatibility of abatement options. Furthermore, some studies ([1], [25], [56]) outline compatibility relations in compatibility matrices. Compatible options can be defined as options that are suitable to combine with different design aspects, such as the vessel, energy systems, operational profile and other abatement options which are not redundant. Compatibility relationships may exist between the alternatives and the ship type, which can be defined for various reasons, such as alternatives that are unfeasible or too large for the considered type of vessel. Furthermore, there are compatibility relations between abatement options and the energy system and between different abatement options. The reduction effects of multiple abatement options are not additive, because of the interdependency between abatement options as acknowledged by several studies ([6], [11], [1]). The summation of reduction effects of multiple abatement options overestimates the total reduction effect. The abatement options can have various system requirements or effects on other systems. For example, the catalysts of the Selective Catalytic Reduction (SCR) require a certain temperature window of the exhaust gases. The use of abatement options may require additives and can therefore increase the operational costs. Some abatement options can have adverse effects on energy systems, such as water injection technologies that can cause corrosion in the fuel systems [77] and thereby increase the maintenance costs. There are also cost-interaction effects between abatement options, the maintenance costs of abatement options such as SCR depend on the sulphur content of the fuel ([5], [77]).

3.6.2. Conflicting effects

Some fuels or abatement options can have conflicting effects. For example, LNG has lower CO_2 emissions but the possible fugitive emission of methane slip dampens the GHG potential [11]. Another common conflicting nature of some abatement options is that they reduce specific emissions, but can slightly increase fuel consumption and therefore fuel-related emissions such as CO_2 [53]. There is often a need from emission regulations to reduce a specific emission, requiring the selection of specific abatement options which can have conflicting effects. A balancing approach such as external costs as discussed in Section 2.5 can therefore be used in the selection tool.

3.7. Conclusion

This chapter has shown that there is need to consider various types of alternatives in the selection tool. The fuel should be considered for the benchmark assessment and as an abatement option. Only technical measures intended for new-building are taken into account, so retrofit measures or operational measures are not further considered. Inevitably, this chapter showed that the dimensional (volume and weight) criteria play an important role in the trade-off, however this is out of the scope as discussed in subsection 1.3.3. In the selection tool, the technologies will be evaluated primarily on two main criteria: environmental and cost criteria. This chapter described the type of factors that play a role in combining different types of technologies. There are compatibility criteria between alternatives and the ship type, between abatement options and energy system. In addition, there are compatibility relations between different types of abatement options. Furthermore, abatement options can have various requirements and may have conflicting (environmental) effects. This section marks the end of the needs analysis part and the following part describes the design of the selection tool.

II

Design of the selection tool

4. Exploration of approaches and concept definition

The previous two chapters described the needed capabilities of the selection tool. The selection tool must have the ability to select abatement options that are feasible and must be evaluated on their environmental and economic performance. This chapter describes the found selection approaches used in literature to acquire the knowledge required to determine the type of selection approach that can be used in the selection tool. Section 4.1 provides the results of the literature review and ends with a synthesis of the studied selection approaches. Thereafter in Section 4.2, the building blocks of the proposed selection tool are conceptually described and visualised in an architecture of the tool. The conclusion is given in Section 4.3.

4.1. Exploration of selection approaches for abatement options

The review starts with defining the research area. A general classification is then given of the type of available decision-making techniques to obtain theoretical insights. Next, the state of the art of techniques is given and other relevant studies are also briefly described. This review is summarised in a concise set of aspects and possible approaches that are relevant for the proposed selection tool.

4.1.1. Type of research area and requirements of selection approach

The research area consists of selection approaches used in the maritime industry to assist decision makers. They usually have to deal with multiple alternatives and several decision (environmental and economic) criteria. The proposed selection tool will be developed for new build vessels, so the selection approaches may need to deal with miscellaneous type of alternative technologies and fuels. In the early stage of the ship design process, the fidelity of the results is not yet critical. Selection approaches will be studied with a high level of abstraction.

The design space of possible combinations can be significant, because the available abatement options (i) from a long list can be combined in many ways. The number of unique combinations can be deduced from Equation 4.1 [96]. The formula is suitable to find the number of combinations, if the order of different outcomes does not matter and if the total combinations contain an empty outcome. As an example; eight unique (including no outcome $\{\}$) combinations can be formed with three abatement options (i). The number of combinations increases rapidly as the initial list of technologies becomes larger. This large design space can be reduced by imposing the various criteria. However, the problem size is still significant and therefore an appropriate selection approach must be chosen.

$$\sum_{i=0}^{I} \binom{i}{I} = 2^{i} \qquad 4.1$$

4.1.2. Classification of decision-making techniques

The type of decision-making techniques used in literature for evaluating and selecting technologies can generally be classified as Operational Research (OR) techniques or as other financial/environmental assessment techniques. This literature study is more focused on OR techniques, because a type of OR technique is needed that can handle many alternatives and multiple criteria. Approaches for such decision-problems with often conflicting criteria can be classified as Multi-Criteria Decision-Making (MCDM) approaches or Operation Research techniques. In this thesis OR techniques are classified as follows: optimisation algorithms (classic and metaheuristic) and Multi Attribute Decision Making (MADM) methods.

A classification of the various decision-making techniques is shown in Figure 4.1. It also shows some specific techniques that are used in the consulted literature.

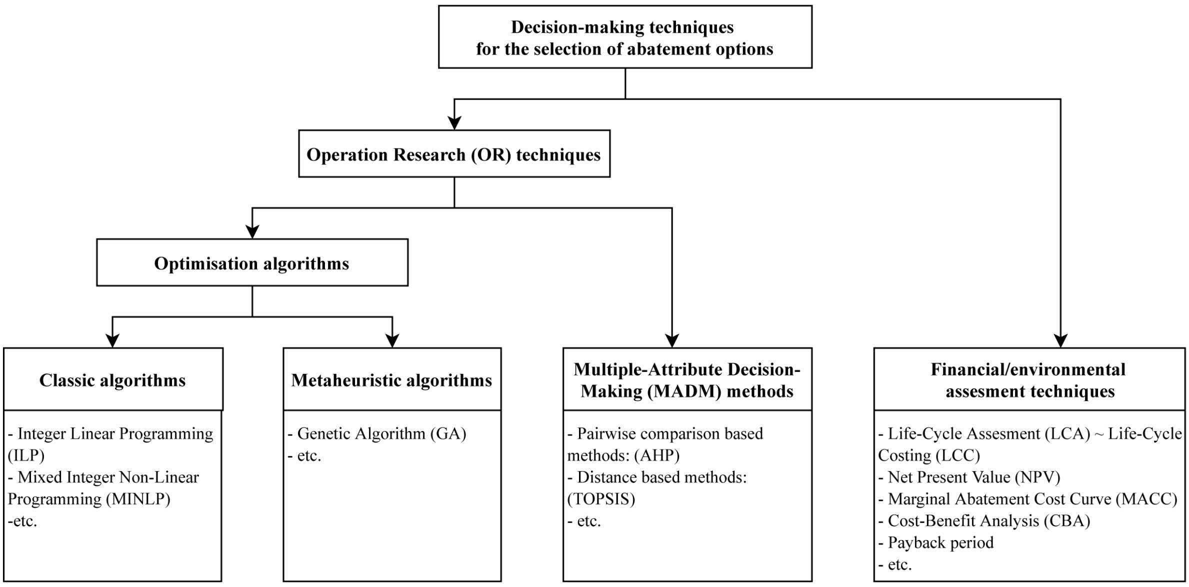


Figure 4.1: Taxonomy of decision-making techniques used in the consulted literature.

MADM methods

Multiple Attribute Decision Making (MADM) methods are suitable for decision problems where a limited number of predetermined alternatives are defined [78]. MADM methods are often used to find a ranking of alternatives or can be used to obtain the weight of the decision criteria. A popular MADM approach is AHP where alternatives are pairwise compared to obtain weights for the criteria ([78]). There are few studies in MADM literature that address approaches to find the best combination of available technologies instead of a finding a ranking of technologies.

Optimisation algorithms

The classification of optimisation algorithms is given in Figure 4.1; it is branched into 'Classic algorithms' and 'Metaheuristic algorithms'. The difference between these algorithms is based on the used search method. Metaheuristic algorithms cannot give the guaranty to find the exact solution, because metaheuristics often implement some randomness in the search method. However, they can be used to solve complex problems faster when near-optimal solutions are satisfactory [37]. The determination of an optimisation algorithm can be based on the aspects of an optimisation problem (as shown in Figure 4.2), in which the search method depends on the type of optimisation algorithm [37]. The domain of selection problem identified in this thesis is a discrete set of abatement alternatives subject to constraints. It can therefore be classified as a constrained discrete optimisation problem.

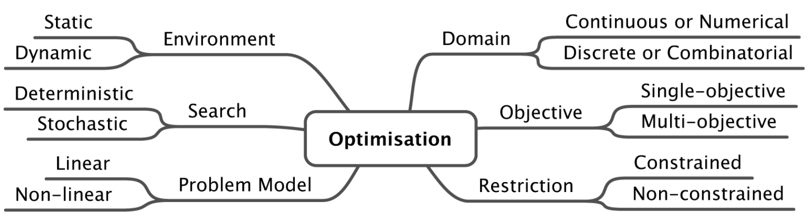


Figure 4.2: Aspects of an optimisation problem. Source: figure obtained from [37]

4.1.3. State-of-the-art studies that use OR techniques

The studies using OR techniques for the selection of abatement options can be classified on the basis of the type of OR techniques and the type of aspects of the defined decision problem.

Type of OR techniques

For the past decade, the use of OR techniques for the selection of abatement options has been increased. The reviewed studies are presented chronologically in Table 4.1, it shows that various OR techniques have been used. The table shows that studies that search for a combination of technologies use an optimisation algorithm and the studies that search for a ranking of technologies use a MADM method. The purpose of the proposed selection tool is to find a combination of technologies, therefore more attention is paid to optimisation algorithms. However, the relevant MADM approaches provide some insight into the type of decision factors.

In maritime industry, the use of an optimisation algorithm for the selection of abatement options can be traced back to the research done in 2005 by Winebrake et al [101]. This study uses a nonlinear optimisation algorithm to find a cost-effective combination of technologies for ferries. Balland et al. also paid of a lot attention to this optimisation problem ([5],[7],[8]). These authors use an integer linear optimisation algorithm for the selection of abatement options. They also addressed in different papers several decision factors, such as changing regulations over time, uncertainty in emission reductions and the simultaneous selection of the machinery systems and other aspects. The simultaneous selection of abatement options and machinery systems has also been addressed by Trivyza et al. [86]. In their study, they use a genetic algorithm to find the most cost-effective combinations of energy systems over the ship's life cycle. This indicates that a variety of algorithms have already been applied for this type of optimisation problem. However, many variations are possible with regard to the approach and decision factors (for example upstream emissions or external costs). Moreover, there is still a potential to apply such tools on different ships with different operational profiles.

Table 4.1: The list of reviewed studies that relate to the selection of abatement options and that use Operation Research (OR) techniques. (R.:ranking, C.:combination, nb:newbuild, rf:retrofit, o:operational, sel.: selection, env.:environmental assessment, ec.a.:economical assessment, ES: Energy System, f.p.:fuel penalty ind.:industrial)

		Output		**Alternatives**			**Assessment**							
Study & year	Type of OR technique	R.	C.	nb	rf	o	Sel. ES	Env. ES	NO_x	SO_x	PM	CO_2 f.p.	Ec.a. type	Notes/ criteria
[98], 2005	Metaheuristic (GA)		1	1			1	1				1	LCC	Building
[101], 2005	Optimisation (MINLP)		1		1	1			1		1	1	Basic	
[17], 2006	MCDM framework		1		1	1			1		1	1	NPV	Uncertainty
[9], 2012	Optimisation (MOO)		1	1	1			1	1			1	Basic	Ind. (~CTS)
[102], 2012	MADM (AHP)	1			1	1			1	1			Basic	Volume
[8], 2014	Optimisation (ILP)		1	1	1	1	1	1	1	1		1	NPV	~CTS, EEDI
[78], 2014	MADM (AHP+ANP)	1			1	1			1	1		1	NPV	Reliability
[7], 2014	Optimisation (ILP)		1	1	1	1						1	Basic	~TRL
[3], 2015	MADM (FMDAM)	1			1	1			1	1	1	1	NPV	~CTS
[76], 2017	MADM (Fuzzy AHP)	1				1			1	1	1	1	Basic	Volume
[86], 2018	Metaheuristic (GA)		1	1	1	1	1	1	1	1		1	LCC	
[90], 2018	MADM (TOPSIS)	1				1	1					1	Basic	~URN
[39], 2019	MADM (AHP)	1				1			1	1	1	1	Basic	

Type of aspects

The type of aspects used in studies carried out in maritime industry are analysed in more detail. These studies can be characterised by the application level (fleet-basis or vessel-basis) and the specific type of vessels. Most studies have focused on retrofit technologies and operational measures, as adjustments to current ships have been required in recent years due to stricter limits. The reviewed studies are characterised by the type of abatement options (alternatives) analysed: technical measures (new-build or retrofit), operational measures or a combination of the foregoing. The simultaneous assessment of abatement technologies and machinery/energy systems has been addressed by several authors ([8], [86]). Most of the studies focus on the major emissions to be controlled (NO_x, SO_x, CO_2) and other emissions such as PM. The energy consumption effect of abatement options and the implementation of energy efficient options have been tackled in different ways. For example, the energy efficient effects have been taken into account through a change of CO_2 emissions [5]. Each study evaluates both investment costs and operational costs, but different types of economical assessment methods are used to assess cost effectiveness. Most MADM approaches have also investigated various other criteria, such as volume or operational aspects. Some studies ([9], [3]) implemented external costs in their decision-making techniques. One MADM study [90] was found that included Underwater Radiated Noise (URN) in the trade-off analysis.

4.1.4. Other relevant tools

In addition to the OR-related methods, relevant decision support tools or calculation tools have been analysed that help the decision-makers in complex selection problems. A decision support tool (system) often includes coupled functional subsystems and consists of a dataset or database and is provided with an interface for easy access. Mansouri et al. [60] investigated decision support tools in the maritime industry and they expect that the next generation of decision support tools will utilise the field of (multi-objective) algorithms. The relevant tools viewed are the following. Calleya [15] has created a model for calculating the impact of combinations of technical and operational energy efficient technologies on the ship design. The Appraisal tool developed by DNV GL [25] is based on cost abatement curves, the tool calculates the effects of technical and operational measures on the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Indicator (EEOI). A concept exploration tool has been developed by Schot [79]; this tool includes the ship design and proposes various zero-emission energy systems for double-ended ferries. Danish Shipping [22] has developed a tool that can calculate the energy consumption and a range of exhaust emissions based on ship characteristics and the application of abatement options.

4.1.5. Synthesis

By synthesising the various studies on selection approaches for abatement options, relevant similarities and differences between the studies can be observed. Different types of Operation Research (OR) techniques are used in literature for the selection of abatement options. An important difference can be observed between studies that search for a combination of technologies and studies that search for a ranking of technologies. Studies that look for a combination of technologies use an optimisation algorithm and studies that search for a ranking use MADM approaches. The similarities between the studies are that they all address (investment and operational) costs and emissions. Most of them concern the most important emissions and address the additional fuel consumption of some abatement options. The studies that use MADM approaches also evaluate other type of criteria such as dimensional criteria, but they often evaluate a smaller set of alternatives. Some studies address the importance of simultaneously assessing energy systems and emissions abatement options. The studied type of selection approaches can lead to a lower fidelity of the results, because the systems are not yet fully integrated. But later on, the ship designer use simulation- based approaches to evaluate the integrated systems in more detail, for example in terms of fuel consumption and emissions.

4.2. Concept of the selection tool

This section describes the development from a collection of ideas towards a conceptual model of the selection tool. It also explains which modelling choices and assumptions are made. This section ends with the selection procedure and a presentation of the architecture of the selection tool.

4.2.1. Performance requirements of the selection tool

The selection tool will primarily support the decision-maker in finding the optimised combination of cost-effective and compatible abatement options to meet emission requirement. As the needs analysis in Chapter 3 has shown, there are different types of technologies and fuels. These types of alternatives will be analysed in different ways in the selection tool. The combinations of abatement options must be optimised by the selection tool. Changing the fuel concept also forms an abatement option and will therefore also be taken into account in the optimisation. The energy systems play a crucial role in the design of low-impact vessels and must be assessed for their environmental performance. They must also be known for the correct implementation of compatible abatement options. The selection of energy systems will not be optimised. It can be acknowledged that simultaneous/concurrently optimisation of both the energy systems and abatement options will result in better overall ship designs. However, the wide variety of energy systems and many performance criteria make this optimum design a complex decision problem and requires another approach. Although the tool can help the ship designer to explore different energy systems and find compatible abatement options.

4.2.2. Functional formulation of the selection tool

The emissions regulations and limits depend on the vessel characteristics, operational profile and the energy systems. Therefore, an energy system and reference fuel will be assessed on environmental performance to check compliance with regulations and to serve as a reference level. The emissions also need to be quantified to calculate the external costs of the benchmark vessel. So the functional requirements for the selection tool with regard to the studied alternatives are specified below.

- Energy system & reference fuel: emission and cost-benchmark must be evaluated.
- Abatement options & fuels: combinations must be optimised.

For the emission and cost-benchmark, the total fuel consumption is taken into account, including the fuel consumption for propulsion and fuel consumption for auxiliary loads. The auxiliary load can be considerable, for example during manoeuvring or during lifting. Multiple energy systems can be selected, but they must be equal sized and of the same system type. The main systems often contribute to the majority of the energy consumption. Moreover, it would result in a lot of extra information in the datasets and similar extra functions that need to be evaluated for other capacities. Furthermore, the proposed selection tool in this thesis is a static approach, making it less suitable to evaluate hybrid configurations (e.g. engine(s) combined with batteries). Therefore, hybrid configurations cannot be chosen as a benchmark. The emission assessment differs considerably and time-domain approaches such as Simulink are more suitable for this.

The abatement options are evaluated on costs and their effects [%] on emissions and fuel consumption. It is assumed that the ships operate in the same operational area (same ECA) over the whole operational profile, therefore fuel switches during the operational profile are not considered. The performance (reduction effect) of some abatement options depends on the engine load or the temperature of the exhaust gasses, for example in the case of a SCR. This part-load performance is not considered in the selection tool, because this data is not widely available for all the different abatement options. The reduction effects are therefore considered to be constant over the load range. Furthermore, uncertainty of reduction effects is not considered in the selection tool.

4.2.3. Selection procedure and architecture of the selection tool

Before using the proposed selection tool, the ship designer must have determined the demanded power and the energy demand for the operational profile of the vessel. It is also assumed that the designer has defined the first sets of energy system configurations that meet technical, functional and practical criteria. Thereafter, this selection tool (including an optimisation algorithm) can be used. To define the optimisation problem, the broader decision-making process is first defined in more detail. The identified steps of this selection procedure are given below.

1. Provision of input (vessel type, required TRL, operational area) and check of applicability in datasets;
2. Selection of benchmark systems and provision of system operational characteristics;
3. Calculation of emission and cost performance of energy systems and fuels;
4. Optimised selection of abatement options (problem formulated in Chapter 6).
5. Evaluation of the output.

The proposed selection tool (as schematised in Figure 4.3) will include a dataset, a user interface (for the benchmark selection) and an optimisation algorithm. The software chosen for storing the datasets and locating the user-interface of the selection tool is Excel. The most important Excel sheet for the user is the user-interface in which most of the steps (1,2,3 and 5) can be done. The obtained decision parameters and calculated benchmark values in Excel are processed into the optimisation model (step 4). After the optimisation, the output can be evaluated (step 5) by the decision-maker.

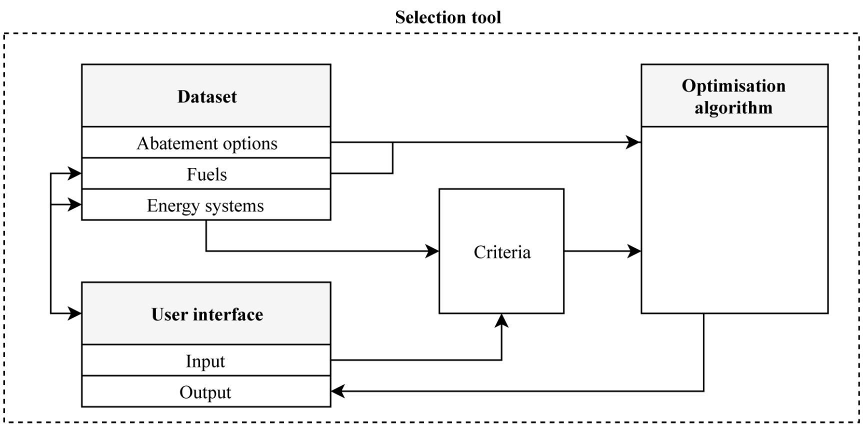


Figure 4.3: High-level scheme of the proposed selection tool

4.3. Conclusion

In this chapter, different types of selection approaches were explored that are intended to find the most satisfactory abatement options. This provided insights into important decision aspects, such as the types of environmental and economical assessment approaches. The aim of this thesis is to find a combination of abatement options from a long list of abatement options. Therefore, an optimisation algorithm will be used and integrated in the selection tool. In addition, modelling choices and assumptions are made and set out in a proposed system. The selection tool consists of two main selection parts. The benchmark energy system can be selected by the decision-maker and the optimisation algorithm can be used to find the optimal combination of abatement options. The developed architecture of the selection tool including the building blocks will form the basis for further development as described in the following chapters.

5. Assessment approaches

This chapter describes the advancement of a concept of the selection tool to a full coupled selection tool. First the input and the benchmark selection are described in Section 5.1. Furthermore, the requirements of the selection tool are converted into a description of how the energy systems and abatement options are evaluated in the selection tool. The economical assessment is described in Section 5.2 and the environmental assessment is explained in Section 5.3. Section 5.4 summarises this chapter and serves as a preparation for defining the optimisation problem in the next chapter.

5.1. Input and benchmark energy system

This section describes the first two selection steps of the selection procedure (as derived in subsection 4.2.3). They concern the provision of input and the selection of the benchmark energy system.

5.1.1. Provision of input and check of datasets

In the user-interface, the decision-maker can select the vessel type and the required TRL level. These choices will reduce the initial long list of abatement options. The operational area must be selected because the regulations depend on the operational area. Furthermore, it can be useful to check the various compatibility relations in the datasets. The compatibility relations between different abatement options can be defined in the optimisation problem (as explained in Section 6.2).

5.1.2. Selection of the benchmark energy system

The energy systems can be selected in the user-interface, they mainly serve as the benchmark. In addition, incompatible abatement options can be automatically removed from further analysis. The user can define the number of energy systems and the capacity of the system, e.g. rated power in case of a diesel engine. Furthermore, only multiple equal sized energy systems of the same type can be selected (as discussed in subsection 4.2.2). There is a difference in approach for the energy systems with or without operational emissions. However, for both energy systems the upstream emissions (as explained in subsection 2.5.3) for producing the fuels are considered. The operational emission performance of an energy system (e.g. diesel engine) depends on various factors such as the engine type, the fuel type and the load point.

The emission factors are predefined for six relevant engine-reference fuel combinations which can be selected as a benchmark energy system. The reduction potential of fuels as abatement options is expressed in relation to the reference fuel of the compatible energy system. If the decision-maker wants to pre-select another fuel, it can enforce this selection by adding a constraint in the optimisation problem (as explained in Section 6.2). The six specific engine-fuel combinations are predefined in the dataset with performance parameters for four load points each. The predefined engine-fuel combinations are specified below. The decision-maker can select a medium-speed or high-speed variant of each combination, which results in a total of six combinations.

- Diesel Compression Ignition (CI) engine with MDO
- Gas (Spark Ignition (SI)) engine with LNG
- Dual fuel (DF) engine with LNG + pilot fuel MDO

After selecting an energy system, the decision-maker can provide the operational characteristics of the engine such as the relative operational time of the machinery and the relative load of the engine. These operational characteristics are used for evaluating the environmental performance and they are further discussed in Section 5.3.

5.2. Economic assessment

This section first describes the exploration of economic assessment methods and approaches to evaluate costs effectiveness. Thereafter, it is described how a suitable economic assessment for the selection tool is determined.

5.2.1. Exploration of economic assessment approaches

The defined decision-problem only includes costs and no monetary benefits (profits). The costs can be evaluated with various cost evaluation methods. For example, Net Present Value (NPV), where the present worth is calculated by using a discount rate that takes the time value of money into account. Life cycle approaches such as Life Cycle Costing (LCC) often use a NPV-based valuation approach and calculate the monetary costs over the ship's lifetime [86]. Equivalent Annual Cost (EAC) approaches are used to make investment decision for systems with unequal lifetime. The disadvantage of using 'time value of money' based approaches is that the defined discount rate can have a significant effect on the outcome [33]. A higher discount rate can lead to the selection of technologies with a lower investment costs, which can be more attractive due to the lower weight for operational costs [33]. In LCC the analysis period can also influence the decisions made, because the length of the analysis period influences the assessment weight of operating costs. Cost effectiveness can be expressed as something with good value, with the benefits (emission reduction) worth paying (e.g. investment and operational costs) for. The cost-effectiveness of abatement options can be based on the marginal costs, which can be derived by dividing the internal costs over the reduced amount (ton) of emissions [101]. Some approaches use Marginal Abatement Cost Curves (MACCs), in which the marginal abatement costs are plotted against the emission reduction potential [97]. It assumes that the most cost-effective abatement options are first installed and that the other abatement options are less cost-effective [97]. A disadvantage of this method is that measures are assessed independently to obtain the MACC [15].

5.2.2. Determination of economic assessment in selection tool

The considered costs are investment and operational costs. The defined investment costs include the costs related to the investment in purchasing the equipment and the installation of these technologies on board of the vessel. The operational costs are defined as the costs of all consumables and maintenance costs within the assumed operational profile at fixed costs for consumables. Other operational costs such as labour costs and overhead costs are therefore not included. The alternatives are evaluated with a basic cost valuation approach for one operational year. This eliminates the need to consider influential parameters such as a discount factor. Moreover, the length of the analysis period is fixed, so that it is no longer a parameter that can influence the decisions. Moreover, cost-effectiveness can be achieved by considering the internal (investment+ operational) costs and the emission reductions.

The decision problem is characterised by a vessel with a certain lifetime (20-25 years) and energy systems and abatement options with an unequal lifetime (ranging from 1-25 years). These technologies may need to be replaced during the economic lifetime of the vessel. The respective investment costs are calculated up to the same annual period. The annual investment costs are calculated by dividing the investment costs of the technology by its useful lifetime (according to Equation 5.1). The financial aspect is not included in this thesis, the financing of the investment costs and associated interest costs of the loan are not considered. However, this can be implemented in the objective functions or it can also be evaluated in the post-selection. If the selection tool contains more accurate cost data and (different sized) technologies from different manufacturers with different costs, it would be interesting to analyse this.

$$\text{Annual investment cost} = \frac{\text{Investment (purchase+installation) costs} - \text{residual value}}{\text{Estimated economic life}} \tag{5.1}$$

5.3. Environmental assessment

This section first describes the type of emission factors and how they are obtained and defined in the selection tool. It is then explained how the benchmark system is evaluated with regard to emission regulations. Thereafter, it is explained how the total fuel consumption and exhaust emissions are quantified and how the reduction effects of the abatement options are defined. This section ends with describing how Underwater Radiated Noise is considered in the optimisation problem.

5.3.1. Emission factors and specific fuel consumption

The emissions can be quantified on the basis of Emission Factors (EFs), which can be expressed by the pollutant emission ratio (per) or by the specific pollutant emission (spe) [85]. The factor per is defined as the emission of pollutants per kilogram of fuel burned and spe is defined as the pollution per generated power [kWh]. The emission factor spe can be calculated by Equation 5.2, in which the specific fuel consumption (sfc) varies for different engine loads and fuel types. The per of SO_x and CO_2 are fuel related. The per for SO_x is based on 20 SO_x gram per kilogram fuel for each percentage sulphur (S) in the fuel [85]. The CO_2 emission factor (per), also known as the carbon conversion factor, is based on the fuel type and the carbon content of the fuel.

$$spe = per \cdot sfc \tag{5.2}$$

where:

spe	Specific Pollutant Emission	[g/kWh]
per	Pollutant Emission Ratio	[g/kg]
sfc	Specific Fuel Consumption	[g/kWh]

The emission factors can be obtained from different sources. For example from emission tests, which are necessary to obtain an Engine International Air Pollution Prevention (EIAPP) certificate. In this emission test the engine is tested on three to four loading points (e.g. 25% MCR, 50% MCR, 75% MCR, 100% MCR). The emissions such as NO_x, SO_2 and CO_2 are measured and reported. In the selection tool, the benchmark emission factors are predefined for six specific engine-fuel combinations with four load points each. The emission factors are also obtained from literature (e.g.,[87] [83]). These obtained parameters can therefore underestimate or overestimate the actual emission levels of the energy system. The performance parameters for load points in between can, for example, be estimated by regression analysis or other interpolation methods. In the selection tool, these parameters are searched with the help of a Forecast function in Excel. This Forecast function uses a linear equation and uses all the available data points and estimates a value based on this data.

5.3.2. Compliance emission regulations and benchmark

The selected benchmark system must be evaluated for its environmental performance with regard to the applicable regulatory limits for (e.g., NO_x, SO_x) emissions. The emission factor (EF) limit for NO_x is expressed as a weighted cycle spe [g/kWh] limit. For SO_x and PM emissions, the limit is related to the fuel type and is expressed as maximum allowable mass content [% m/m]. In the selection tool, the weighted cycle value for NO_x emissions is evaluated for the selected benchmark system. The emission benchmark can also be lower than the emission limit. This means that no abatement option needs to be installed, but if no emission constraints are implemented there is a chance that the emissions regulations can be violated. Only allowing abatement options with better performance than the benchmark is not entirely correct, because the emissions may be higher than the benchmark, unless they remain below the limit. Therefore, the NO_x emission benchmark is included in the emission constraints (as discussed in subsection 6.2.3).

The annual fuel consumption is calculated to evaluate the exhaust emissions and external costs. The upstream emissions are evaluated for each energy system. For the engines, the daily operational emissions (E_p) are evaluated over the operational profile and they are based on the predefined pollutant emission ratio (per) factors according to Equation 5.3. Where p represents the type of pollutant emissions. The emissions are calculated by the multiplication of per with the specific fuel consumption (sfc), the power and the running hours. The power and the sfc are depending on the engine load in each operational phase (t). The emission factor expressed as spe can also be used in this equation, according to Equation 5.2.

$$E_p = n_e \cdot \sum_{t=1}^{T} per_{p,t} \cdot sfc_t \cdot P_t \cdot h_t \qquad 5.3$$

where:

E_p	Daily emitted emissions of emission type p	[ton/day]
n_e	Number of engines	[%]
$per_{p,t}$	Pollutant emission ratio for emission type p at engine load in phase t	[g/kg]
sfc_t	Specific fuel consumption at engine load in phase t	[g/kWh]
P_t	Power at engine load in phase t	[kW]
h_t	Running hours	[h]

5.3.3. Approach to URN emissions

The Underwater Radiated Noise (URN) can be considered relevant to be taken into account in the optimisation problem, because there exists a trade-off in propeller design between the open water efficiency of a propeller and URN [47]. The tightened energy-efficiency requirements can lead to ships that are noisier than the predecessors as pointed out by Jalkanen et al. [47]. Airborne noise levels (dB) of machinery system are published, but quantifying URN is more difficult, because URN depends on a lot of other factors such as ship design, speed and cavitation [47]. The benchmark URN level is therefore difficult to predict, and the quantitative reduction potential of abatement options is not widely available [41]. Therefore, a constraint can be added in which one option from a certain category of applicable abatement options must be installed that can reduce a specific URN effect. For example, if it is indicated that the URN caused by a propeller must be reduced. The optimisation algorithm must choose one abatement option from the relevant category of abatement options.

5.4. Conclusion

This chapter described the benchmark selection and the type of environmental and economical assessments used. For each benchmark energy system, fuel consumption and corresponding upstream emissions are quantified based on predefined emission factors. In the economic assessment, the energy systems and abatement options are evaluated for operational and investment costs. The costs are analysed on annual basis in order to reduce uncertain and influential parameters. For engines (with operational emissions) the environmental assessment is based on predefined emission factors for six relevant engine-fuel combinations with four load points each. The quantified emissions are converted to external costs by using external cost factors. If emission performance parameters are available (e.g. from emission tests), these can easily be entered into the dataset. In conclusion, this chapter and the previous chapter have set out the coupled system of the selection tool in order to define the optimisation problem. The optimisation problem is described in the following chapter.

6. Optimisation problem

This chapter describes how the identified optimisation aspects can be integrated into a whole. The possible formulation approaches to define the optimisation objectives are first explored and the chosen formulation type is verbally formulated in Section 6.1. Thereafter, the optimisation problem is mathematically formulated in Section 6.2. The defined optimisation problem is characterised in Section 6.3 to find a suitable optimisation algorithm in the next chapter. This chapter is concluded in Section 6.4.

6.1. Defining the optimisation problem

This section describes how the identified optimisation problem can be formulated. The decision factors are first briefly described. Then different type of possible objectives of the stakeholders are explored to determine a suitable objective formulation. This section ends with describing the defined problem formulation and how the identified decision factors are considered.

6.1.1. Problem scope and decision criteria

The core optimisation problem is the selection of optimal combinations of feasible abatement options at minimum costs that at least meet the emission requirements. Certain assumptions have been made in Section 4.2 for defining the optimisation problem. The abatement options will be optimised over one type of energy system. Furthermore, it is assumed that the reduction effect of an abatement option is constant over different engine loads. A basic cost valuation is used, and the emissions and costs are analysed over one year. The combination of abatement options must be technically feasible, therefore compatibility relationships between different abatement options must be considered.

6.1.2. Exploration of objective formulations

This subsection describes different types of objective formulations and gives the benefits or disadvantages. In this thesis, a trade-off has been identified between two types of preferences. The desire of the decision-maker can be expressed in two preferences: one preference is low internal costs and the other preference is compliance with emission regulations. Depending on the decision-maker, the second preference can be defined more strictly: compliance with emission regulations and further reduction of external costs. These preferences are specified below.

- Preference (Obj) 1 : Low internal (investment + operational) costs
- Preference (Obj) 2 : Compliance with emission regulations and depending on the decision maker: low external costs (related to exhaust emissions)

These preferences do not necessarily have to be formulated as objectives in the optimisation problem. These goals can also be achieved indirectly through the implementation of cost- or emission constraints, as discussed in the different types of explored formulations below. These formulations are based on the explored studies presented in subsection 4.1.3.

Single objective: internal cost minimisation (Obj 1)

This objective formulation with cost minimisation is based on Winebrake et al. [101] and Balland et al. [7]. Usually, the decision-maker has no specific interest in reducing the external costs of emissions, because the external/societal costs are not borne by the shipping company. In this situation, the optimisation problem can be defined as a single-objective (cost minimisation) problem, which is subject to regulatory emission constraints.

Single objective: external cost minimisation (Obj 2)
This objective formulation is based on Winebrake et al. [101]. Another situation can arise when there is a maximum budget and the user wants to minimise the emissions as much as possible. Then the internal costs are not minimised and only the emissions (or individual emissions) can be minimised in the objective function. The internal costs can then be defined as a monetary budget constraint of the optimisation problem.

Single scalarized objective: e.g. weighted sum (w1*Obj1+w2*Obj2)
This objective formulation is based on Bari et al. [9]. There are various methods to scalarize multiple objective functions into a single objective function, e.g. by using a weighted sum method. In the weighted sum method, it is required to prioritise, scale or weight the objectives based on the relative importance of the objective [74]. If the weighted sum method is used, a unique solution can be found in one optimisation run, which can be an optimal solution. However, the use of weighted sum methods can lead to leaving regions of solutions undiscovered [86], as it may be difficult to set the weights to find solutions in a specific region of the objective space.

Multi-objective (Obj 1 and Obj 2)
This objective formulation is based on Wang et al. [98] and Trivyza et al. [86]. The decision problem can be defined as a multi-objective optimisation problem, where the conflicting preferences can be defined as two separate objective functions. These two objective functions can be optimised at the same time. Such a multi-objective approach can find a diverse set of solutions in the objective space.

6.1.3. Defined objective formulation

The defined objective formulation is a multi-objective formulation with two separate objective functions, because for the identified optimisation problem, both objective functions must be evaluated. If there are no operational emissions and respective emission regulations, e.g. in the case of a battery-electric vessel, the reduction of the energy consumption (and potential upstream emissions) can be stimulated by the external cost function. Moreover, such a multi-objective approach can find a wide range of solutions. By using a multi-objective approach, the trade-off between internal costs and external costs can be clearly demonstrated. The proposed method type can be called a posteriori method, because the decision-maker can evaluate the generated Pareto optimal solutions by using criteria weights to find the most satisfactory solutions. In addition, costs budgets can be used in the post-selection to find solutions within the decision-maker's budget.

Pareto front
In a multi-objective optimisation problem, there are usually two opposing criteria. A set of optimal solutions in a multi-objective optimisation problem is known as a set of Pareto-optimal solutions [74]. The set of Pareto-optimal solutions on a Pareto front are non-dominated solutions [74]. This means that they are non-dominated with respect to each other, they can not be improved on objective 1 without having an adverse effect on objective 2. The most satisfactory combination of abatement options can then be found by attaching criteria weights to the objective functions, which must be determined by the decision-maker.

6.2. Mathematical formulation of optimisation problem

In this section the optimisation problem is formulated mathematically. A short overview of the mathematical formulation is given in the first subsection.

6.2.1. Overview of optimisation problem

The indices and sets used throughout the optimisation problem are defined below. The set (I) of applicable options (compatible with the vessel type and selected energy system) is evaluated in the optimisation problem. The selection evaluates various type of exhaust emissions, represented by set P that includes the NO_x, SO_x, PM, VOC and CO_2 emissions.

i	Abatement option i from a set of I abatement options
p	Emission type p from a set of P emission types

The decision variable of the optimisation problem is constrained to be a binary decision variable as shown in Equation 6.1. In the mathematical formulation as described in this section, auxiliary variables are used (e.g. in the objective functions), which depend on the decision variable (x_i). This is also clarified in the local description of variables.

$$x_i \in [0, 1] \qquad i \in I \tag{6.1}$$

where:

x_i Binary variable = 1 if abatement option i has to be installed, and 0 otherwise

Overview of constraints

The optimisation problem is further subjected to the following constraints:

- Emission constraints (as explained in subsection 6.2.3)
- Compatibility constraints (as explained in subsection 6.2.4)
- Additional constraints (as explained in subsection 6.2.5)
- EEDI constraint (as explained in subsection 6.2.6)

6.2.2. Objective functions

The optimisation problem is formulated as a multi-objective optimisation problem and is defined by two separate objectives (F_1 and F_2).

First objective: investment and operational costs

The first objective, given in Equation 6.2, is to minimise the annual internal costs, including annual investment costs and operational costs. The operational costs include fuel costs and maintenance costs. These operational costs may change as a result of the implementation of abatement options that have an effect (R_{tot}^{FC}) on the fuel consumption.

$$min\ F_1 = \overbrace{\sum_{i}^{I}\left(x_i \cdot C_i^{Inv.}\right)}^{\text{Investment costs}} + \overbrace{\sum_{i}^{I}\left(x_i \cdot C_i^{Fuel} + x_i \cdot C_i^{Maint.}\right) \cdot \left(1 - R_{tot}^{FC}\right)}^{\text{Operational costs}} \tag{6.2}$$

where:

C_i^{Fuel}	Fuel costs of abatement option i	[€]
$C_i^{Inv.}$	Investment costs of abatement option i	[€]
$C_i^{Maint.}$	Maintenance costs of abatement option i	[€]
R_{tot}^{FC}	Total effect on Fuel Consumption (FC); $f(x_i)$ see Equation 6.7	[%]

Second objective: external costs

The second objective, given in Equation 6.3, is to minimise the total emissions expressed by the annual external costs [€]. It includes the external costs [€] that are caused by the upstream (WTT) emissions and that are caused by the operational (TTP) exhaust emissions. The upstream emissions can be changed by due to the effect (R_{tot}^{FC}) on the fuel consumption. The operational emissions ($E_p^{TTP,n}$) can be changed due to the effect on fuel consumption and/or the emission factor.

$$min\ F_2 = \overbrace{C_{CO_2-eq}^{WTT} \cdot FC_{tot}^{old} \cdot (1 - R_{tot}^{FC}) \cdot EF_{CO_2-eq}^{WTT}}^{\text{Upstream emissions}} + \overbrace{\sum_{p}^{P} \left(C_p^{TTP} \cdot E_p^{TTP,n} \right)}^{\text{Operational emissions}} \quad 6.3$$

where:

$C_{CO_2-eq}^{WTT}$	External costs of upstream (WTT) (CO_2-eq) emissions	[€/ton]
FC_{tot}^{old}	Total fuel consumption (benchmark)	[kWh]
R_{tot}^{FC}	Total effect on Fuel Consumption (FC); $f(x_i)$ see Equation 6.7	[%]
$EF_{CO_2-eq}^{WTT}$	Emission factor CO_2-eq emissions	[g/kWh]
C_p^{TTP}	External costs of TTP emission type p	[€/ton]
$E_p^{TTP,n}$	Total TTP emissions of emission type p; $f(x_i)$, see Equation 6.8	[ton]

6.2.3. Emission calculations and constraints

The optimisation problem is subject to emission constraints, which are explained in this section.

Percentage effect

The performance of abatement options is expressed in percentage effects and can therefore also be used for different capacities of systems. An abatement option can have an effect on the emission factor (EF) or the fuel consumption (FC). This percentage effect can be a reduction effect or an increasing effect. In this thesis this effect is further referred to as a reduction effect (r), with a positive percentage ⟨0;100%] indicating a reducing effect and a negative percentage $\langle \leftarrow, 0 \rangle$ indicating an increasing effect.

Total effect on emission factor

The total effect on the emission factor can be estimated by the recurrence relation as given in Equation 6.4. The total effect ($R_{tot,p}^{EF}$) on the emission factor of emission (p) of multiple implemented abatement options (i) is a product ($\prod$) of the complements of the effects ($r_{i,p}^{EF}$). For example, the combination of two implemented abatement options (i) such as EGR (45% [101]) and SCR (80% [101]) results in a total reduction effect ($R_{tot,p}^{EF}$) of 88 % on the NO_x emission factor.

$$R_{tot,p}^{EF} = 1 - \prod_{i}^{I} \left(1 - x_i \cdot r_{i,p}^{EF} \right) \quad 6.4$$

where:

$R_{tot,p}^{EF}$	Total effect on Emission Factor (EF) of emission p	[%]
$r_{i,p}^{EF}$	Effect on Emission Factor (EF) of emission p by abatement option i	[%]

SO_x emission constraint
The emission constraint for SO_x and PM emissions (as shown in Equation 6.5) is based on the sulphur content (SC) of the fuel [43]. The fuel sulphur content (SC_i) is not allowed to exceed the applicable maximum sulphur content (SC^{req}) unless abatement options are installed. For example, a SO_x scrubber must be installed in combination with high sulphur fuels (e.g. HFO) to meet the emission limits.

$$SC_i \cdot (1 - R^{EF}_{tot,SO_x}) \leq SC^{req} \qquad 6.5$$

where:

SC_i	Sulphur content of fuel i	[%m/m]
SC^{req}	Allowable fuel sulphur content	[%m/m]

NO_x emission constraint
The NO_x emission constraint is related to the emission factor (EF), which is expressed as a weighted cycle [g/kWh] limit. This constraint is given in Equation 6.6. As an illustration, the actual weighted cycle value ($EF^{old}_{NO_x}$) of NO_x can be required to be reduced from 10.5 [g/kWh] to 2 [g/kWh], which requires a total reduction (R^{EF}_{tot,NO_x}) of more than 81 %.

$$EF^{old}_{NO_x} \cdot (1 - R^{EF}_{tot,NO_x}) \leq EF^{req}_{NO_x} \qquad 6.6$$

where:

$EF^{old}_{NO_x}$	Benchmark weighted cycle NO_x value	[g/kWh]
$EF^{req}_{NO_x}$	Applicable weighted cycle NO_x limit	[g/kWh]

Total effect on fuel consumption
The total effect (R^{FC}_{tot}) on the fuel consumption can be calculated by Equation 6.7. The use of some abatement options can lead to an increase of fuel consumption. On the other hand, there are also abatement options that can lead to a reduction of energy consumption such as a hull coating.

$$R^{FC}_{tot} = 1 - \prod_{i}^{I}\left(1 - x_i \cdot r_i^{FC}\right) \qquad 6.7$$

where:

R^{FC}_{tot}	Total reduction effect on Fuel Consumption (FC)	[%]
r_i^{FC}	Effect on Fuel Consumption (FC) by abatement option i	[%]

Quantification of resulting emissions after installation of options
The total resulting operational (TTP) emissions for emission type (p) after the installation of abatement options can be calculated according to Equation 6.8. The old quantified emissions ($E_p^{TTP,o}$) of the benchmark energy system are multiplied by the complement of a product. This product contains the multiplication of the (total) fuel consumption effect and the (total) effect on the emission factor.

$$E_p^{TTP,n} = E_p^{TTP,o}\left(1 - (R^{FC}_{tot} \cdot R^{EF}_{tot,p})\right) \qquad 6.8$$

where:

$E_p^{TTP,o}$	Total (old/benchmark) emissions of emission type p	[ton]
R^{FC}_{tot}	Total effect on Fuel Consumption (FC); $f(x_i)$, see Equation 6.7	[%]
$R^{EF}_{tot,p}$	Total effect on p Emission Factor (EF); $f(x_i)$, see Equation 6.4	[%]

The quantification of the SO_x emissions differs slightly as shown in Equation 6.9. The resulting SO_x emissions are also calculated by including the reducing effect R^{EF}_{tot,SO_x} of SO_x reducing measures such as scrubbers. However, this calculation also includes an additional multiplication of the reduction effect (R^{SC}_{tot,SO_x}) by another fuel that may have another sulphur content (SC) than the benchmark fuel.

$$E^{new}_{SO_x} = E^{old}_{SO_x}\left(1 - (R^{FC}_{tot} \cdot R^{EF}_{tot,SO_x} \cdot R^{SC}_{tot,SO_x})\right) \quad 6.9$$

R^{SC}_{tot,SO_x} Reduction effect, due to other sulphur content of fuel ($f(x_i)$) [%]

6.2.4. Compatibility constraint

The abatement options that are not compatible with the energy systems and vessel have already been removed from the long list of options. There are compatibility constraints between abatement options, these compatibility constraints must be implemented in the optimisation problem and are defined as follows.

Inclusive sets

Some abatement options may be required if a certain abatement option is selected. In case of the installation of a Diesel Particulate Filter (DPF) or a Diesel Oxydation Catalyst (DOC), an inclusive constraint can be set that a low-sulphur fuel must be selected. The optimisation algorithm can only select the DPF if it selects a fuel with a low sulphur content (less than 500 ppm, 0.05%S [77]). This is shown in Equation 6.10. For some abatement options the inclusive relationship can also be the other way around, the relationship must then be rearranged by changing the variables.

$$\sum_{i}^{I_{fuels(low\%S)}} (x_i) - x_{DPF} \geq 0 \quad 6.10$$

Furthermore, other inclusive constraints can be implemented such as the DOC, which is often installed in combination with a DPF. There are also abatement options that are not particularly useful without the implementation of another technology. Therefore, such options might be added as one alternative in the dataset. For example, an Ammonia Slip Catalyst (ASC) may only be useful to implement if the SCR is installed.

Exclusive sets

Some types of abatement technologies are redundant to be installed together, for example a SO_x scrubber and LNG. To ensure that these abatement options are not selected together, the constraint as given in Equation 6.11 can be used. However, such combinations are often not selected, because LNG already reduces the SO_x emissions.

$$x_{LNG} + x_{Scrubber} \leq 1 \quad 6.11$$

Exclusive sets can also be defined for a certain category of abatement options, for example abatement options that introduce water into the combustion engine may be redundant. A constraint as given in Equation 6.12 can be implemented to ensure that only a maximum of one option can be selected from this emission reducing (er) category based on the introduction of water.

$$\sum_{i}^{I_{er-water}} x_i \leq 1 \quad 6.12$$

6.2.5. Additional constraints

The constraint that ensures that abatement options need to be installed if the decision-maker defines that a certain propeller makes too much Underwater Radiated Noise (URN) is given in Equation 6.13. There may be several measures that can reduce this specific URN.

$$\sum_{i}^{I_{URN\ measures}} x_i = 1 \tag{6.13}$$

Fuel constraint

Furthermore, a fuel constraint is used so that only one fuel is selected by the optimisation algorithm. This is ensured by the relation given in Equation 6.14. If the decision-maker prefers one specific fuel (or another abatement options) to include in the final selection (e.g. due to tender specifications), an equal constraint can be added to the optimisation problem.

$$\sum_{i}^{I_{fuels}} x_i = 1 \tag{6.14}$$

6.2.6. EEDI constraint

The reduction of CO_2 emissions is encouraged by the IMO through the EEDI regulation. The applicability of this EEDI requirement depends on the type of ship, system configuration and the operational area. If the selection tool is used for a vessel that must comply with the EEDI regulations, a EEDI constraint could be added to the optimisation problem. The emission constraint (based on Balland et al. [7]) as given in Equation 6.15 can be implemented, in this constraint the attained EEDI should be smaller than the required EEDI. The attained EEDI can be reduced due to the implementation (x_i) of abatement options of a set of energy efficient technologies (I_{ee}).

$$\overbrace{\frac{\sum\left(P_{ME}\cdot C_{f,ME}\cdot sfc_{ME}\right)-\sum_{i}^{I_{ee}}\left(P_{eff,i}\cdot C_{f,ME}\cdot sfc_{ME}\cdot x_i\right)}{DWT\cdot V_{ref}}}^{\text{Attained EEDI}} <= \text{Required EEDI} \tag{6.15}$$

where:

P_{me}	Power main engine at 75 % MCR	[kW]
$C_{f,me}$	Carbon factor of fuel used in main engine	[t CO_2/t]
P_{eff}	Power reduction of the main engine due to energy efficient technology	[kW]
DWT	Deadweight	[DWT]
V_{ref}	Speed at 75% MCR shaft power	[kn]

6.3. Characterisation of optimisation problem

The optimisation problem in this thesis can be considered as a constrained and multi-objective combinatorial optimisation problem. Since the type of optimisation problem influences the choice for the optimisation solver type and algorithm, the optimisation problem is further characterised according to the classification as given in Figure 4.2. The environment can be defined static, because the algorithm does not have to be able to continuously adapt the solution to a dynamic environment [37], for example due to time dependency. The problem model can be defined as non-linear, due to the multiplicative reduction potential of multiple options (as shown in Equation 6.4 and Equation 6.7. In addition, non-linearity is introduced by Equation 6.8 for the total emission output, which is based on the product of the total emission-reduction effect and the total energy-efficiency effect.

The characterisation of the optimisation problem in this thesis is summarised below.

- Domain: discrete (binary) decision variables.
- Objective: multi-objective.
- Restriction: constrained.
- Problem model: non-linear.
- Search: depends on algorithm type.
- Environment: static.

6.4. Conclusion

This chapter defined the optimisation problem, first verbally and thereafter mathematically. In this report, two types of preferences have been identified: reducing the 'internal' costs (including the annual investment costs and operational costs) and reducing the exhaust emission expressed by the external costs. A single objective has been considered, but such an optimisation provides less information about the potential design space. Furthermore, a weighted sum objective is not used, because this can lead to undiscovered solutions. The suitable type of selection approach is a multi-objective type of optimisation problem. A single and exact optimal combination of abatement options may not be important yet at this stage of the ship design process, because the feasible ship design space can still be significant.

The decision variable to install an abatement or not is a binary number. The optimisation problem is subject to emission constraints, compatibility constraints and some additional constraints as summarised on page 39. Issues regarding functional performance are solved by defining suitable objective functions and constraints. The multi-objective optimisation problem defined has also been further characterised. It has been found that the problem model is non-linear as described in Section 6.3. In contrast to other studies, the emission factor effect is multiplied with the fuel consumption effect, which also adds extra non-linearity to the problem. The environment of the optimisation problem is static as no time-aspects are involved. Based on the characterisation of the optimisation problem, the type of optimisation algorithm can be chosen, as discussed in the following chapter.

7. Optimisation algorithm and output

In the previous chapter the optimisation problem was described, in this chapter a suitable optimisation algorithm is determined that can be integrated into the selection tool. The determination of a suitable optimisation algorithm is given in Section 7.1. Section 7.2 describes the background of the optimisation algorithm used. The translation of the optimisation problem into the optimisation solver is briefly discussed in Section 7.3. Section 7.4 explains the output generation and how the optimisation algorithm is integrated in the selection tool. Section 7.5 explains the output evaluation and how this output can be interpreted by the decision-maker. The methodological part of this report ends with the verification as described in Section 7.6. This chapter is summarised in Section 7.7.

7.1. Determination of optimisation solver and algorithm

This section describes the criteria for selecting a suitable optimisation solver. Thereafter, the studied optimisation solvers are discussed. This section ends with describing the reasoning for choosing the used optimisation solver.

7.1.1. Criteria for optimisation solvers and algorithms

Choosing the appropriate optimisation solver and algorithm can be a challenge, because there are numerous approaches to solve an optimisation problem. An optimisation problem can be solved in different optimisation algorithms in different modelling environments that in turn are based on different programming languages. The determination of an appropriate optimisation solver (and algorithm) is based on the criteria defined below.

- Optimisation solver must be interfaced with the Excel dataset
- Optimisation solver is practical to install and to use by the decision maker.
- Optimisation algorithm can solve the defined (non-linear) optimisation problem (as described in Section 6.3).
- Satisfactory result in reasonable computation time.

7.1.2. Explored optimisation solvers and algorithms

Different types of optimisation solvers have been considered during this thesis work. The types of optimisation solvers and assessed types of algorithms are depicted in Table 7.1. There are many other optimisation solvers including algorithms, but many of them are commercial solvers and have a certain threshold number of decision variables that can be defined and tested in the 'test' optimisation solver.

Table 7.1: Considered optimisation models (L=linear, NL=non-linear)

Programming language	Modelling environment	Possible types of problems	Assessed solver	Assessed optimisation algorithm
Python	PULP	L	CPLEX	ILP
Python	Pyomo	L & NL	Bonmin	MINLP
MATLAB	YALMIP	L	CPLEX	ILP
MATLAB	OPTI-Toolbox	L & NL	Bonmin	MINLP
MATLAB	NGPM	L & NL	NGPM	GA (NSGA)

The benefits and issues of the considered optimisation models and algorithms are as follows. As shown in Table 7.1, two modelling environments (PULP and YALMIP) are evaluated that only allow linear problem formulations. This is possible, because the multiplicative reduction effect of multiple abatement options can also be linearized [6]. However, the non-linearity introduced by the multiplication (see Equation 6.8) of the product of the total reduction effects of fuel consumption and emission factor becomes more complex to linearize. The Pyomo environment in combination with the Bonmin solver is not used, because the installation of Bonmin takes a lot of effort. The OPTI toolbox in combination with the Bonmin solver is also not used. Bonmin is a deterministic solver that can in principle find an exact optimal solution, but depending on the type of decision problem this solution can be found globally or locally. A front of solutions in a multi-objective problem is easier to find with a genetic algorithm. The NGPM optimisation solver is an implementation of the NSGA algorithm and can be used to generate satisfactory results in reasonable computation time. A disadvantage of genetic algorithms (including NSGA) is that it can be difficult to fine-tune the optimisation options and to find the optimal results in each optimisation run.

7.1.3. Selected optimisation solver and algorithm

The selected optimisation model that meets the criteria is the NGPM model. It contains a genetic algorithm for solving optimisation problems. This optimisation model NPGM stands for a ”NSGA-II Program in Matlab” and is programmed by Song [58]. This NGPM model is capable of solving various types of optimisation problems in reasonable computation time and gives appropriate results in one computation run. Moreover, the NGPM optimisation solver is suitable, because it supports both real and integer coding for discrete decision variables and gives the opportunity to view the different (intermediate) optimisation results [58]. Furthermore, MATLAB also has some advantages such as the calculation of array structures. An overview of the characterisation of the optimisation solver selected is given in Table 7.2.

Table 7.2: Used optimisation model (L=linear, NL=non linear)

Programming language	Modelling environment	Possible types of problems	Assessed solver	Optimisation algorithm
MATLAB	NGPM	L & NL	NGPM	GA (NSGA)

7.2. Background of the optimisation algorithm

The used optimisation solver NGPM is an implementation of the Non-dominated Sorting Genetic Algorithm II (NSGA-II). First the background of a Genetic Algorithm (GA) is explained. The type of genetic algorithm (NSGA) used is then further explained.

7.2.1. Genetic algorithm

The GA is a subclass of evolutionary algorithms that are population-based metaheuristic optimisation algorithms. The GA is inspired by biological theories, such as mutation, recombination and selection and has similarities with the ’survival of the fittest’ concept in evolution theory [37].

Background of genetic algorithm

The GA starts with the initialisation of a set of individuals, this set is called the population. The population size is the number of individuals. Each individual from the population can be a solution to the optimisation problem and is represented by a string (chromosome) of binaries (genes) [74]. There is a fitness value associated with each individual of a population. The type of the fitness function depends on the specific type of GA. In the selection phase, individuals are evaluated on their fitness value.

The individuals will undergo different variations to generate new solutions, first by crossover and secondly by mutation. Two individuals will undergo crossover, a crossover point is chosen at a random point. Mutation works on one individual and some binaries of a string can be flipped. This variation allows the algorithm to search through the domain of feasible solutions. Converging to a global optimum can be a challenge, therefore the GA parameters for the above operations may need to be fine-tuned to introduce enough variation in the optimisation process [74]. The GA can be defined either as a single-objective GA or as multi-objective GA. The multi-objective GA can simultaneously search different regions of a solution space [74] and can find a set of optimal solutions in one run. GAs also have the goal to maintain a diverse set of optimal solutions and to retain the best individuals [74].

Steps of genetic algorithm
The standard procedure [74] of a GA is given below, in which the steps are executed by the GA until the termination condition is reached.

- Initialisation of random population of individuals.
- Repeat until termination condition is satisfied
  - Selection of parent solutions based on fitness values.
  - Application of genetic operations such as crossover and mutation to generate new offspring.
  - Evaluation of fitness function of each individual of the population.
  - Replacement of least-fit populations with new offspring.
- Print the result if termination condition is satisfied.

The above procedure is also visualised in Figure 7.1, which clearly shows the loop of a GA until the termination condition is reached.

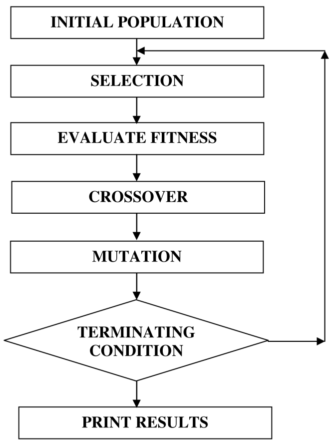


Figure 7.1: Loop of a genetic algorithm
Source: figure obtained from [74]

7.2.2. NSGA-II algorithm

The optimisation solver NGPM used in this thesis is an implementation of the Non-dominated Sorting Genetic Algorithm II (NSGA-II). The NGSA-II is a multi-objective GA developed by Deb [23]. This NSGA-II is the most common evolutionary algorithm used for generating sets of Pareto optimal solutions for optimisation problems [37]. The GA is often used, because this algorithm has proven to be fast, effective and is a robust technique for solving multi-objective optimisation problems [37].

In the selection step of the NSGA-II algorithm, two pairs of individuals are selected, and the most fit pair is selected to produce offspring (new individuals). Binary tournament selection is used for the selection of the parents for reproduction [23]. The fitness value is based on the ranking of the individuals that is determined based on the feasibility of the individual and the Pareto front [23]. This selection also considers how severe the optimisation constraints are violated. After selection, genetic operations are executed on the population. In binary optimisation problems, a part of the binaries is swapped with a part of another individual, this happens with a certain crossover probability. After that the mutation takes place on every decision variable.

Crowding distance metric

The NSGA-II algorithm calculates the crowding distance as shown in Figure 7.2 by a summation of the edge length of the square [23]. The crowding distance metric is a measure of the diversity of the solutions along a non-dominated front. It measures the density of solutions around the considered solution (i) [37]. This crowding distance metric works as truncation operator; individuals with less crowding distance are removed [37].

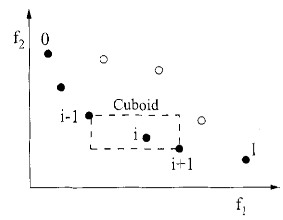


Figure 7.2: Crowding-distance calculation.
Source: figure obtained from [23]

Dominance-sorting

The procedure of the NSGA-II is visualised in Figure 7.3. It shows that the parent population (Pt) and the offspring (new population) (Qt) are merged. The replacement in the NSGA-II algorithm is based on dominance-sorting according to feasibility, constraint violation and the Pareto front [37]. The population is sorted in Pareto fronts (F1, F2, F3), the first level is the best level of the population. The last front is rejected according to the crowding-distance metric. If there are constraints in the optimisation problem, the solutions are evaluated and sorted based on their feasibility.

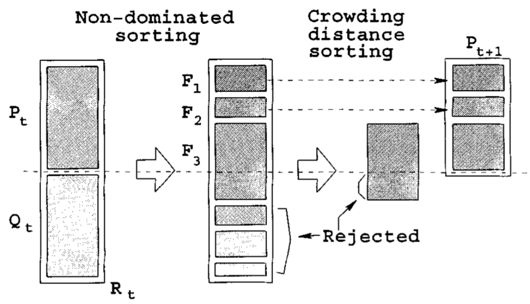


Figure 7.3: NSGA-II procedure
Source: figure obtained from [23]

7.3. Implementation of the problem in the optimisation solver

This section describes how the optimisation problem is implemented in the optimisation (NGPM) solver. First by describing how the decision parameters are processed in MATLAB. Then it is explained how the mathematical optimisation problem is translated into the optimisation solver. Finally, the optimisation options of the algorithm are discussed.

7.3.1. Pre-processing decision parameters

The pre-processing script reads the necessary decision parameters from the user-interface in Excel. This information includes the external costs as provided in Table 2.5. Furthermore, the total fuel consumption [MWh/y] and quantified emissions [ton/y] are read from Excel. In addition, the actual and required NO_x emission factor, the maximum allowable sulphur content and the required EEDI are processed into MATLAB. Furthermore, Underwater Radiated Noise (URN) sources can be specified, the algorithm will select the related and most satisfactory measures for these sources. In Excel, the abatement options are pre-selected based on their TRL and compatibility to the vessel type and the energy systems. Only the applicable abatement options from the dataset are considered in the optimisation algorithm, this thereby reduces the rows of the data array. The pre-processing script reads the relevant decision parameters of these applicable abatement options. The relevant decision parameters of the abatement options include the types and categories of the options and respective reduction effects and costs.

7.3.2. Translation of optimisation problem into optimisation function

The mathematical formulation as derived in Section 6.2 must be translated into the language of the used optimisation solver. The decision variables (x) in the optimisation problem are binary (0 or 1) variables and the vector size depends on the number of applicable abatement options. The type of variables is specified in the options structure of the NGPM solver by adjusting the variable type and setting the lower bound (0) and upper bound (1) of the decision variable [58]. The two objective functions are defined in an objectives value vector (y). The recurrence relations for evaluating the total effects are performed in the optimisation function.

Constraint violations

The optimisation constraints must be rearranged into constraint violation form. The constraints can be arranged by shifting the right-hand side to the left-hand side of the equation. Furthermore, equal constraints can also be translated into inequality functions. Equation 7.1 shows the rearrangement to constraint violation as shown in Equation 7.2. It is demonstrated for an exclusive set constraint (e.g. LNG and a SO_x scrubber).

$$x_{LNG} + x_{scrubber} <= 1 \tag{7.1}$$

$$x_{LNG} + x_{scrubber} - 1 \leq 0 \tag{7.2}$$

The severity of the constraint violation can be used to decide which solutions should be selected. Some genetic algorithms use the constraint violation as a penalty function added to the objective function. However, the NSGA as implemented in the NGPM solver uses the amount of constraint violation for the ranking of different individuals in the selection step [23].

7.3.3. Optimisation options

The optimisation options for the genetic algorithm (GA) include options related to the genetic operators of the algorithm and options which must be determined case-by-case. First the default options are described, then the case-specific options and then a summary of these options.

Default used options of the algorithm

The optimisation solver is set by default to minimise the objective functions. In addition, options related to the NSGA need to be defined, most of these options are already predefined by default options in the NPGM model. The population is initialised by the standard method, using a uniform distribution with equal probability (1/2) to generate random binary (0 or 1) numbers [58]. The optimisation problem can be solved relatively fast from scratch; therefore, no previous optimisation results are used for the initial population. Binary tournament selection is used by default for the selection of the parents for reproduction [58]. The parents with the best fitness are selected for further genetic operations. The fitness is based on feasibility, constraint violation, Pareto front and the crowding distance metric. The genetic operator for crossover is set by default to use intermediate (arithmetic) crossover in which two parents are linearly combined to produce offspring [58]. In addition, the NGPM solver uses Gaussian mutation as a genetic operator. A Gaussian distributed random number is added to the binary genes (0 or 1) of the individual, causing some binary genes to be flipped, and that variation is created [58].

Case-specific options of the algorithm

In the optimisation algorithm, the population size and the maximum number of generations must be defined case-specific and can be calibrated by trail and error. The underlying idea for determining the population size is based on the desired number and variability of solutions. The maximum number of generations serves as a termination condition of the algorithm, this can be deduced from the number of generations before the genetic algorithm converges to the desired solutions. These GA options are dependent on the number (i) of abatement options and are therefore determined separately in each case study. Due to the existence of two objectives, the average sum of the objectives cannot simply be used as performance indicators, because the values of the different objectives may have a different order of magnitude. The GA is a probabilistic search algorithm and uses randomness to create the initial population and therefore there can be great variability in the solutions of different runs. Even if all the optimisation options of the genetic algorithm are the same, the results can vary for each optimisation run as shown in the case-specific tables (see Table 8.4 and Table 9.5).

Summary of options for the algorithm

The algorithm options, as discussed above, are summarised below.

- (Default) Initial population: uniform distribution random number;
- (Default) Selection: binary tournament selection;
- (Default) Crossover: Intermediate;
- (Default) Mutation: Gaussian distribution;
- (User-specified) Population size: needs to be defined case-specific;
- (User-specified) Maximum number of generations: needs to be defined case-specific.

7.4. Output generation and integration of algorithm

This section describes the different types of output that are generated by the NGPM model in MATLAB, during and after the optimisation. It is also described how the MATLAB output is transferred to the Excel environment for further evaluation. This section ends with summarising the selection tool and how the optimisation algorithm is integrated into this tool.

7.4.1. Intermediate results in MATLAB

The NGPM model developed by Song [58] contains a Graphical User Interface (GUI) figure in which the individuals of the population are plotted and can be checked during the optimisation run. The GUI figures for a population size of 200 and 50 generations are provided in Figure 7.4 and Figure 7.5. Figure 7.4 shows the population after 1 generation and Figure 7.5 shows the population after 50 generations. The population after 50 generations shows signs of a Pareto front, in which the Pareto-optimal individuals are non-dominating to the other individuals laying on the Pareto front.

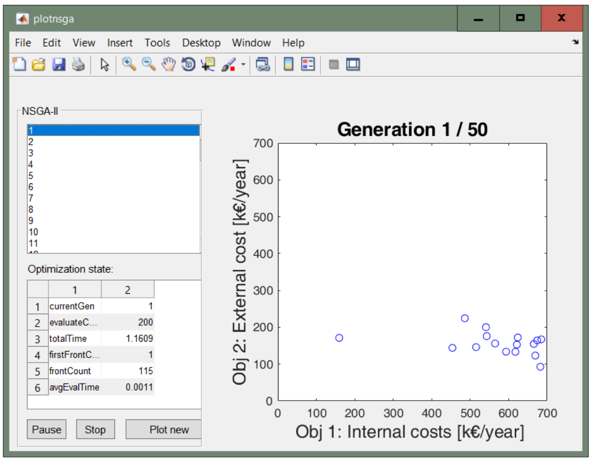


Figure 7.4: First population output after 1 generation

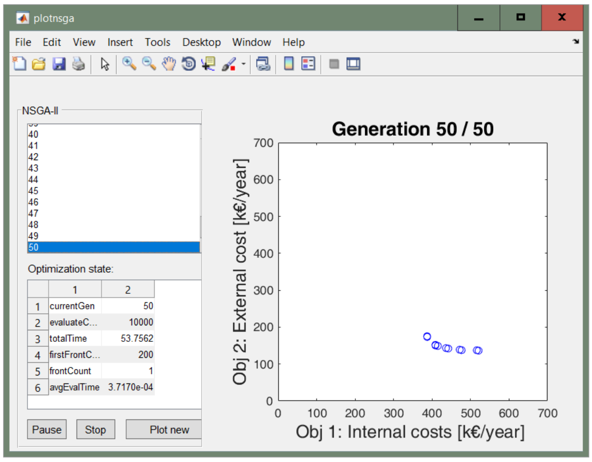


Figure 7.5: Final population output after 50 generations

The first generation may include infeasible individuals who violate the constraints, for example in the case as shown above. The violation of constraints can be deduced from the generated text files by the NGPM model as shown in Figure 7.6. These indicated individuals (objective value) are also not shown in the objective spaces shown in the figures above. The numbers below (cons) indicate the absolute amount of constraint violation (as defined in subsection 7.3.2). In the NSGA selection step, individuals with zero or smaller amount of constraint violations are preferred over individuals with larger constraint violations [23].

Var21	Var22	Var23	Var24	Obj1	Obj2	Cons1	Cons2	Cons3	Cons4	Cons5	Cons6	Cons7	Cons8
1	1	1	0	1084.06	121.367	0	0	0	0	0	1	1	1
0	1	1	0	2200.37	73.0671	0	0	1	0	0	0	3	3
1	1	0	0	2383.3	123.815	0	0.56595	3	0	0	1	2	1
1	0	0	0	3919.97	78.3686	0	0.003	3	1	0	1	4	3

Figure 7.6: Example of 4 individuals from a population after 1 generation, indicating the binary decision variables, the objective values and the amount of constraint violations

7.4.2. Post processing the results in MATLAB and Excel

The optimisation function in MATLAB returns the objective (y) values and the decision variable (x) vectors to the script file. This NGPM optimisation output can be analysed in the result structure in MATLAB or in the generated text file [58]. Each individual represents a generated decision variable vector (x) that can be used to evaluate other related output data of the individual.

The output (MATLAB) data relating to the individuals from a population are displayed in Figure 7.7. It shows the objective values including cost elements, the binary output of the decision variables and corresponding types of abatement options. This table also shows how many constraints are violated and the amount of the total constraint violation. Furthermore, it provides the achieved total reduction effects for the different type of emissions.

11x15 table

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	idxsol	obj1	obj2	Var4	Var5	xrow	techTable	nCons\	nConsV	R_NOx	R_SOx_tot	R_PM_tot	R_VOC_tot	R_CO2_tot	R_fc_tot
1	1	386.9964	175.3567	10.2300	376.7664	'0 0 1 0 0 0 ...	1x24 table	0	0	0.8750	0	0.3500	0	-0.0612	0.0034
2	2	387.1915	173.5857	14.2300	372.9615	'0 0 1 0 0 0 ...	1x24 table	0	0	0.8750	0	0.3500	0	-0.0612	0.0135
3	3	408.5432	152.0491	26.4992	382.0439	'0 0 1 0 0 0 ...	1x24 table	0	0	0.9500	0	0.6750	0	-0.0612	-0.0066
4	4	408.6849	150.5136	30.4992	378.1857	'0 0 1 0 0 0 ...	1x24 table	0	0	0.9500	0	0.6750	0	-0.0612	0.0036

Figure 7.7: Example of 4 individuals from a population after 50 generations, as displayed in MATLAB table.

Post processing the output to Excel

The optimisation algorithm generates a Pareto front and this front (short list) can still contain many non-dominated solutions. It may be necessary that the decision-maker can further evaluate the combinations of abatement options. Therefore, the solutions of the optimisation algorithm are transferred back to the user-interface in Excel. The generated results as displayed in Figure 7.7 are given for the reduced array (applicable abatement options). The reduced array is converted back to the original array, in order to evaluate the corresponding parameters of the abatement options in Excel.

7.4.3. Integration of the optimisation algorithm in the selection tool

A suitable optimisation solver and an optimisation algorithm are determined to solve the defined optimisation problem (step 4 from subsection 4.2.3). The optimisation solver uses the generated information of the benchmark assessment in Excel (step 1, 2 and 3) and generates the desired output which can be further evaluated in Excel (step 5). The selection tool encompasses the entire selection approach. It consists of Excel datasets, a user-interface in Excel and the MATLAB optimisation solver as visualised in Figure 7.8. The optimisation model includes two files important to the user: a script file for pre-processing and post-processing and a function file in which the optimisation problem can be defined by the decision-maker.

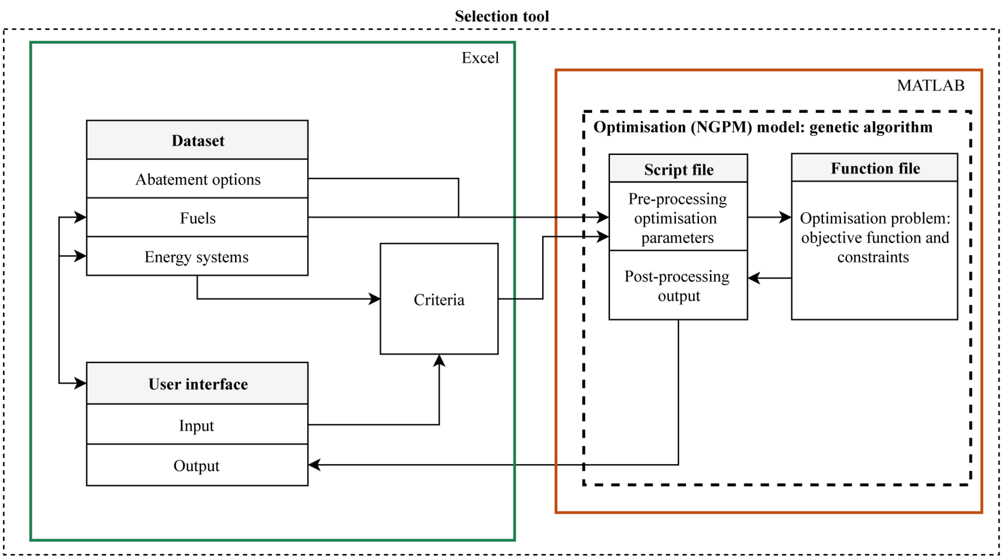


Figure 7.8: Flow chart of the selection tool (detailed version is given in Appendix F)

7.5. Output evaluation

This section describes how the output of the optimisation algorithm can be evaluated in Excel and how the output evaluation is related to the decision context.

Resulting ranking in Excel

The multi objective optimisation algorithm in MATLAB can generate different Pareto optimal combinations, these combinations do not dominate the other combinations on the Pareto front. Therefore, a ranking approach is needed to find the most satisfactory combination of abatement options for the decision-maker. The ranking can be based on criteria weights. The transferred optimisation output to Excel offers the possibility to support the decision based on various criteria. For example, the total emission-reduction effects or by evaluating the secondary parameters (e.g. dimensional information) of the abatement options.

Output evaluation in relation to decision-context

The desired output of the optimisation algorithm is a short list of satisfactory cost-effective combinations of abatement options. The extended version of the decision context as defined in subsection 1.3.1 is given in Figure 7.9. The decision maker can determine the criteria weights to find a satisfactory ranking of combinations from the generated short list. If the ranking of most preferred abatement options is known, the data of the options can be adjusted by more realistic data from suppliers. The generated combinations of abatement options can also be further evaluated for environmental performance with more detailed analysis tools. If large data adjustments are required, the selection tool may need to be iterated with these adjusted parameters (shown as a dotted line in Figure 7.9). The analysed alternatives ultimately form a final set with realistic data that are of value for the design process of the ship. They can then be integrated with other ship design aspects and evaluated together to find a feasible ship design space.

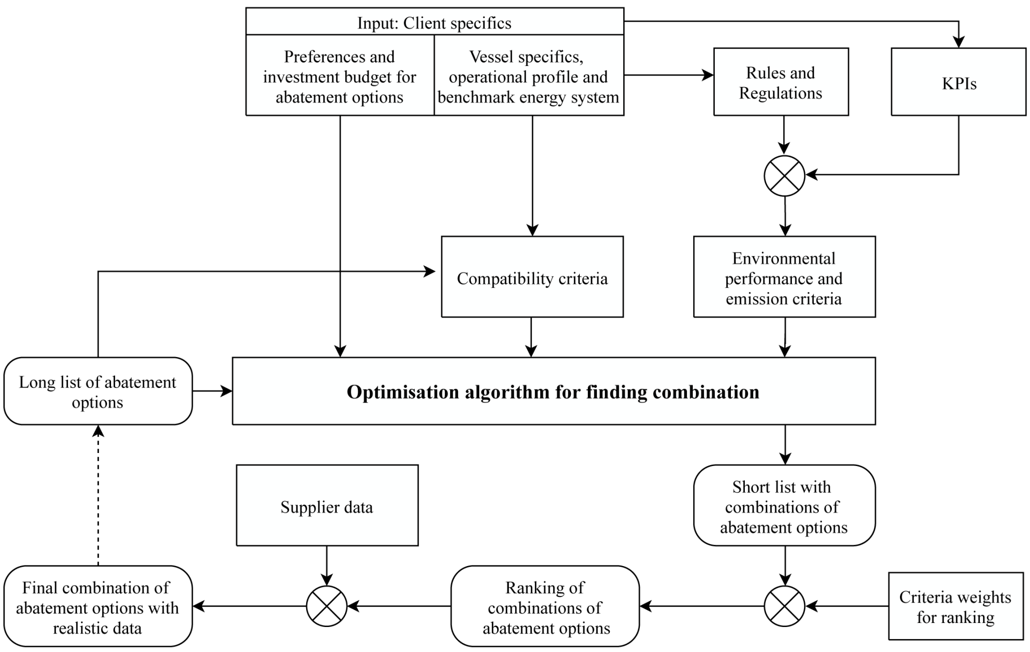


Figure 7.9: Decision context of the selection tool including output evaluation

7.6. Validation and verification

To validate the calculation performance of the developed selection tool, the resulting ship design must be compared with actual measured emission data on board of the modified vessel. However, this measurement data of the (modified) vessel is not available, therefore the selection tool can not be validated by real world data. A great deal of data on the (emission) performance and costs of technologies has been obtained from the literature and must be validated by data from the manufacturer. This more accurate information is, however, not widely published by manufacturers or is more difficult to obtain. So, data validity has been done by comparing the numbers from different literature sources or from available emission tests. Once the selection tool has been used, the environmental performance can be validated by evaluating the combination of technologies with more advanced simulation models. For example, with those models/tools that will be developed in the NAVAIS project as described in Appendix A.

The developed selection tool in this thesis can be verified by checking whether the required capabilities are correctly implemented into the selection tool. The intended purpose and the required capabilities of the selection tool are set out in Section 4.2. A selection tool has been formed with a suitable optimisation solver which is able to solve the defined optimisation problem. The tool is therefore able to find the optimised combination of cost-effective and compatible abatement options to at least meet the emission requirements.

7.7. Conclusion

This chapter described the optimisation algorithm for solving the defined optimisation problem. First, different types of optimisation algorithms (of which some earlier identified) were investigated. Some explored optimisation algorithms cannot solve the determined type of optimisation problem or have other issues. The NGPM optimisation solver is an appropriate optimisation, because it can solve the defined optimisation problem and it allows non-linear models. Furthermore, it gives various satisfactory solutions in reasonable computation time. The used NGPM model is programmed by Song [58] in MATLAB and this optimisation solver is an implementation of the NSGA algorithm [23]. In addition, this chapter described how the optimisation problem can be implemented in the optimisation solver. The constraints have to be translated into constraint violations form, because the NSGA uses this violation information for the ranking of the individuals. The individuals are represented by strings of binaries in which a binary represents a certain abatement option.

The output generation is then explained. It is also shown how the optimisation solver is integrated in the selection tool. A part of the MATLAB output is sent to the user-interface in Excel for further evaluation, therefore these two software programs are integrated. An overview of the determined software elements of the selection tool is given in Figure 7.8. In multi-objective problems, there exists a Pareto front in which the individuals do not dominate each other. A possible further evaluation of the output is given in the extended decision context as shown in Figure 7.9. The resulting ranking marks the end of one iteration of the identified decision-making process. The developed selection tool is tested with two case studies as explained in the following two chapters.

III

Test and evaluation

8. Case study road ferry

The developed selection tool is first tested with a case study for the road ferry. The vessel type road ferry is introduced in Section 8.1. A reference road ferry is then selected in Section 8.2, which serves as the benchmark and is assessed for the economical and environmental performance. For this road ferry combinations of abatement options are optimised in Section 8.3. Thereafter, a sensitivity analysis is presented in Section 8.5 and the conclusion is given in Section 8.6.

8.1. Introduction vessel type

The road ferry serves as one of the demonstrators in the NAVAIS project and will be designed as a double-ended configuration. It has an intended capacity of up to 450 passengers and 150 cars and it will operate in Northern Europe (Baltic Sea) [69]. In this section, the road ferry is introduced from a general perspective by first explaining the design characteristics and then describing the type of operational profile. This section ends with an exploration of energy system configurations for road ferries.

8.1.1. Vessel characterisation

The road ferry is a passenger and car ferry and offers a transport link for passengers and their associated vehicles. It typically sails on short sailing routes with a high intensity of number of trips. The configuration of the road ferry can be single-ended or double-ended. The single-ended configuration is a conventional ship configuration and the double-ended configuration has a symmetrical hull with two equal fore and aft bodies. Each end of the double-ended road ferry is either a bow or stern, depending on the direction of sailing. The combination of many and short daily trips of a road ferry makes the reduction in turnaround time and improving the transport flow desirable. Therefore, the road ferry often has a double ended configuration (as shown in Figure 8.1), allowing the ferry to sail between terminals without having to turn around. Factors that influence the type of ferry include the payload, speed and operational area. The superstructure of the road ferry consists of a wheelhouse/bridge and, if necessary, a passenger accommodation. The type of superstructure is related to the provided services that often depend on the duration of the trip and the climate of the ferry route. This superstructure can be partly open (shown in Figure 8.1) or fully enclosed (shown in Figure 8.2). The position of the superstructure and bridge is often centred and overhanging but can also only be one-sided. The road ferry often has one wheelhouse/bridge that is arranged symmetrically.

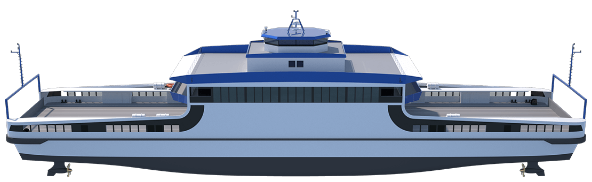


Figure 8.1: Double-ended road ferry 8521. Source: figure obtained from [21].

Figure 8.2: Double-ended road ferry TESO Texelstroom with two bridges. Source: figure obtained from [13].

The transport capacity of the road ferry is often expressed as the number of passengers and the number of equivalent passenger cars or trucks or a combination of these. Another expression used for the transport capacity is the number of lane meters (lm) available for vehicles. The road ferry is characterised by one or more decks for vehicles or trucks.

The available deck area is the prime selling point of the road ferry. The ferry can be considered as a volume-critical vessel [54] as there is need for a certain deck area for vehicles. The dimensions of the vehicle deck area largely determine the overall dimensions of the ship design. It is less strongly related to the number of passengers due to geographical differences in passenger use of the cars and of the ferry itself.

8.1.2. Mission and operational profile

The road ferry sails on short routes and its mission is to transport passengers and their associated vehicles between terminals. The ferry links are part of national transport networks or international transport networks. In addition to the transport task, a ferry also offers a certain type of service to the passengers, which can be a day/overnight accommodation and accommodation related facilities. The operational area of the road ferry varies from urban areas to coastal areas to open seas. The operational profile of road ferries can be classified in three sailing profiles; being a shuttle profile, a round-trip profile and a line-service (multiple terminals) profile [79]. The most common type of sailing profile is a shuttle profile; in the shuttle profile the road ferry sails back and forth between two terminals. Schot [79] estimated the average sailing distances for road ferries with a shuttle profile: about 30% of the vessels have a trip distance less than 5 km and 90% of less than 25 km. The transit/cruise speed of road ferries given by shipbuilders and ship operators varies from 10 knots to 25 knots and most common travel times varies from 30 minutes up to 100 minutes. The energy consumption can be derived based on installed power and trip time; most road ferries have an energy consumption per trip of 1000 to 2000 kWh [79].

8.1.3. Energy system configurations

An important system requirement for the road ferry is good manoeuvring capabilities, because the ferry operates in shallow waters and has to berth in sometimes narrow terminals. The operational profile of a road ferry is predictable due to regular sailing routes and regular sailing times, which offers the possibility to match the energy system better to the operational profile of the vessel. For years, the most widely used system architectures in ferries are fossil-fuel based system configurations. There are different configurations such as diesel-direct (diesel-mechanical), diesel-electric or diesel-hybrids, or more emerging gas-based configurations. Nowadays, more and more new builds of road ferries are, if profitable, powered by batteries. For the longer routes, a significant number of road ferries with hybrid combinations of batteries and diesel or gas electric propulsion can be expected. The road ferry sector is known for the early adaption of alternative energy system configurations. For example, zero-emission ferries such as the first (2014) electric-powered road ferry M/F Ampere. This vessel sails on a 6 km crossing and makes 34 trips a day and each trip take approx. 20 minutes (Vs=10kn) [34]. Also other innovative concepts are currently being developed for the road ferry market. Two hybrid hydrogen-electric road ferries are being developed for Norled, one powered by liquid hydrogen and another powered by compressed hydrogen [61]. The liquid hydrogen (LH_2) powered road ferry uses a energy split of batteries and hydrogen fuel cells, where the liquid hydrogen is stored on top of the ferry [61].

8.1.4. Recap of road ferry

The discussed features of the road ferry viewed from a general perspective are specified below.

- Key selling point: Transport deck area.
- Average operational profile: Regular and range 5 km-25 km, travel time between 30-100 minutes.
- Conventional system configurations: Diesel-based.
- Emerging alternative system configurations: Battery-electric or hybrids.

8.2. Benchmark assessment of reference vessel

This section describes the assessment of the selected road ferry with an assumed operational profile. First the specifics of the reference vessel are given, then the operational profile is described. The applicable emission regulations are then described. This section ends with the presentation of the economic and environmental performance.

8.2.1. Specifics reference vessel

The electric road ferry 9819 has been chosen as the reference vessel for the case study, because it has similar characteristics to the intended concept design in the NAVAIS project. It is also a double-ended ferry configuration, has a comparable capacity and has a full-electrical propulsion.

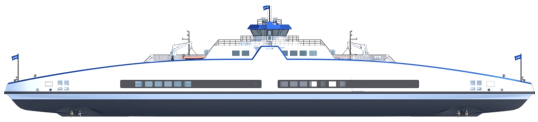


Figure 8.3: Damen road ferry 9819. Source: figure obtained from [18]

The details of this reference vessel are given in Table 8.1. The energy system configuration of the road ferry 9819 is full-electric, in which the four azimuth thrusters are electrically driven. The road ferry has diesel generator sets which are required by SOLAS regulations for passenger vessels as an emergency generator for redundancy. In addition, the reference ship is designed for an operational area which can have ice conditions. In that case, the diesel generators can be used to give an extra boost in addition to the power obtained from the batteries. However, the aforementioned scenarios are rare, so it can be assumed that the road ferry will mainly sail electrically with the power being obtained from the batteries.

Table 8.1: Ship specifics of the reference vessel: Road ferry 9819 [18]

Parameter	Value	Unit
Length	98.4	m
Beam	20.2	m
Azimuth thrusters	4*520	kW
Diesel gensets	2*565	ekW
Battery pack	4000	kWh

8.2.2. Assumed operational profile

Only the performance of the full-electric battery-mode is evaluated as the benchmark and not the mode in which the diesel gensets may be used. Therefore, only the installed battery is evaluated in the benchmark assessment. The environmental and economic performance of the reference vessel is evaluated based on the annual operational profile. The annual profile is based on an availability of 97%, in which 10 days can be reserved for maintenance work, so the case study is evaluated over 354 operational days. The operational profile is divided into free sailing, manoeuvring and at berth.

The assumed operational profile for a (30 minutes, one way) trip of the road ferry is given in Table 8.2. At berth, the electric ferry will use shore power for recharging the batteries.

Table 8.2: Assumed operational profile of the reference vessel: Road ferry 9819

Phase	Description phase	Time
		[minutes]
1	Free sailing	15
2	Manoeuvring	4
3	At berth charging	11

The assumed energy consumption is roughly estimated at around 550 kWh per trip. This is based on the required propulsion power to drive the four azimuth thrusters (e.g. distribution of 70% aft and 30% fwd), an effective efficiency, trip time and an assumed auxiliary load (approx. 50 kWh). It is assumed that the the road ferry is operational for 15 hours a day, resulting in a total of 30 trips. This gives a total energy consumption of 16.5 MWh per day and 5841 MWh per year. Based on the assumed energy consumption above, it is estimated that a portion of 85% of the annual energy consumption is used for propulsion power and the other 15 % is used for the auxiliary energy consumption such as Heating Ventilation and Air Conditioning (HVAC).

8.2.3. Applicable emission regulations and limits

The benchmark for road ferries is only evaluated for battery mode and not for the mode in which the diesel generators may be used. The assumed operational area is the Baltic Sea, which is a SO_x-ECA and was recently designated by the IMO as NO_x-ECA. If the ship sails in this NO_x-ECA and if it is constructed on or after 1 January 2021, it must comply with the strictest Tier III limits [42]. Although the road ferry rarely uses the Tier II diesel generator sets, it is subject to the strict NO_x and SO_x emission requirements. Low-sulphur fuels or abatement options must, therefore, be chosen to comply with the emission regulations. The EEDI is a design requirement for a road ferry (ro-ro passenger ship) over 400 GT, if it applies to the energy system configuration and if the ferry sails in international waters. The considered road ferry is likely to sail only in national waters in the Baltic region. Therefore, the EEDI does not apply and is not considered as an emission constraint in the optimisation problem. The Underwater Radiated Noise (URN) can be radiated during off-design conditions (accelerating and decelerating). The propellers are then more heavily or lightly loaded, leading to an increase of cavitation, which, if it occurs, is a dominant source of URN [69]. The potential Underwater Radiated Noise (URN) produced during accelerating and decelerating can be reduced by design measures related to the reduction of cavitation.

8.2.4. Benchmark performance

The internal costs and external costs of the benchmark energy system are summarised in Table 8.3. This table shows the build-up of the internal costs on annual basis, which is a summation of the annual investment costs and the operational costs. Furthermore, it shows that the annual investment costs are in the same order as the operational costs. The benchmark electricity is assumed to be produced from a European mix of energy sources, including more polluting sources such as coal. This electricity has upstream emissions from the production, which are based on a European average carbon intensity (emission) factor of 466 gCO_2-eq/kWh (based on [65] and [36]). A European average industrial electricity (mix) price of 70 [€/MWh] is used, which is based on values from [29].

Table 8.3: Benchmark performance of the road ferry

	B	C	D
51	**Selected energy system**	**Batteries (lithium-ion)**	
52	Predefined fuel	**Electricity[mix]**	
53	Energy delivered by energy system [MWh/year]	**3564**	
54	Fuel consumption [MWh/year]	**4950**	
55	**Internal (investment+operational) costs**		
56	Total investment (equipment+installation) costs [k€]	**k€**	**2800.0**
57	Annual investments costs [k€/year]	**k€|y**	**280.0**
58	Operational costs: fuel cost factor [€/MWh]	**€**	**70.00**
59	Operational costs: fuel costs [k€/year]	**k€|y**	**346.5**
60	Operational (maintenance) costs [k€/year]	**k€|y**	**5.3**
61	Total operational costs [k€/year]	**k€|y**	**351.8**
62	Total annual internal costs [k€/year]	**k€|y**	**631.8**
63	**External costs of (WTT+TTP) emissions**		
64	**External costs of upstream (WTT) emissions**		
65	E_CO_2-eq [ton/year] & External costs CO_2-eq [k€/year]	**t|y 2316.6**	**k€|y 125.1**
66	**External costs of operational (TTP) emissions**		
67	E_NO_x [ton/year] & External costs NO_x [k€/year]	**t|y -**	**k€|y -**
68	E_SO_x [ton/year] & External costs SO_x [k€/year]	**t|y -**	**k€|y -**
69	E_PM [ton/year] & External costs PM [k€/year]	**t|y -**	**k€|y -**
70	E_VOC [ton/year] & External costs VOC [k€/year]	**t|y -**	**k€|y -**
71	E_CO_2 [ton/year] & External costs CO_2 [k€/year]	**t|y -**	**k€|y -**
72	**Total external costs (WTT+TTP) [k€/year]**		**k€|y 125.1**

8.3. Optimisation of abatement options

This section first describes the pre-selection of feasible abatement options relevant for the road ferry. The case-specific optimisation options are then determined. The output of the optimisation algorithm is then described and this section ends with the evaluation of the output.

8.3.1. Pre-selection of feasible abatement options

The irrelevant abatement options for the (battery-electric and double-ended) road ferry are excluded from the dataset. The emission-reducing abatement options are excluded from the further analysis, because only the battery-mode is considered in the optimisation problem. Furthermore, energy-efficient measures not applicable to this ship type and operational profile are excluded. This results in a total of 11 feasible abatement options for the road ferry.

8.3.2. Determination optimisation options

The optimisation algorithm is tested for different population sizes and number of generations. The population size largely determines the variability in the solutions, however a larger population size together with a larger amount of generations increase the solution time. For this type of decision context, the emphasis is not on the exact solution, but on scanning and finding a feasible design space for possible combinations within a reasonable calculation time. From the Graphical User Interface (GUI) (as described in subsection 7.4.1), it was determined after how many generations the algorithm had converged. Furthermore, the number of solutions and solution time were noted. The performance in a multi-objective (minimisation) optimisation can be deduced from the mean/average distance of the origin [0,0] to the solutions from the last generated Pareto front [81]. In this case, the origin indicates the most ideal solution: zero internal costs and zero external costs.

The equation to calculate the mean distance is given in Equation 8.1. This mean distance is practically a weighted sum approach in which equal criteria weights are given to two different objective values. Therefore, to demonstrate the individual function improvements, the average objective values of both objective functions are also reported.

$$\text{Mean distance}_O = \text{mean}\left(\sqrt{(obj1(:).^2 + obj2(:).^2)}\right) \tag{8.1}$$

The test overview for the road ferry is presented in Table 8.4. It shows that the optimisation run is often converged after about 10 generations, therefore the selected number of generations is 20 to include a margin. Furthermore, it appears that the results are the same if the population size increases. Therefore, the selected population size is 50.

Table 8.4: Determination of population size and number of generations for road ferry case (Nr.=number, gen.=generation)

Population size	Nr. gen.	Convergence after gen.	Nr. of solutions	Solution time [sec]	Mean distance w.r.t. [0,0]	Mean Obj 1 [k€/y]	Mean Obj 2 [k€/y]
50	10	10	18	3.3	400.2	673.6	92.6
50	20	15	28	6.9	392.0	664.4	95.5
50	30	13	25	7.6	392.0	664.4	95.5
100	20	10	21	11.4	392.0	664.4	95.5
200	20	11	21	15.6	392.0	664.4	95.5

8.3.3. Output of optimisation algorithm

The optimisation algorithm is performed for an initial population size of 50 and 20 generations. The computation time to generate the solutions was 7.0 seconds and there are 33 solutions generated. It gives a mean distance of 392.0, a mean objective 1 of 664.4 and a mean objective 2 of 95.5. The final solution is visualised in Figure 8.4. This figure shows the benchmark performance in terms of the internal costs and external costs (as determined in Table 8.3). It shows how the combinations (bullets) lead to a reduction (↓) of the external costs of emissions and an increase (→) or reduction (←) of the internal costs.

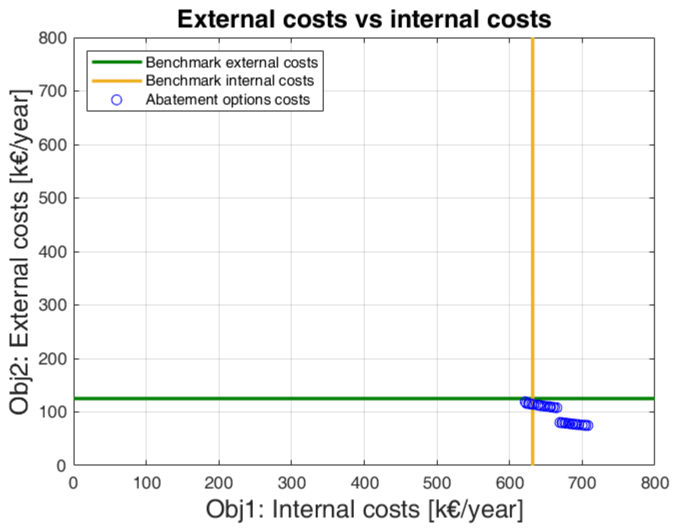


Figure 8.4: Output case study road ferry relative to benchmark. Objective 1 according to Equation 8.2.

The bullets in Figure 8.4 represent the performance of the combinations of abatement options expressed by the external costs (objective 2) and the summed internal costs (as explained below). In the optimisation problem, objective 1 represents the internal costs of abatement options according to Equation 6.2 and includes the fuel costs. The summed internal costs (of the abatement options and energy systems) are calculated according to Equation 8.2. It contains the annual investment costs plus the maintenance costs of the benchmark energy system and the optimised internal costs (Obj1) of the abatement options including the fuel costs. The (different) fuel costs are therefore not charged twice.

$$\begin{aligned}\text{Summed internal costs} = \text{Annual investment costs benchmark} + \text{Maintenance costs benchmark}\\ + \text{Internal costs of abatement options (Obj1)}\end{aligned} \quad (8.2)$$

8.4. Output evaluation

This section explains how the obtained output is evaluated, by first dividing the objective space in different areas. Thereafter, the solutions from these areas are analysed in more detail.

8.4.1. Division output in areas

As discussed in Section 6.3, criteria weights can be used to find the most satisfactory solutions from the obtained Pareto front as given in Figure 8.4. However, it can also be useful to interpret the regions/areas of solutions from the objective space. To evaluate the output, the obtained solutions are grouped into the regions based on their locations in the objective space. The grouping of the solutions into a blue area and green area is shown in Figure 8.5. The objective values of the solutions (laying in the blue area and green area) are studied in more detail below this figure. The objective values are compared with the benchmark performance as given in Table 8.3. In the following subsections, a top three of solutions is obtained by evaluating the weighted sum and varying the criteria weights.

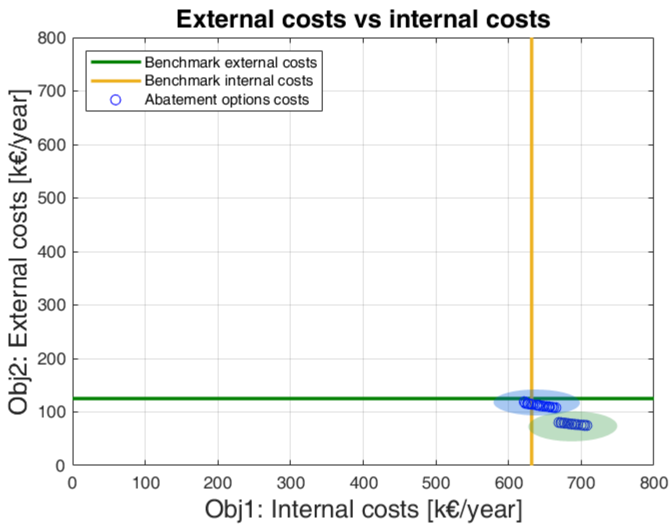


Figure 8.5: Grouping of combinations of abatement options. Objective 1 according to Equation 8.2.

Blue area:

This area shows solutions with a reduction (5%-14%) of external costs w.r.t. the benchmark for a decrease (-2%) or increase (5%) of internal cost w.r.t. the benchmark.

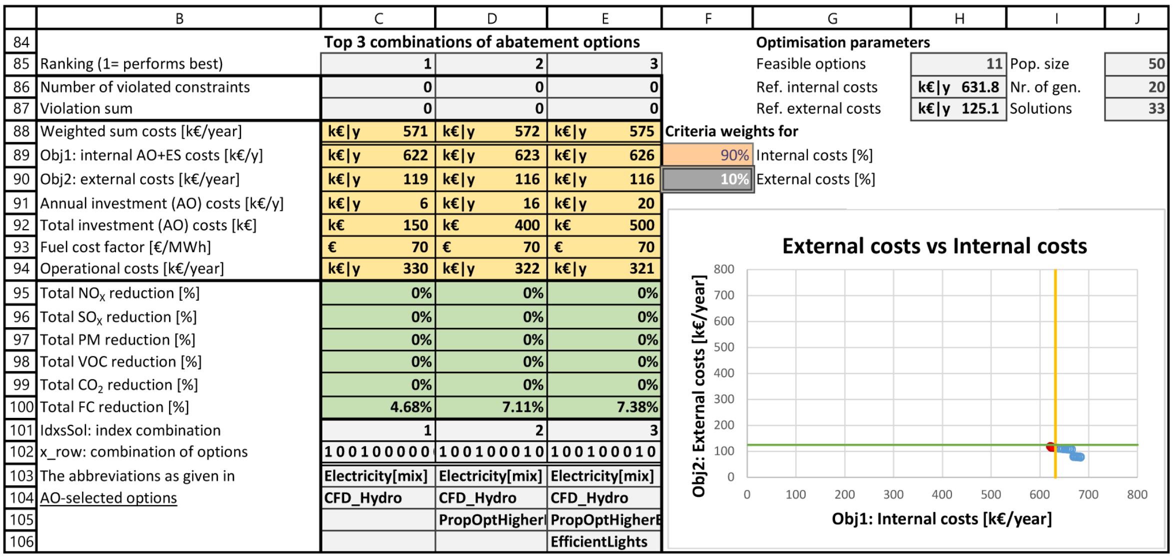
	Obj1 [k€/y]	Obj2 [k€/y]
Benchmark	631.8	125.1
Combination most left	621.6	119.2
Combination most right	647.2	108.0

Green area:
This area shows solutions with a reduction (36%-40%) of external costs w.r.t. the benchmark. This is achieved by a relatively high increase (6-12%) of internal costs w.r.t. the benchmark.

	Obj1 [k€/y]	Obj2 [k€/y]
Benchmark	631.8	125.1
Combination most left	669.2	80.5
Combination most right	707.7	74.8

8.4.2. Blue area

A top three of combinations from the blue area is shown in Figure 8.6. This figure shows the different types of (annual) costs represented by the yellow rows and the total reduction effects represented by the green rows. It also shows (a part of) the rows of binaries that represent the installation of abatement options or not. The implemented types are also given by the shown abbreviations of the abatement options (AO). The top three of combinations shown are also indicated in the output graph by the red dots. The output shows that the most satisfactory solutions contain the benchmark electricity [mix] type. It also shows measures such as hydrodynamic optimised hull (CFD hydro) and energy efficient (LED) lighting.



	B	C		D		E		F	G	H	I	J
84		Top 3 combinations of abatement options							Optimisation parameters			
85	Ranking (1= performs best)		1		2		3		Feasible options	11	Pop. size	50
86	Number of violated constraints		0		0		0		Ref. internal costs	k€|y 631.8	Nr. of gen.	20
87	Violation sum		0		0		0		Ref. external costs	k€|y 125.1	Solutions	33
88	Weighted sum costs [k€/year]	k€|y	571	k€|y	572	k€|y	575	Criteria weights for				
89	Obj1: internal AO+ES costs [k€/y]	k€|y	622	k€|y	623	k€|y	626	90%	Internal costs [%]			
90	Obj2: external costs [k€/year]	k€|y	119	k€|y	116	k€|y	116	10%	External costs [%]			
91	Annual investment (AO) costs [k€/y]	k€|y	6	k€|y	16	k€|y	20					
92	Total investment (AO) costs [k€]	k€	150	k€	400	k€	500					
93	Fuel cost factor [€/MWh]	€	70	€	70	€	70					
94	Operational costs [k€/year]	k€|y	330	k€|y	322	k€|y	321					
95	Total NO_X reduction [%]		0%		0%		0%					
96	Total SO_X reduction [%]		0%		0%		0%					
97	Total PM reduction [%]		0%		0%		0%					
98	Total VOC reduction [%]		0%		0%		0%					
99	Total CO_2 reduction [%]		0%		0%		0%					
100	Total FC reduction [%]		4.68%		7.11%		7.38%					
101	IdxsSol: index combination		1		2		3					
102	x_row: combination of options	1 0 0 1 0 0 0 0 0		1 0 0 1 0 0 0 1 0		1 0 0 1 0 0 0 1 0						
103	The abbreviations as given in	Electricity[mix]		Electricity[mix]		Electricity[mix]						
104	AO-selected options	CFD_Hydro		CFD_Hydro		CFD_Hydro						
105				PropOptHigher		PropOptHigherE						
106						EfficientLights						

Figure 8.6: Top three combinations from the blue area.

8.4.3. Green area

A top three of solutions from the green area is given in Figure 8.7. In the solutions shown, green electricity (including a larger portion of renewable energy sources) is selected as fuel. This green electricity enables a reduction of the external costs. Although it is assumed that it still has upstream emissions (324 gCO_2-eq/kWh based on [65]). However, this green electricity type has a higher energy cost factor based on [29]; it is assumed to be 80 [€/MWh]) compared to the benchmark (mix) electricity (70 [€/MWh]). In addition, these solutions demonstrate the presence of an optimised propeller for higher efficiency.

	B	C	D	E	F	G	H	I	J
84		Top 3 combinations of abatement options				Optimisation parameters			
85	Ranking (1= performs best)	1	2	3		Feasible options	11	Pop. size	50
86	Number of violated constraints	0	0	0		Ref. internal costs	k€|y 631.8	Nr. of gen.	20
87	Violation sum	0	0	0		Ref. external costs	k€|y 125.1	Solutions	33
88	Weighted sum costs [k€/year]	k€|y 139	k€|y 139	k€|y 139	Criteria weights for				
89	Obj1: internal AO+ES costs [k€/y]	k€|y 683	k€|y 678	k€|y 681	10%	Internal costs [%]			
90	Obj2: external costs [k€/year]	k€|y 78	k€|y 79	k€|y 79	90%	External costs [%]			
91	Annual investment (AO) costs [k€/y]	k€|y 41	k€|y 32	k€|y 36					
92	Total investment (AO) costs [k€]	k€ 650	k€ 675	k€ 775					
93	Fuel cost factor [€/MWh]	€ 80	€ 80	€ 80					
94	Operational costs [k€/year]	k€|y 357	k€|y 361	k€|y 360					
95	Total NO_x reduction [%]	0%	0%	0%					
96	Total SO_x reduction [%]	0%	0%	0%					
97	Total PM reduction [%]	0%	0%	0%					
98	Total VOC reduction [%]	0%	0%	0%					
99	Total CO_2 reduction [%]	0%	0%	0%					
100	Total FC reduction [%]	9.87%	8.82%	9.09%					
101	IdxsSol: index combination	24	22	23					
102	x_row: combination of options	0 1 0 1 0 0 1 1 0	0 1 1 1 0 0 0 1 0	0 1 1 1 0 0 0 1 0					
103	The abbreviations as given in	Electricity[Rene	Electricity[Rene	Electricity[Rene					
104	AO-selected options	CFD_Hydro	CFD_Aero	CFD_Aero					
105		HighEffProp	CFD_Hydro	CFD_Hydro					
106		PropOptHigherE	PropOptHigherI	PropOptHigherE					
107			SolarPanels	EfficientLights					
108				SolarPanels					

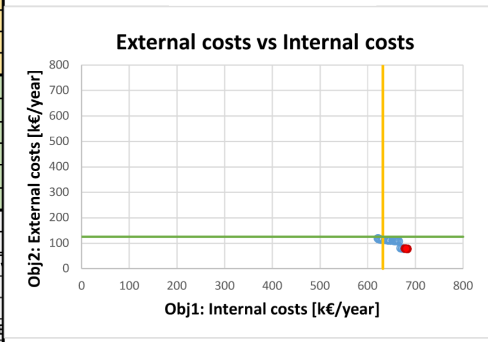


Figure 8.7: Top three combinations from the green area.

8.5. Sensitivity analysis

In this sensitivity analysis, two scenarios are tested to evaluate the functioning of the selection tool. In the first scenario, the decision parameters are varied and in the second scenario, the functioning of the selection tool is evaluated.

8.5.1. Other fuel cost and emission factor for green electricity

In this scenario, the used green electricity contains more cost-effective renewable energy sources. It is assumed that this can lead to a reduction of the energy cost factor from 80 [€/MWh] to 72 [€/MWh]. And a reduction of the upstream emission factor from 324 gCO_2-eq/kWh to 180 gCO_2-eq/kWh based on [36]. The resulting combinations (as shown in Figure 8.8) show a longer bottom row, indicating more solutions that include green electricity.

	B	C	D	E	F	G	H	I	J
84		Top 3 combinations of abatement options				Optimisation parameters			
85	Ranking (1= performs best)	1	2	3		Feasible options	11	Pop. size	50
86	Number of violated constraints	0	0	0		Ref. internal costs	k€|y 631.8	Nr. of gen.	20
87	Violation sum	0	0	0		Ref. external costs	k€|y 125.1	Solutions	24
88	Weighted sum costs [k€/year]	k€|y 571	k€|y 572	k€|y 573	Criteria weights for				
89	Obj1: internal AO+ES costs [k€/y]	k€|y 622	k€|y 623	k€|y 631	90%	Internal costs [%]			
90	Obj2: external costs [k€/year]	k€|y 119	k€|y 116	k€|y 46	10%	External costs [%]			
91	Annual investment (AO) costs [k€/y]	k€|y 6	k€|y 16	k€|y 6					
92	Total investment (AO) costs [k€]	k€ 150	k€ 400	k€ 150					
93	Fuel costs factor [€/MWh]	€ 70	€ 70	€ 72					
94	Operational costs [k€/year]	k€|y 330	k€|y 322	k€|y 340					
95	Total NO_x reduction [%]	0%	0%	0%					
96	Total SO_x reduction [%]	0%	0%	0%					
97	Total PM reduction [%]	0%	0%	0%					
98	Total VOC reduction [%]	0%	0%	0%					
99	Total CO_2 reduction [%]	0%	0%	0%					
100	Total FC reduction [%]	4.68%	7.11%	4.68%					
101	IdxsSol: index combination	1	2	6					
102	x_row: combination of options	1 0 0 1 0 0 0 0	1 0 0 1 0 0 0 1	0 1 0 1 0 0 0 0					
103	The abbreviations as given in	Electricity[mix	Electricity[mix	Electricity[Rer					
104	AO-selected options	CFD_Hydro	CFD_Hydro	CFD_Hydro					
105			PropOptHighe						
106									

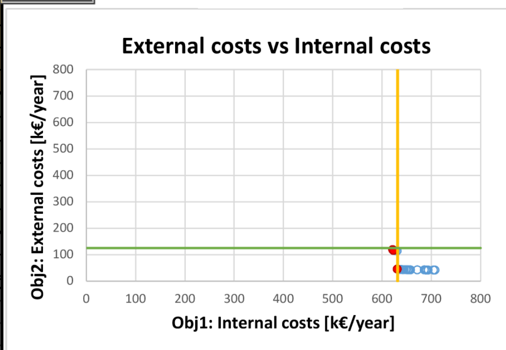


Figure 8.8: Top three combinations in a scenario with another cost and emission factor

8.5.2. Implementation of URN measures

In this scenario, the selection tool is evaluated for the Underwater Radiated Noise (URN) constraints. It is assumed that the URN is produced due to (potential) propeller cavitation, hull fouling and hull design (as indicated in Figure 8.9).

	J	K	L	M
55	**Number**	**Source category**		**Abbreviation**
56	1	Propeller (cavitation)	1	URN_prop
57	2	Onboard machinery	0	URN_mach
58	3	Hull fouling	1	URN_foul
59	4	Hull design & inflow	1	URN_hullD

Figure 8.9: Indicating the URN sources from the road ferry in the user-interface

In the optimisation function, the URN constraints are activated. The resulting output is shown in Figure 8.10; the internal costs of the resulted combinations are shifted (→). The hydrodynamic optimised hull leads to a reduction of potential turbulence. In addition, hull coating is implemented to reduce potential hull fouling. Furthermore, the propeller is optimised to reduce cavitation.

	B	C	D	E	F	G	H	I	J
84		**Top 3 combinations of abatement options**				**Optimisation parameters**			
85	Ranking (1= performs best)	1	2	3		Feasible options	11	Pop. size	50
86	Number of violated constraints	0	0	0		Ref. internal costs	k€|y 631.8	Nr. of gen.	20
87	Violation sum	0	0	0		Ref. external costs	k€|y 125.1	Solutions	16
88	Weighted sum costs [k€/year]	k€|y 618	k€|y 620	k€|y 621	**Criteria weights for**				
89	Obj1: internal AO+ES costs [k€/y]	k€|y 673	k€|y 676	k€|y 677	90%	Internal costs [%]			
90	Obj2: external costs [k€/year]	k€|y 119	k€|y 119	k€|y 118	10%	External costs [%]			
91	Annual investment (AO) costs [k€/y]	k€|y 29	k€|y 33	k€|y 37					
92	Total investment (AO) costs [k€]	k€ 425	k€ 525	k€ 500					
93	Fuel costs factor [€/MWh]	€ 70	€ 70	€ 70					
94	Operational costs [k€/year]	k€|y 359	k€|y 358	k€|y 355					
95	Total NO_X reduction [%]	0%	0%	0%					
96	Total SO_X reduction [%]	0%	0%	0%					
97	Total PM reduction [%]	0%	0%	0%					
98	Total VOC reduction [%]	0%	0%	0%					
99	Total CO_2 reduction [%]	0%	0%	0%					
100	Total FC reduction [%]	4.70%	4.99%	5.66%					
101	IdxsSol: index combination	1	2	3					
102	x_row: combination of options	1 0 0 1 1 0 0 0	1 0 0 1 1 0 0 0	1 0 0 1 1 0 0 0					
103	The abbreviations as given in	Electricity[mi	Electricity[mi	Electricity[mi					
104	AO-selected options	CFD_Hydro	CFD_Hydro	CFD_Hydro					
105		HullCoating	HullCoating	HullCoating					
106		PropOptLowe	PropOptLowe	PropOptLowe					
107			EfficientLights	SolarPanels					

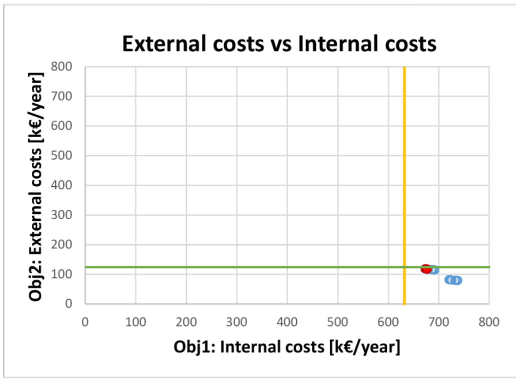


Figure 8.10: Top three combinations in a scenario with the implementation of URN measures

8.6. Conclusion

This chapter described the case study for a double-ended road ferry that is assumed to be used as 'shuttle' road ferry. The battery-electric road ferry 9819 is selected as a reference vessel. For the benchmark performance, the battery mode with an assumed operational profile is evaluated. In the battery-mode there are no operational emissions, therefore only upstream emissions are considered. There are 11 feasible energy-efficient options. Different population sizes and number of generations have been tested and evaluated. The resulting optimisation output shows the presence of the same benchmark electricity (mix) and measures such as hydrodynamic (CFD) optimised hull and energy efficient lightning. Two scenarios were evaluated in the sensitivity analysis to evaluate the functioning of the selection tool. In the first scenario, the green electricity price and upstream emission factor were reduced, which resulted in a larger presence of combinations with green electricity. The selection tool has also been tested for the functioning of the URN constraints, which also functioned. In these scenarios the developed selection tool functioned as desired.

9. Case study workboat

The developed selection tool is secondly tested with a case study for the workboat. The vessel type workboat is first introduced in Section 9.1. Thereafter, a reference workboat is selected in Section 9.2 which serves as the benchmark and is assessed for the economical and environmental performance. For this workboat, the optimal combinations of abatement options are evaluated in Section 9.3. Thereafter, a sensitivity analysis is presented in Section 9.5. The conclusion is given in Section 9.6.

9.1. Introduction vessel type

The workboat also serves as a demonstrator the NAVAIS project. It will be designed as an aquaculture support vessel with a gross tonnage of up to 500 GT. This section discusses the design characteristics, the operational profile and energy system configuration. It describes workboats in general and provides further explanation for aquaculture support vessels.

9.1.1. Vessel characterisation

Workboats are characterised by a relatively large open work deck area and the workboats are mostly equipped with a deck crane for light lifting tasks. The configuration and design of the workboat depend on the tasks that the client requires. The functions of a workboat configuration are combined if the vessel performance requirements are similar or complementary. This combination of functions leads to numerous configuration options of workboats. The different types of workboats shown in Figure 9.1 are designed for specific tasks such as buoy laying, pollution control, fire-fighting, survey and research work, maintenance work and aquaculture support [19]. An important design criterion for workboats is to reduce the gross tonnage (GT); the gross tonnage is a measure of the ships' internal volume. Regulations are often dependent on the size and power of the workboat. Gross tonnage is, for example, used by regulatory authorities for manning regulations.

Figure 9.1: Different configurations of Damen workboat/utility vessel 2510. Source: figure obtained from [19]

The working deck area of the workboat is important for storing the equipment and it is necessary to fulfil the specific tasks. The workboat is furthermore characterised by a low freeboard for ease of handling and lifting of equipment on board. The carrying capacity of the workboat is expressed as deadweight (DWT) and indicates, among other things, how much equipment weight the workboat can carry. The weight that can be stored on the deck is specified as the deck load. The available working deck area, deadweight/deckload and lifting capacity are important selling points of a workboat.

9.1.2. Mission and operational profile

The workboat, generally, performs various tasks and provides services and support to different types of activities or projects. Workboats are usually equipped with a deck crane for light duty hoisting tasks and towing equipment for light duty towing tasks. They are generally, suitable for carrying out tasks in inland waters, coastal areas or on the open sea. The operational profile of the workboats differs significantly from that for road ferries and the sailing profile is more variable. The sailing distance from the base port to the working location can be relatively short or long and the endurance of the operation of a workboat can vary up to several weeks on the sea. Therefore, the workboat has also overnight accommodation for the crew. An aquaculture support vessel facilitates different types of tasks with different durations. The aquaculture farms are often located in sheltered areas near the coast but can be at a distant sailing distance from the base port. The aquaculture support vessel can be used for plant or fish handling operations, delousing operations, maintenance work and installation/removal of the aquaculture infrastructure [20]. The operational modes can be divided in three main operational modes: free sailing, station keeping and moored alongside the fish farms.

9.1.3. Energy system configurations

The aquaculture support vessel must have good manoeuvring capability and must be able to keep station while performing support tasks. The conventional system configurations are based on fossil fuels, which can be diesel-direct (diesel-mechanical), diesel-electric or diesel-hybrids. The technology shift of low-impact vessels is also visible in the sector of aquaculture support vessels. Several alternative system configurations (battery-electric or hybrid-electric) are being developed for aquaculture support vessels. Although some differ considerably in size and power requirements.

9.1.4. Recap of workboat

The discussed features of the workboat viewed from a general perspective are specified below.

- Key selling points: working deck area, deckload, holding capacity, lifting capacity.
- Average operational profile: highly variable and endurance max. 2 weeks.
- Common system configurations: diesel-direct or diesel-electric.

9.2. Benchmark assessment of reference vessel

First the characteristics of the selected reference vessel are given and then the assumed operational profile is described. Thereafter, the applicable emission regulations are described. Finally, the economic and environmental performance of the benchmark is assessed.

9.2.1. Specifics reference vessel

The Damen workboat UV 4312 (as shown in Figure 9.2) is chosen as the reference vessel for this case study, because the UV 4312 has similar dimensions to the intended NAVAIS subject. In addition, the reference vessel has also recently been launched as an aquaculture support vessel.

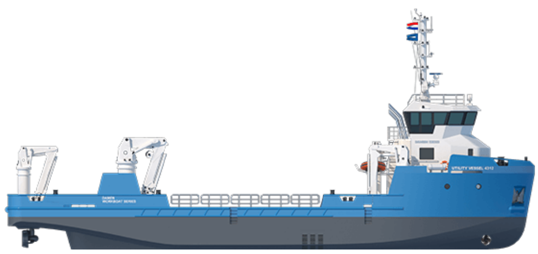


Figure 9.2: Reference vessel Damen workboat UV 4312. Source: figure obtained from [20]

The ship specifics of the selected reference vessel are shown below in Table 9.1. This selected reference vessel UV 4312 has a gross tonnage of 499 GT. The energy system configuration is diesel-electric, in which two nozzled thrusters are electrically driven by two electric motors. The vessel has three diesel gensets (Volvo D16) with a rated power of 470 ekW each [20]. The workboat is not subject to the SOLAS regulations for an emergency generator. The reference vessel also has a smaller diesel genset (Volvo D7) of 139 ekW. This small diesel genset is able to support the main diesel gensets or to provide the power for smaller loads. The diesel-electric configuration with a total of four diesel gensets, provides flexible power supply for the 750 kW propulsion system and other loads on board. The high-speed diesel engine is the most suitable type for this type of workboat, because of the power range and there is limited space in the machinery room. Therefore, medium and low speed engines are not applicable as they are too powerful and too space consuming.

Table 9.1: Ship specifics of the reference vessel (UV 4312). Source: numbers obtained from [20]

Parameter	Value	Unit
Length	43.27	m
Beam	12	m
Azimuth thrusters	2	
Bow thruster	1	
Electric motors	2*375	ekW
Main diesel gensets (Volvo D16)	3*470	ekW
Small diesel genset (Volvo D7)	1*139	ekW

9.2.2. Assumed operational profile

The workboat is almost always operational on year-basis and is laid-up for maintenance and classification every five years, therefore the assumed annual operational profile is based on 354 operational days. The operational profile of an aquaculture support vessel can vary greatly. The reference vessel is designed for an endurance of maximum two weeks. The assumed operational profile is based on Automatic Identification System (AIS) data of the reference vessel (e.g. [67]) and information from the shipbuilder. The assumed average operational profile is defined on the basis of 12 hours a day and is given in Table 9.2. The profile is divided into three operational phases. The table shows the assumed operational characteristics of the diesel gensets. The time factor is the relative operational time of the diesel gensets and the load factor is expressed with respect to Maximum Continuous Rating (MCR). The ship's Power Management System (PMS) regulates the number of diesel gensets based on the changing load and strives to ensure that each diesel generator works at an optimum load. In free sailing, two diesel gensets are capable to generate the propulsion power of 750 ekW. In station keeping both azimuth thrusters and bow thruster can be used. In the moored phase the load can be significant, e.g. due to the required power for deck machinery. If necessary, depending on the location and occupation of the ship, the energy demand during the night for Heating Ventilation Air Conditioning (HVAC) can be generated by the small diesel generator (D7).

Table 9.2: Assumed average operational profile and operational characteristics of the diesel generator sets, the workboat has 3 main diesel gensets (Volvo D16) and one small diesel genset (Volvo D7)

Phase	Description phase	Time	Time factor	Engine(s) operating	Load factor
		[hours/day]	[% time]	[#]	[% MCR]
1	Free sailing	5	100 %	2*D16	90 %
2	Station keeping (DP)	2	80 %	2*D16	90 %
3	Moored (different tasks)	5	70 %	2*D16 + D7	90 %

9.2.3. Applicable emission regulations and limits

The assumed operational area of the workboat is the North Sea, which is a SO_x-ECA. The North Sea has recently also been designated by the IMO as NO_x-ECA [43]. The actual NO_x value and the applicable NO_x limit are described in the following subsection. The smaller engine Volvo D7 has a capacity of less than 140 kW, therefore the NO_x emission regulations do not apply to this engine. The CO_2 related measure, the EEDI, is not applicable for the workboat, because this vessel type is not included in the vessel categories of the EEDI. Workboats do not carry cargo and the EEDI is not suitable for a workboat due to varying workboat configurations/designs and variable operational profiles. So, the PM, VOC and CO_2 emissions are not subject to emission requirements. The URN can be radiated for example during station keeping in Dynamic-Positioning (DP) mode [53].

9.2.4. Benchmark performance

The energy consumption is calculated based on the factors in Table 9.2 and the power of the respective diesel gensets as given in Table 9.1. It has been calculated that the smaller engine (D7) delivers 4% of the total daily energy consumption. In the event that the smaller engine would also be used at night, the total load of the small engine could amount to around 8% of the total energy consumption. However, in the defined assessment approach as discussed in subsection 4.2.2 only one (same) type of energy system is considered. Therefore, only the fuel consumption and the emissions of the main diesel genset (D16) are further evaluated in this case study. Based on the defined operational profile and calculated energy consumption, it can be stated that free sailing accounts for approximately 50% of the total main energy consumption. This energy ratio is used for evaluating the reduction effect of energy-efficient options.

Engine (Volvo D16) performance

The specific fuel consumption (sfc) parameters are adjusted to the numbers of the product sheet and the emission certificates (EIAPP) of the engine manufacturer ([94] and [95]). The total delivered power by the three diesel gensets and the interpolated specific fuel consumption are displayed in Table 9.3. It also shows the daily fuel consumption for the assumed operational profile, which gives a total fuel consumption of 1.76 ton diesel fuel per day.

Table 9.3: Performance of the three diesel gensets (Volvo D16) for the assumed operational profile.

Phase	Description phase	Total power	sfc	Total fuel consumption
		[kW]	[g/kWh]	[ton/day]
1	Free sailing	846	205.8	0.87
2	Station keeping (DP)	846	205.8	0.28
3	Moored (different tasks)	846	205.8	0.61

Actual emission values

The actual emission factors of the Volvo D16 are obtained from the emission test report [95]. The test data from the E3-cycle test are used, because the reference vessel has azimuth thrusters with Fixed-Pitch Propellers (FPPs) [20]. The engine has been tested on a marine distillate fuel oil, more specifically ISO-F-DMA. This is further referred to as Low Sulphur Marine Gas Oil (LSMGO). This LMSGO has a sulphur content of 1000 ppm, also expressed as 0.1 [%m/m]. The reported exhaust emissions used are the NO_x, SO_x and CO_2 emissions. The emissions factors of PM and VOC are based on other studies. The actual weighted cycle NO_x emission value of the Tier II engine is reported to be 5.26 [g/kWh] [95]. The Tier II (Volvo D16) engine has a maximum rated engine speed of 1800 rpm and the weighted cycle NO_x emission limit is therefore 2.01 [g/kWh] (according to Table 2.3). Therefore, the NO_x emission factor must at least reduced with a percentage of 61.8 %.

Cost and emission performance

The benchmark performance including internal costs and external costs is summarised in Table 9.4. The upstream (CO_2 equivalent) emissions are based on an emission factor of 43 gCO_2-eq/kWh for (LS)MGO ([26], [92]). The quantified emissions are in the same order as other studies (e.g. [59], [68]). The fuel cost of LSMGO (610 €/ton) is based on bunkerprices for Rotterdam ([82]) from last year. The total annual internal costs (404 k€/y) and the total external costs (307 k€/y) are in the same order.

Table 9.4: Benchmark performance of energy systems (three Volvo D16 gensets), where 1000 €/y is replaced by 1 k€/y.

	B	C		D	
51	**Selected energy system**	**HS-4s Diesel (CI) engine (Tier II)**			
52	Predefined fuel	**LSMGO**			
53	Energy delivered by energy system [MWh/year]	**3594**			
54	Fuel consumption [MWh/year]	**7375**			
55	**Internal (investment+operational) costs**				
56	Total investment (equipment+installation) costs [k€]	**k€**			**423.0**
57	Annual investments costs [k€/year]	**k€|y**			**16.9**
58	Operational costs: fuel cost factor [€/ton]	**€|t**			**610**
59	Operational costs: fuel costs [k€/year]	**k€|y**			**379.7**
60	Operational (maintenance) costs [k€/year]	**k€|y**			**7.2**
61	Total operational costs [k€/year]	**k€|y**			**386.9**
62	Total annual internal costs [k€/year]	**k€|y**			**403.8**
63	**External costs of (WTT+TTP) emissions**				
64	**External costs of upstream (WTT) emissions**				
65	E_CO_2-eq [ton/year] & External costs CO_2-eq [k€/year]	**t|y**	**318.6**	**k€|y**	**17.2**
66	**External costs of operational (TTP) emissions**				
67	E_NO_x [ton/year] & External costs NO_x [k€/year]	**t|y**	**15.9**	**k€|y**	**119.8**
68	E_SO_x [ton/year] & External costs SO_x [k€/year]	**t|y**	**1.2**	**k€|y**	**12.0**
69	E_PM [ton/year] & External costs PM [k€/year]	**t|y**	**1.5**	**k€|y**	**49.0**
70	E_VOC [ton/year] & External costs VOC [k€/year]	**t|y**	**0.6**	**k€|y**	**1.7**
71	E_CO_2 [ton/year] & External costs CO_2 [k€/year]	**t|y**	**1995.7**	**k€|y**	**107.8**
72	**Total external costs (WTT+TTP) [k€/year]**			**k€|y**	**307.4**

Visualisation of emissions and external costs

The quantified emissions and external costs are also plotted in Figure 9.3. It shows that the external costs of NO_x, PM and CO_2 contribute significantly to the total external costs. The quantified CO_2 emission is 1955.7 ton/year, which stands out, therefore the bar is broken in this figure. The PM emissions contribute significantly to the external costs, due to the high external cost factor (as given in Table 2.5).

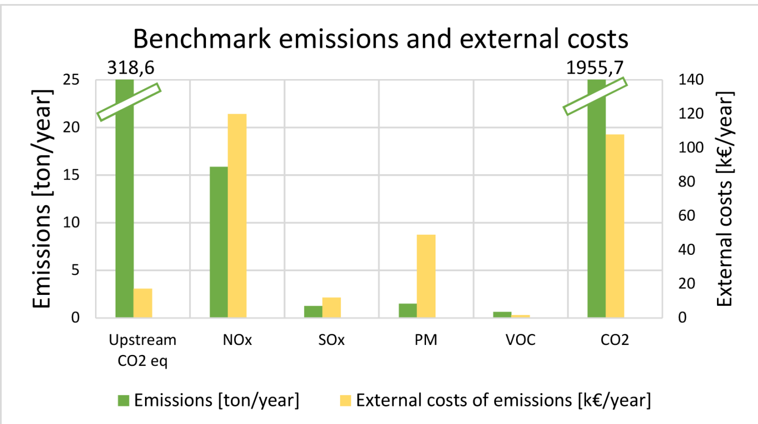


Figure 9.3: Benchmark (workboat) emissions and external costs, with the external costs shown on the secondary axis

9.3. Optimisation of abatement options

This section first describes the pre-selection of feasible abatement options that are relevant to optimise for the benchmark system. The case-specific optimisation options are then determined. The optimisation output and the evaluation of this output are then described.

9.3.1. Pre-selection of feasible abatement options

The abatement options that are non-relevant for the selected high-speed diesel engine (Volvo D16) are pre-excluded. As shown in in the compatibility columns from the dataset given in Appendix F. Furthermore, a Technology Readiness Level (TRL) between 6 and 9 is used as a selection filter. Pure Heavy Fuel Oil (HFO) is excluded, because the fuel systems and the combustion system of the high-speed diesel engine can not run on HFO. HFO has a high viscosity and other characteristics that can deteriorate the combustion performance of the high-speed engine. Furthermore, alternative fuels such as LNG are not applicable to the diesel engine (Volvo D16). Furthermore, SO_x scrubbers are excluded as they take too much space and weight on board of this type of workboat. The same reasoning can also be given for a Carbon Capture and Storage (CCS) system, which, however, is expensive and in development phase (TRL<6). Energy efficient options such as air (cavity) lubrication, Propulsion Improving Devices (PID), solar panels are not considered relevant for this vessel type and operational profile. The pre-selected feasible set contains 22 abatement options.

9.3.2. Determination optimisation options

For the predefined set of 22 applicable abatement options, the optimisation algorithm was tested to find the appropriate optimisation options. Different populations sizes and number of generations are varied as shown in the first two columns in Table 9.5. The shown optimisation runs contain all feasible combinations of abatement options. For each optimisation run, different data such as the number of solutions and the solution time are noted. The optimisation options are determined in the same way as in the road ferry case (as described in subsection 8.3.2). The mean distance to the origin and the mean average objective values are used as performance indicators. It can be deduced that 20 generations and 30 generations were too small as termination condition, because the optimisation algorithm was still trying to find better solutions. A population size of 300 and 40 generations (as marked in Table 9.5) are suitable to find good results (both objective functions) in reasonable solution time.

Table 9.5: Determination of population size and number of generations for a set of 22 abatement options for the workboat (Nr.=number, gen.=generation)

Population size	Nr. of gen.	Convergence after gen.	Nr. of solutions	Solution time [sec]	Mean distance w.r.t. [0,0]	Mean Obj 1 [k€/y]	Mean Obj 2 [k€/y]
50	20	14	1	9.9	954	944	254
50	30	29	2	11.8	665	669	160
50	40	33	4	12.3	619	618	176
100	30	23	8	16.1	520	513	176
100	40	32	4	20.3	501	495	171
200	40	33	12	43.5	489	486	169
200	50	31	9	43.9	480	472	172
300	40	32	13	64.9	473	465	170
300	50	33	8	72.4	475	466	173

9.3.3. Output of optimisation algorithm

The optimisation algorithm is performed for the determined optimisation options: an initial population size of 300 and a total number of 40 generations. The output of a genetic algorithm can vary for different optimisation runs (as pointed out in subsection 7.3.3). Therefore, the optimisation output with the lowest objective values is selected and the corresponding output data is also noted. First of all, the 11 generated solutions are all feasible. The solution time of this optimisation run was 65.6 seconds and the optimisation converged after 32 generations. The last generation gives a mean distance of 463, a mean objective 1 of 452 [k€/year] and a mean objective 2 of 176 [k€/year].

The last generation is visualised in Figure 9.4. This figure also shows the benchmark performance in terms of the internal costs and external costs as determined in Table 9.4. The summed internal costs (of the abatement options and energy systems) is calculated according to Equation 8.2 (similarly as for the road ferry). In the following figures, these summed internal costs are further used to visualise the difference with the benchmark. The figure below shows how a reduction (↓) of the external costs of emissions can be achieved by an increase (→) of the internal costs. The solutions are close to the internal costs of the benchmark, because the internal costs can also be reduced by other fuels or energy efficient options which decrease the fuel consumption and respective costs.

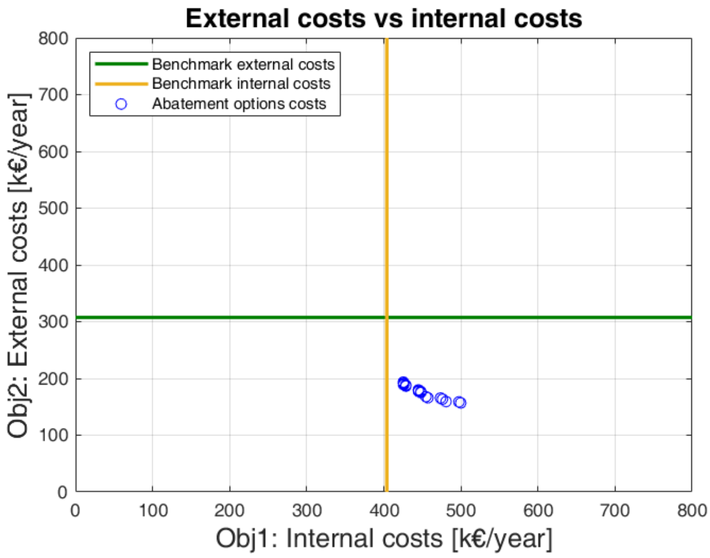


Figure 9.4: Output case study workboat relative to benchmark. Objective 1 according to Equation 8.2. (population size: 300, nr. generations: 40).

9.4. Output evaluation

This section explains how the obtained output is evaluated by first dividing the objective space into different areas. The solutions from these areas are then analysed in more detail.

9.4.1. Division output in areas

To evaluate various obtained combinations, they are divided into two different regions based on their location in objective space. The Selective Catalytic Reduction (SCR) can be found in any combination, this SCR is the most suitable abatement option for the high-speed diesel engine to reduce the NO_x emissions to meet Tier III requirements.

The grouping of the solutions in a blue area and green area is shown in Figure 9.5. The objective values of the solutions (laying in the blue area and green area) are studied in more detail below this figure. They are compared with respect to the benchmark performance (as given in Table 9.4). A top three of solutions is obtained by evaluating the weighted sum and by varying the criteria weights until the top three solutions are laying in the area concerned.

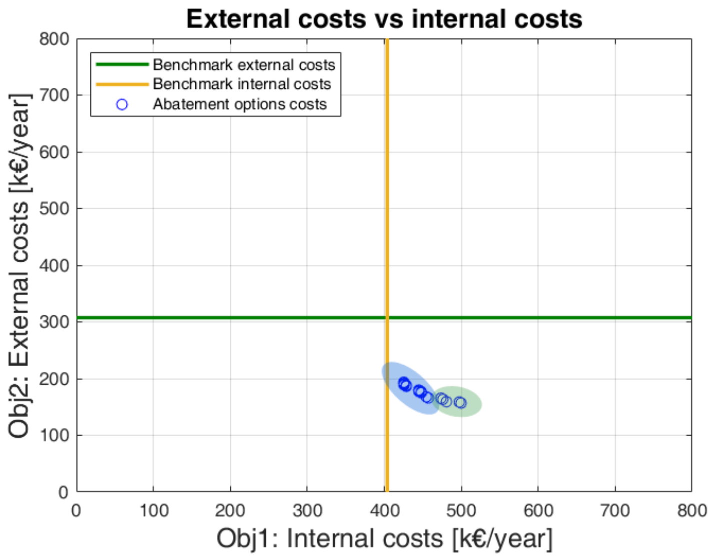


Figure 9.5: Grouping of combinations of abatement options. Objective 1 according to Equation 8.2.

Blue area:
In this area there is at least compliance with emission regulations. This area shows solutions with relatively high extra reduction (37%-46%) w.r.t. the benchmark external costs for a relatively small increase (5-13%) of internal costs w.r.t. the benchmark.

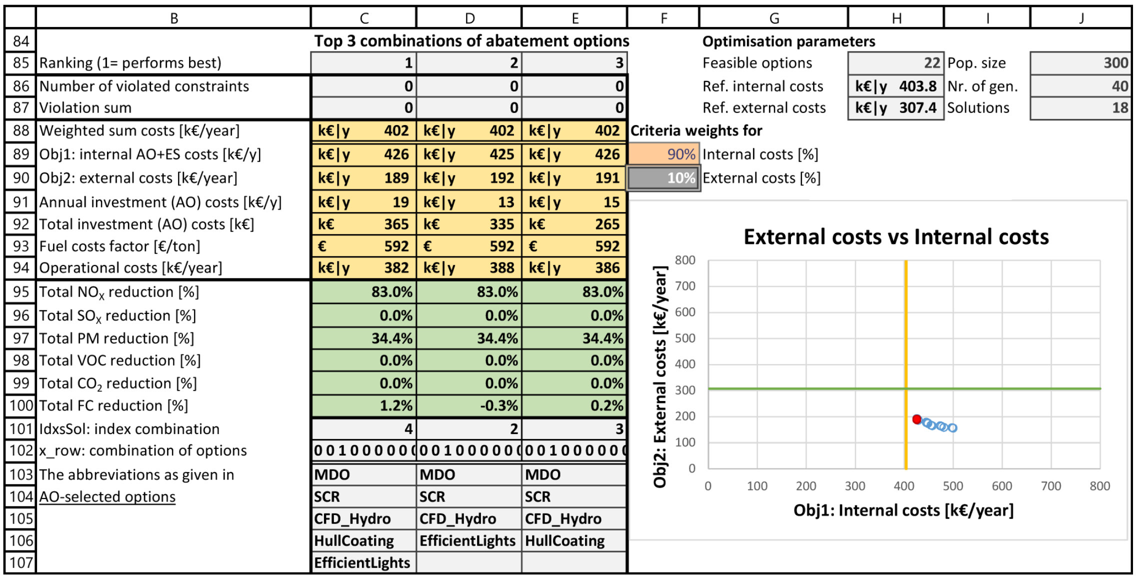
	Obj1 [k€/y]	Obj2 [k€/y]
Benchmark	404	307
Combination most left	425	194
Combination most right	457	166

Green area:
This area shows solutions with a relatively small extra reduction (46%-49%) of external costs w.r.t. the benchmark. This is achieved by a relatively high increase (17-24%) of internal costs w.r.t. the benchmark.

	Obj1 [k€/y]	Obj2 [k€/y]
Benchmark	404	307
Combination most left	474	165
Combination most right	500	160

9.4.2. Blue area

A top three of combinations from the blue area is shown in Figure 9.6. The SCR ensures compliance with the (NO_x) Tier III limit and also reduces the PM emissions. These solutions contain the sulphur (0.1%S) compliant Marine Diesel Oil (MDO). This is selected, because the assumed MDO price (592 €/ton) is lower than LSMGO. Furthermore, energy-efficient measures have been implemented such as a hydrodynamic optimised (CFD) hull and energy efficient lights to reduce the energy consumption.

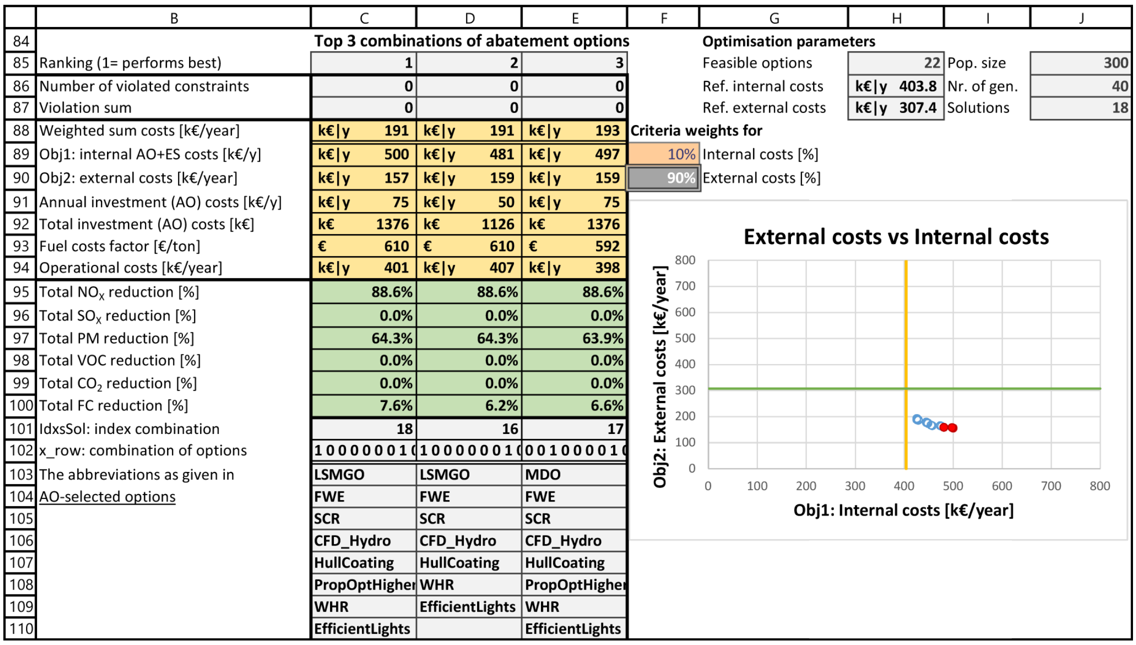


	B	C	D	E	F	G	H	I	J
84		Top 3 combinations of abatement options				Optimisation parameters			
85	Ranking (1= performs best)	1	2	3		Feasible options	22	Pop. size	300
86	Number of violated constraints	0	0	0		Ref. internal costs	k€|y 403.8	Nr. of gen.	40
87	Violation sum	0	0	0		Ref. external costs	k€|y 307.4	Solutions	18
88	Weighted sum costs [k€/year]	k€|y 402	k€|y 402	k€|y 402	Criteria weights for				
89	Obj1: internal AO+ES costs [k€/y]	k€|y 426	k€|y 425	k€|y 426	90%	Internal costs [%]			
90	Obj2: external costs [k€/year]	k€|y 189	k€|y 192	k€|y 191	10%	External costs [%]			
91	Annual investment (AO) costs [k€/y]	k€|y 19	k€|y 13	k€|y 15					
92	Total investment (AO) costs [k€]	k€ 365	k€ 335	k€ 265					
93	Fuel costs factor [€/ton]	€ 592	€ 592	€ 592					
94	Operational costs [k€/year]	k€|y 382	k€|y 388	k€|y 386					
95	Total NO_x reduction [%]	83.0%	83.0%	83.0%					
96	Total SO_x reduction [%]	0.0%	0.0%	0.0%					
97	Total PM reduction [%]	34.4%	34.4%	34.4%					
98	Total VOC reduction [%]	0.0%	0.0%	0.0%					
99	Total CO_2 reduction [%]	0.0%	0.0%	0.0%					
100	Total FC reduction [%]	1.2%	-0.3%	0.2%					
101	IdxsSol: index combination	4	2	3					
102	x_row: combination of options	0 0 1 0 0 0 0 0 (	0 0 1 0 0 0 0 0 (	0 0 1 0 0 0 0 0 (					
103	The abbreviations as given in	MDO	MDO	MDO					
104	AO-selected options	SCR	SCR	SCR					
105		CFD_Hydro	CFD_Hydro	CFD_Hydro					
106		HullCoating	EfficientLights	HullCoating					
107		EfficientLights							

Figure 9.6: Top three combinations from the blue area.

9.4.3. Green area

A top three of solutions from the green area is shown in Figure 9.7. These solutions lead to a significant increase of the total investment costs. These solutions contain the Waste Heat Recovery (WHR) system, which can increase the energy efficiency on board of the ship. Furthermore, these solutions show that in two combinations the (benchmark) fuel LMSGO has been selected. In addition, Fuel Water Emulsion (FWE) has been selected, which in combination with the SCR can further reduce the NO_x and PM emissions. Other energy efficient options such as an optimised propeller and hull coating have also been implemented.



	B	C	D	E	F	G	H	I	J
84		Top 3 combinations of abatement options				Optimisation parameters			
85	Ranking (1= performs best)	1	2	3		Feasible options	22	Pop. size	300
86	Number of violated constraints	0	0	0		Ref. internal costs	k€|y 403.8	Nr. of gen.	40
87	Violation sum	0	0	0		Ref. external costs	k€|y 307.4	Solutions	18
88	Weighted sum costs [k€/year]	k€|y 191	k€|y 191	k€|y 193	Criteria weights for				
89	Obj1: internal AO+ES costs [k€/y]	k€|y 500	k€|y 481	k€|y 497	10%	Internal costs [%]			
90	Obj2: external costs [k€/year]	k€|y 157	k€|y 159	k€|y 159	90%	External costs [%]			
91	Annual investment (AO) costs [k€/y]	k€|y 75	k€|y 50	k€|y 75					
92	Total investment (AO) costs [k€]	k€ 1376	k€ 1126	k€ 1376					
93	Fuel costs factor [€/ton]	€ 610	€ 610	€ 592					
94	Operational costs [k€/year]	k€|y 401	k€|y 407	k€|y 398					
95	Total NO_x reduction [%]	88.6%	88.6%	88.6%					
96	Total SO_x reduction [%]	0.0%	0.0%	0.0%					
97	Total PM reduction [%]	64.3%	64.3%	63.9%					
98	Total VOC reduction [%]	0.0%	0.0%	0.0%					
99	Total CO_2 reduction [%]	0.0%	0.0%	0.0%					
100	Total FC reduction [%]	7.6%	6.2%	6.6%					
101	IdxsSol: index combination	18	16	17					
102	x_row: combination of options	1 0 0 0 0 0 0 1 (	1 0 0 0 0 0 0 1 (	0 0 1 0 0 0 0 1 (					
103	The abbreviations as given in	LSMGO	LSMGO	MDO					
104	AO-selected options	FWE	FWE	FWE					
105		SCR	SCR	SCR					
106		CFD_Hydro	CFD_Hydro	CFD_Hydro					
107		HullCoating	HullCoating	HullCoating					
108		PropOptHigher	WHR	PropOptHigher					
109		WHR	EfficientLights	WHR					
110		EfficientLights		EfficientLights					

Figure 9.7: Top three combinations from the green area.

9.5. Sensitivity analysis

A sensitivity analysis is performed to evaluate the functioning of the selection tool. This section first describes the type of scenarios in which different variations are analysed.

9.5.1. Overview of variations

The decision problem contains various decision factors and parameters, that may need to be accurately defined. There are also some factors that are not studied for various reasons. The external costs of emissions are not varied, for example, because they are based on complex assessment methods (as described in Section 2.5). The scenarios studied and respective subsections are specified below. The data of the solutions located in the blue area are analysed, because it can be assumed that this solution area is the most interesting design area for the ship operators.

- Stricter SO_x emission regulations (see subsection 9.5.2).
- Diesel engine with other operational profile (see subsection 9.5.3).
- LNG engine as benchmark system (see subsection 9.5.4).

9.5.2. Stricter SO_x emission regulations

In this fictive scenario, it is assumed the workboat must meet a tight SO_x limit of 0.005 %S (50 ppm) instead of 0.1 %S (1000 ppm). Therefore, low-sulphur fuels must be used, because the exhaust gas (SO_x) scrubber is not applicable. It is assumed that the high-speed marine diesel engine can run on low-sulphur fuels such as Ultra-Low Sulphur Diesel (ULSD) [48] and (blends of) biodiesel. Figure 9.8 gives the output and shows that ULSD is selected as fuel. ULSD is the type of diesel fuel (EN-590) used in vehicles and inland waterway vessels [48]. The ULSD has a sulphur content of less than 10 ppm, but the desulphurisation leads to small increase in upstream emissions, the emission factor is assumed to be 50.4 gCO_2-eq/kWh. Figure 9.8 shows that the internal costs are increased (shifted) due to higher fuel cost factor of ULSD. These ULSD fuel costs are assumed to be 650 €/ton, based on a price difference with (LS)MGO [92]. The operation on low sulphur fuel makes it possible to implement aftertreatment such as DOC and DPF to reduce the PM emissions.

	B	C	D	E
84		Top 3 combinations of abatement options		
85	Ranking (1= performs best)	1	2	3
86	Number of violated constraints	0	0	0
87	Violation sum	0	0	0
88	Weighted sum costs [k€/year]	k€|y 417	k€|y 434	k€|y 435
89	Obj1: internal AO+ES costs [k€/y]	k€|y 444	k€|y 463	k€|y 465
90	Obj2: external costs [k€/year]	k€|y 177	k€|y 174	k€|y 170
91	Annual investment (AO) costs [k€/y]	k€|y 15	k€|y 40	k€|y 20
92	Total investment (AO) costs [k€]	k€ 265	k€ 515	k€ 279
93	Fuel costs factor [€/ton]	€ 640	€ 640	€ 640
94	Operational costs [k€/year]	k€|y 405	k€|y 399	k€|y 421
95	Total NO_X reduction [%]	83.5%	83.5%	83.5%
96	Total SO_X reduction [%]	0.0%	0.0%	0.0%
97	Total PM reduction [%]	37.6%	37.6%	53.2%
98	Total VOC reduction [%]	0.0%	0.0%	20.0%
99	Total CO_2 reduction [%]	0.0%	0.0%	0.0%
100	Total FC reduction [%]	1.6%	3.1%	1.1%
101	IdxsSol: index combination	1	2	3
102	x_row: combination of options	0 0 0 1 0 0 0 0 (	0 0 0 1 0 0 0 0 (	0 0 0 1 0 0 0 0 1
103	The abbreviations as given in	ULSD	ULSD	ULSD
104	AO-selected options	SCR	SCR	DOC
105		CFD_Hydro	CFD_Hydro	SCR
106		HullCoating	HullCoating	CFD_Hydro
107			PropOptHigher	HullCoating

	F	G	H	I	J
84		Optimisation parameters			
85		Feasible options	20	Pop. size	300
86		Ref. internal costs	k€|y 403.8	Nr. of gen.	40
87		Ref. external costs	k€|y 307.4	Solutions	14
88	Criteria weights for				
89	90%	Internal costs [%]			
90	10%	External costs [%]			

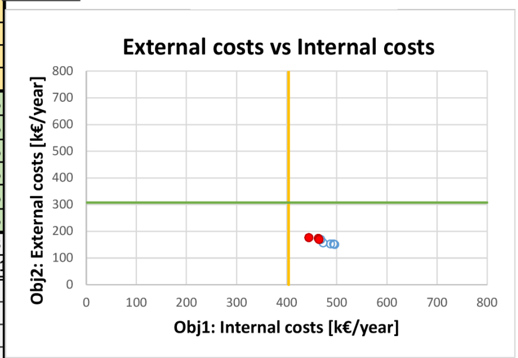


Figure 9.8: Top three combinations in a scenario with stricter SO_x emission regulations.

9.5.3. Diesel engine with other operational profile

The varied operational profile is shown in Table 9.6. In this profile it is assumed that the workboat will sail on one day to a specific location and stays there for two weeks for various (maintenance/installation) tasks. Therefore, on average, the free sailing phase just accounts for 1 hour. It is assumed that during the mooring phase three main diesel generator (Volvo D16) sets are used to obtain the required power for deck machinery to fulfil various tasks. The total fuel consumption is increased from 1.75 [ton/day] to 2.92 [ton/day].

Table 9.6: Other operational profile and operational characteristics of the diesel generator (Volvo D16) sets.

Phase	Description phase	Time	Time factor	Engine(s) operating	Load factor
		[hours/day]	[% time]	[#]	[% MCR]
1	Free sailing	1	100 %	2*D16	90 %
2	Station keeping (DP)	1	80 %	2*D16	90 %
3	Moored (different tasks)	10	100 %	3*D16	90 %

The resulting output for this scenario is shown in Figure 9.9. It is compared with the benchmark performance (see Table 9.4). The total internal costs are increased from 403 [k€/y] to 659 [k€/y] and the total external costs are increased from 307 [k€/y] to 511 [k€/y]. The optimisation output shows the same solutions as described in Figure 9.4.3.

	B	C	D	E	F	G	H	I	J
84		Top 3 combinations of abatement options				Optimisation parameters			
85	Ranking (1= performs best)	1	2	3		Feasible options	22	Pop. size	300
86	Number of violated constraints	0	0	0		Ref. internal costs	k€|y 658.7	Nr. of gen.	40
87	Violation sum	0	0	0		Ref. external costs	k€|y 511.4	Solutions	14
88	Weighted sum costs [k€/year]	k€|y 655	k€|y 660	k€|y 672	Criteria weights for				
89	Obj1: internal AO+ES costs [k€/y]	k€|y 692	k€|y 697	k€|y 712	90%	Internal costs [%]			
90	Obj2: external costs [k€/year]	k€|y 324	k€|y 323	k€|y 311	10%	External costs [%]			
91	Annual investment (AO) costs [k€/y]	k€|y 13	k€|y 19	k€|y 42					
92	Total investment (AO) costs [k€]	k€ 335	k€ 365	k€ 1040					
93	Fuel costs factor [€/ton]	€ 592	€ 592	€ 592					
94	Operational costs [k€/year]	k€|y 652	k€|y 651	k€|y 643					
95	Total NO_x reduction [%]	83.0%	83.0%	83.0%					
96	Total SO_x reduction [%]	0.0%	0.0%	0.0%					
97	Total PM reduction [%]	34.4%	34.4%	34.4%					
98	Total VOC reduction [%]	0.0%	0.0%	0.0%					
99	Total CO_2 reduction [%]	0.0%	0.0%	0.0%					
100	Total FC reduction [%]	-1.8%	-1.6%	2.2%					
101	IdxsSol: index combination	1	2	3					
102	x_row: combination of options	0 0 1 0 0 0 0 0 0	0 0 1 0 0 0 0 0 0	0 0 1 0 0 0 0 0 0					
103	The abbreviations as given in	MDO	MDO	MDO					
104	AO-selected options	SCR	SCR	SCR					
105		CFD_Hydro	CFD_Hydro	CFD_Hydro					
106		EfficientLights	HullCoating	WHR					
107			EfficientLights	EfficientLights					

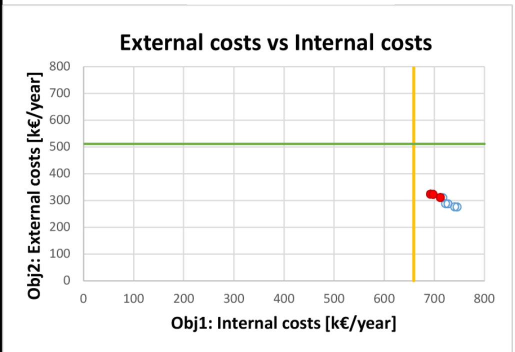


Figure 9.9: Top three combinations in a scenario with another operational profile.

9.5.4. LNG engine as benchmark

In this scenario a high-speed gas (LNG) engine is evaluated as benchmark. In the trade-off, the dimensional impact of LNG storage must, however, also be considered. Engine manufacturer MTU has developed the MTU 4000 high-speed marine gas engines for the relevant power range and speed range, including an eight-cylinder model with a power range of 750-1000 kW [66]. In this scenario, two 750 kW (Spark Ignition) gas engines are installed on the workboat. The same operational profile as shown in Table 9.2 is considered, however the load factors are lowered to 60 %, since a similar energy demand is assumed. The used upstream emission factor for LNG is 36 gCO_2-eq/kWh (based on [26] and [92]).

The benchmark performance for the gas engine is displayed in Table 9.7. It is compared with the diesel benchmark as shown in Table 9.4. The total investment costs for the gas engine are increased from 423 [k€] to 900 [k€]. However, the total annual internal cost for the LNG engine are reduced from 403 [k€/y] to 260 [k€/y]. The assumed fuel cost factor of LNG (400 €/ton) is lower than the benchmark fuel LSMGO (610 €/ton). The total external costs are decreased from 307 [k€/y] to 141 [k€/y]. The NO_x, SO_x and PM emissions are reduced and there is compliance with the NO_x (Tier III) and SO_x regulations. However, the (potential) VOC including methane emissions are increased w.r.t. the diesel engine. Therefore, abatement options such as an oxidation catalyst may be implemented to reduce the methane slip.

Table 9.7: Benchmark performance of LNG engine

	B	C		D	
51	**Selected energy system**				**HS-4s Gas (SI) engine**
52	Predefined fuel				**LNG**
53	Energy delivered by energy system [MWh/year]				**3823**
54	Fuel consumption [MWh/year]				**7291**
55	**Internal (investment+operational) costs**				
56	Total investment (equipment+installation) costs [k€]	**k€**			**900.0**
57	Annual investments costs [k€/year]	**k€|y**			**36.0**
58	Operational costs: fuel cost factor [€/ton]	**€|t**			**400**
59	Operational costs: fuel costs [k€/year]	**k€|y**			**216.0**
60	Operational (maintenance) costs [k€/year]	**k€|y**			**7.6**
61	Total operational costs [k€/year]	**k€|y**			**223.7**
62	Total annual internal costs [k€/year]	**k€|y**			**259.7**
63	**External costs of (WTT+TTP) emissions**				
64	**External costs of upstream (WTT) emissions**				
65	E_CO_2-eq [ton/year] & External costs CO_2-eq [k€/year]	**t|y**	**262.5**	**k€|y**	**14.2**
66	**External costs of operational (TTP) emissions**				
67	E_NO_x [ton/year] & External costs NO_x [k€/year]	**t|y**	**2.5**	**k€|y**	**19.3**
68	E_SO_x [ton/year] & External costs SO_x [k€/year]	**t|y**	**0.0**	**k€|y**	**0.2**
69	E_PM [ton/year] & External costs PM [k€/year]	**t|y**	**0.2**	**k€|y**	**6.4**
70	E_VOC [ton/year] & External costs VOC [k€/year]	**t|y**	**12.5**	**k€|y**	**33.5**
71	E_CO_2 [ton/year] & External costs CO_2 [k€/year]	**t|y**	**1485.1**	**k€|y**	**80.2**
72	**Total external costs (WTT+TTP) [k€/year]**			**k€|y**	**153.6**

9.6. Conclusion

The reference workboat (UV) 4312 has a diesel-electric configuration with three main high-speed diesel engines. For the benchmark assessment, it is assumed that it operates as an aquaculture support vessel in the North Sea. The benchmark fuel is LSMGO (0.1%S) and the emission factors are checked. Thereafter, incompatible abatement options/fuels such as HFO and SO_x scrubbers were pre-excluded from the dataset. The resulting combinations from the optimisation algorithm show the presence of MDO (0.1%S) and Fuel Water Emulsion (FWE). In addition, various energy efficient options are selected. The Selective Catalytic Reduction (SCR) is the technology of choice to assure compliance with NO_x (Tier III) regulations. Furthermore, the functioning of selection tool was evaluated by three scenarios. In the scenario with stricter SO_x requirements, the low-sulphur fuel ULSD is selected. This low-sulphur fuel allows the implementation of PM abatement options such as the DPF or the DOC. In another scenario, a high-speed LNG engine is evaluated as benchmark which shows good emission and cost performance. It assures compliance with NO_x and SO_x regulations. In short, this workboat case study and variations show that the selection tool can evaluate different energy systems and can propose different compatible abatement options.

10. Conclusions and recommendations

The conclusions are given in Section 10.1 and the recommendations are given in Section 10.2.

10.1. Conclusions

The main objective of this thesis was to improve the selection of the optimal combination of feasible abatement options at minimum costs that at least meet the emission requirements. This study is designed to first consider the decision problem from a general point of view in order to develop a universal selection tool. The developed selection tool includes Excel datasets with miscellaneous alternatives and an optimisation algorithm in MATLAB to find the optimal combination of abatement options. The functioning of the developed selection tool is evaluated by case studies for the NAVAIS subjects, a road ferry and a workboat, both for European waters.

The developed selection tool is particularly suitable for evaluating abatement options for exhaust emissions (NO_x, SO_x, PM, VOC and CO_2), but it also takes into account measures for discharges to sea such as Underwater Radiated Noise (URN). The IMO emissions regulations are strict environmental criteria for operational exhaust emissions (e.g. NO_x and SO_x). The reduction of certain emissions may require certain abatement options that may have a conflicting effect on the environment. Both upstream (WTT) exhaust emissions of alternative fuels and operational (TTP) exhaust emissions are evaluated in the selection tool, because zero (operational) emission fuels can have significant upstream (WTT) emissions. The external costs of exhaust emissions are used, which can be considered as weighting approach of exhaust emission effects and it facilitates the trade-off between the external costs and the internal costs borne by the shipowner. The considered internal costs are the operational (fuel and maintenance) costs and the annualised investment (equipment and installation) costs. The emissions and internal costs are evaluated annually and a basic cost-evaluation approach is used to provide a neutral view. Moreover, it is not certain how emissions regulations and technological progress will evolve in the long term.

The energy system must be selected and serves as an emission- and cost benchmark. The design space of possible combinations (of abatement options including fuels) in the decision-problem is significant. That is why it is required to use an optimisation algorithm. The design space is bounded by emission constraints and compatibility constraints between the alternatives. The optimisation problem defined in this thesis can be classified as a constrained combinatorial optimisation problem, where the decision variable is a binary variable. The optimisation problem is formulated as a multi-objective optimisation problem. The first objective is to minimise the internal (investment+operational) costs and the second objective is to minimise the external costs of emissions. This approach introduces cost-effectiveness in the selection process and encourages the reduction of the overall environmental impact.

The optimisation problem can further be classified as a non-linear optimisation problem, due to (the product of) the recurrence relations for calculating the total reduction effects of combinations of abatement options. From the results of the exploration of optimisation algorithms, it can be concluded that the NGPM model is suitable for solving this optimisation problem. This NGPM optimisation solver in MATLAB is an implementation of the NSGA, a type of genetic algorithm. It is suitable for the optimisation problem, because it offers satisfactory solutions in a reasonable calculation time. In a multi-objective problem, Pareto fronts are typically generated. Therefore, in the post-selection, the optimisation output is evaluated based on criteria weights and the location of the solutions (combinations) in objective space.

The developed selection tool has been tested with case studies for the road ferry and the workboat. The population size and number of generations were determined for each case study. The execution time of the optimisation algorithm is relatively short (less than 2 minutes on average) for both case studies. In the ferry case study, the battery mode was analysed, because the diesel generator sets are rarely used. The road ferry therefore has no operational emissions, although it does have upstream (WTT) emissions for the production of the used electricity. Therefore, eight energy efficient options have been included in the analysis to reduce the fuel consumption over the annual operational profile. In the workboat case study, the diesel generator sets are evaluated on an assumed operational profile for an aquaculture support vessel. Different types of feasible abatement options are included in the analysis. To meet the strict NO_x emission requirements (Tier III), the Selective Catalytic Reduction (SCR) can be found in every solution. Furthermore, the selection tool was tested on a scenario with stricter SO_x regulations that enforce a low-sulphur fuel. This also allows the implementation of PM reducing measures such as a Diesel Particle Filter (DPF). Furthermore, a LNG engine has been evaluated as a benchmark that shows good benchmark performance and meets the (NO_x and SO_x) emission requirements. The developed selection tool is more suitable for vessels with energy system configurations that have operational emissions that can be reduced by various type of abatement options.

10.2. Recommendations

Various recommendations can be made, because this decision problem is part of a complex overall ship design process. There are many other decision criteria such as dimensional criteria, safety aspects, changing regulations over time, fuel (infrastructure) availability or (port) incentives. It can be acknowledged that dimensional criteria of alternative technologies and fuels can determine their use in shipping. This dimensional information can be used, for example, in the pre-selection to exclude alternatives that exceed a certain threshold value. The used emission reduction effects of abatement options are obtained from literature, which can be defined for design conditions or given in a wide range of (uncertain) percentages. In this thesis, the reduction effects of abatement options are considered constant. If more information is available about the off-design performance, it may be useful to define the optimisation problem over different operational phases or to add uncertainty ([8]). It may be useful to simultaneously assess and select the energy systems, fuels and abatement options (e.g., [7], [86]). Changing the type of energy system can lead to a different set of abatement options and there is also a reverse design impact. It can also be useful to evaluate multiple different (sized) energy systems or hybrid configurations, and to select the appropriate abatement options. In that case, multiple benchmark emissions levels must be evaluated, and multiple sets of abatement options must be optimised in the optimisation algorithm.

Due to randomness and probability in the genetic algorithm used, it may be useful to compare the performance of the optimisation algorithm with other optimisation algorithms that can solve this optimisation problem. The created datasets contain numerous data and some decision parameters such as the costs and the emission reduction effects are estimated and may need to be adjusted. In addition, upstream (WTT) emissions are defined by a single emission factor (CO_2-eq). This emission factor can, if available, also be defined for other type of exhaust emissions similar to the operational exhaust emissions. The developed selection tool can perhaps be tested with other ship types, where other types of abatement options are suitable. For example, vessel types with more space on board or another operational profile that sail longer routes through different operational areas with different emission regulations.

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Nomenclature

Acronyms

CH_4	Methane
CO_2	Carbon Dioxide
CPP	Controllable-Pitch Propeller
DPF	Diesel Particulate Filter
DOC	Diesel Oxydation Catalyst
ECA	Environmental Control Area
EEDI	Energy Efficiency Design Index
EGR	Exhaust Gas Recirculation
ESS	Energy Storage Systems
FPP	Fixed-Pitch Propeller
GA	Genetic Algorithm
GHG	Green House Gas
HFO	Heavy Fuel Oil
IMO	International Maritime Organisation
KPI	Key Performance Indicator
LNG	Liquefied Natural Gas
LSMGO	Low Sulphur Marine Gas Oil
MADM	Multiple-Attribute Decision Making
MCDM	Multiple-Criteria Decision Making
MCR	Maximum Continuous Rating
MDO	Marine Diesel Oil
MEPC	Marine Environmental Protection Committee of IMO
MGO	Marine Gas Oil
NMVOC	Non-Methane Volatile Organic Compounds
NAVAIS	New, Advanced and Value Added-Innovative Ships
N_2O	Nitrous Oxides
NO_x	Nitrogen Oxides
NSGA	Non-dominated Sorting Genetic Algorithm
OR	Operation Research
PM	Particulate Matter
SCR	Selective Catalytic Reduction
SO_x	Sulphur Oxides
TRL	Technology Readiness Level
TTP	Tank To Propeller
URN	Underwater Radiated Noise
VOC	Volatile Organic Compounds
WTP	Well To Propeller
WTT	Well To Tank

Symbols

η_e	Effective efficiency	-
E	Emission quantity	[ton]
EF	Emission Factor	[g/kWh] or [g/kg]
h^L	Lower Heating Value	[kJ/kg]
n_e	Number of engines	[#]
p	Type of pollutant emission	[-]
P	Power	[kW]
per	Pollutant Emission Ratio	[kg/ton] or [g/kg]
sfc	Specific Fuel Consumption	[g/kWh]
spe	Specific Pollutant Emission	[g/kWh]

Appendices

A. Context NAVAIS and identified emissions

Section A.1 provides a short background of the NAVAIS project. Section A.2 gives an overview of the identified emissions and their relevance for the workboat and the road ferry.

A.1. Context NAVAIS project

The NAVAIS partnership contains 16 partners, including technology providers, technology integrators and technology users [28]. The NAVAIS project is funded under the European research and innovation programme Horizon 2020 [28] (ID: 769419). The overall objective of this Horizon 2020 programme is to ensure Europe's global competitiveness. The current thesis topic is related to the specific objective of the Horizon's (smart, green and integrated) transport challenge and is as follows: "to achieve a European transport system that is resource-efficient, climate- and environmentally- friendly, safe and seamless for the benefit of all citizens, the economy and society" [27]. The NAVAIS project has set the goal: "to maintain world leadership in complex, value-added and highly specialised vessels", by improving the efficiency of ship design and ship building [28].

The environmental performance of the ship designs will be evaluated and assessed with simulation models and calculation tools. In order to quantify the energy efficiency of the ship and the exhaust emissions over the operational profile, use will be made of SEECAT (Ship Energy Efficiency Calculation and Analysis Tool) in the NAVAIS project. SEECAT is a Modelica-based simulation model developed by Bureau Veritas. This model simulates the energy usage on board the ship for in time domain different energy flows and energy systems [80]. For the evaluation of discharges to the sea, prediction tools are being developed by the NAVAIS participants (MARIN) [69], specifically for the Underwater Radiated Noise (URN) for highly or lightly loaded propellers and thrusters.

A.2. Identified emissions

In the NAVAIS project, various emissions and the respective regulations have been evaluated on their applicability on the road ferry and the workboat for the Key Performance Indicator (KPI). More details on this work can be found in Work Package 4 Deliverable 4.1 (WP4-D4.1) [70]. This section first describes the non-relevant emissions and the relevant emissions.

A.2.1. Non-relevant emissions

These emissions are considered non-relevant, as generally their impact is small or because the respective regulations are not generally applicable to the considered vessel. The specific reasons for considering the identified emissions as not relevant are briefly paraphrased from Deliverable 4.1 [70]. The impacts 'noxious liquid substances' and 'harmful substances in packaged form' are not considered relevant, because they are applicable for vessels carrying chemicals. Pollution from garbage is not considered to be a matter of design or equipment, because it is mainly an operational issue for those on board of the vessel. 'Above water noise' is not considered relevant, because it is difficult to quantify a general maximum level due to the variety of different regulations, in particular locally varying regulations. Surface waves (wash) are not considered relevant, because general regulations are not available, but surface waves can also be reduced due to low wave-resistance ship designs. 'Electromagnetic radiation' is not considered relevant, because the respective regulations are related to operation.

Heat is not considered relevant, but the amount of released heat can be reduced by improving the energy efficiency. For commercial vessels, infrared light might be important from the perspective of detecting heat loss, however it is not considered a relevant emission in the NAVAIS project. The visible light in terms of navigation lighting and exterior lighting has to set at an intensity that complies with regulations. Therefore, the light emissions are not considered relevant for KPI setting. Ballast water is not considered relevant, because the road ferry and workboat usually only sail in one regional area. In that case discharge of untreated ballast water is allowed.

A.2.2. Relevant emissions

The following emissions are taken into account in the selection tool. The relevant exhaust emissions are the following: Nitrogen Oxides (NO_x), Sulphur Oxides (SO_x) , Particulate Matter (PM), Volatile Organic Compounds (VOC) and Carbon Dioxide (CO_2). Furthermore, Underwater Radiated Noise (URN) (a discharge to sea) is taken into account in the selection tool. These evaluated exhaust emissions and considered discharge to sea are described in Chapter 2 and summarised in Table 2.1.

The identified oil and sewage are considered relevant for the road ferry and workboat [53], but are not taken into account as described in Section 2.1. The effects of oil and sewage and the regulations are described below. The pollution by (fuel/bilge) oil is harmful for the marine ecosystem and can damage birds and the fur of marine mammals, furthermore oil spillages can also affect the air quality. Oil can be released into the marine environment due to (un)intentionally oil spillage. The prevention is regulated by different measures from MARPOL I [53]. A fuel tank arrangement with an aggregate fuel capacity of more than 1000 m^3 is regulated by Reg. 12A [53]. Furthermore, a filtering is required according Reg.14. The maximum (<15 ppm) concentration of oil residues (sludge) is regulated by Reg.15 [53]. Discharged sewage can cause harmful effects on the marine environment, due to the containment of bacteria etc. The prevention is regulated by Annex IV. Annex 4 states that every ship must be equipped with a sewage system and there must have connections for discharge into a reception facility [53]. The sewage system can be either a treatment plant, a sewage comminuting and disinfecting system or a holding tank [53]. The sewage may be discharged into the sea at least 12 miles off the coast when the ship has an approved treatment system. In the case of a comminuting system, the sewage can be discharged 3 miles from land.

B. Energy systems

This appendix describes the energy systems relevant for the selection tool and the considered vessels. Section B.1 gives an overview of the types and the used description structure. The energy systems are described in Section B.2 to Section B.6. The dataset with the performance data is given in Section F.1.

B.1. Types and description structure

The described energy systems are subsystems of the power plant and they are grouped as follows:

- Internal Combustion Engine (Section B.2);
- Energy Storage Systems (ESSs) (Section B.3, Section B.4);
- Fuel cell (Section B.6);

There are various other energy systems, which are not evaluated. For example, gas turbines, they have a significant higher fuel consumption than combustion engines. However, they can be for various reasons applied, e.g. in the case of high-speed ferries due their high specific power. Auxiliary energy systems (HVAC) or gas/oil boilers are also not considered.

Description structure

The energy systems are described in a uniform way and the following features of the energy systems are described:

a) Alternative specification, operational aspects, application and advantages.

b) Off-design performance and limitations such as ship-design impacts, costs, etc.

c) Compatibility (inclusive, exclusive, redundant) or interactions with other alternatives.

d) Demonstrations on road ferries, workboats or other ship types.

The weight and space performance of different energy systems (ESSs) are shown in Figure B.1. The sloping timeline indicates the required time to obtain the power, i.e. to discharge an ESS [32].

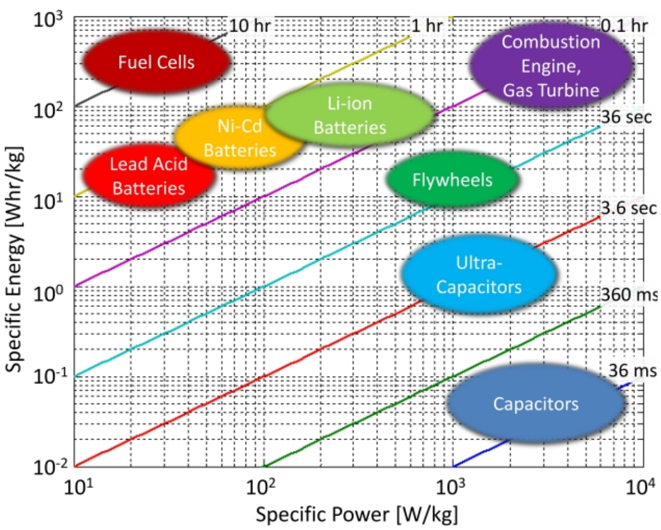


Figure B.1: Ragone plot of energy systems, the axes are logarithmic. Source: figure obtained from [32]

B.2. Internal combustion engines

a) Internal combustion (IC) engines can be classified based on different aspects: speed (low, medium, high), number of strokes per cycle (2 or 4), nature of thermodynamic cycle (Otto, Diesel, Dual combustion) or method of ignition (Spark Ignition (SI), Compression Ignition (CI)). In diesel (CI) engines the air is compressed so much that it heats up and ignites the fuel. Whereas in spark-ignition (SI) engines the fuel-air mixture is compressed and ignited [64]. IC engines are conventionally used [64], because they have a high efficiency and are cost effective [91]. They have high specific power compared with other energy systems (as shown in Figure B.1) and they can run on (diesel) fuels with high specific energy.

b) Due to fuel-air reaction in IC engines and nitrogen in the fuel, NO_x emissions can be formed at high temperatures [50]. Furthermore fuel-related emissions are created in the combustion process. Gas (SI) engines have higher investment costs and maintenance costs than diesel (CI) engines [46].

c) Diesel (CI) engines can also use alternative fuels such as biodiesel. Spark ignited engines can run on sole gaseous fuels such as LNG and hydrogen. Dual fuel (DF) engines can run both on diesel fuels and gaseous fuels (such as LNG) combined with a pilot fuel. Current diesel engines must be equipped with after-treatment systems (see Appendix D) to comply with IMO Tier III limits [26].

d) Diesel engines, specifically high-speed (4 stroke) engines are conventionally used in the road ferry and the workboat. The medium and lower speed engines are generally not applicable as they are too powerful and take up more space [50].

B.3. Batteries

a) A battery is a type of Energy Storage System (ESS). It stores chemical energy that can be converted into electric energy by an electrochemical reaction. Conventional batteries are for example lead-acid batteries [73]. Lead-acid batteries are relatively low in price, but they have a relatively low specific energy and power as shown in Figure B.1. Emerging battery technology is Lithium-Ion (Li-Ion) battery, it has high specific energy and high specific power compared to the other batteries (as shown in Figure B.1). There are various other battery technologies being developed, e.g. flow batteries [73].

b) However, batteries have relatively low specific power and specific energy. Furthermore, the investment costs of batteries are relatively high. Another matter of concern of (Li-Ion) batteries is the fire safety of the flammable electrolyte. However, this is improved by new chemistries and improved battery management systems [73]. Furthermore, batteries have a shorter lifetime than conventional diesel engines. This cycle life depends on the amount of capacity that is used (expressed by the depth of discharge (DOD) [32])

c) In hybrid configurations, the batteries allow engines to operate at the optimal operating point for a larger portion of time [24]. During peak loads the extra power can be obtained from the batteries (peak shaving) [24]. When the power demand is low the batteries can be charged (load levelling).

d) Lithium-ion batteries are applied on several (hybrid-electric or battery-electric) road ferries. The full electric road ferry Ampere is powered by Corvus lithium-ion battery pack (total 1000 kWh) and uses 150 kWh per trip (3nm) [34]. The reference road ferry 9819 uses NMC battery technology.

B.4. Ultracapacitor

a) An ultracapacitor stores electrical energy in an electric field. They have higher capacitance than capacitors. The ultracapacitor has high specific power and can be rapidly discharged and recharged compared with batteries [73]. They also have a higher lifecycle compared with batteries [73].

b) Ultracapacitors have high costs and the specific energy is lower than batteries.

c) The combination of ultracapacitors (supercapacitors) with batteries can improve the battery life, increase the power density and improve the power response time [73].

d) Supercapacitors are demonstrated in the passenger ferry Ar Vag Tredan [73] which operates on 2.5 nm trip. The recharging is done 28 times per day and it takes 4 minutes via a 400V supply [16].

B.5. Flywheel storage sytem

a) A Flywheel Storage System (FSS) consists of a disk (flywheel) which is connected via a shaft to a permanent magnet motor and a power converter [71]. The kinetic energy is stored in the flywheel, which can be accelerated ('charged') by the electric motor. And the flywheel can be decelerated ('discharged') by the electric motor functioning as a generator [71]. The flywheel has relatively high specific energy and specific power, as shown in Figure B.1. It has a high lifetime compared with other ESS types.

b) However, the design of a flywheel storage system is relatively complex [71] and additional safety cautions must be taken compared with other storage systems.

c) Flywheel energy systems can be applied in hybrid configurations.

d) As far as known, the flywheel is not yet applied in maritime industry [71].

B.6. Fuel cell

a) A fuel cell converts chemical energy directly into (DC) electrical energy [91]. It consists of an anode, a cathode and an electrolyte like a battery. However, in fuel cells the reactants are stored externally. The fuel cell stack can be supplied with a fuel and oxygen, the same as in an IC engine. Fuel cell technology is emerging such as Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC) or Proton Exchange Membrane Fuel Cell (PEMFC) [91]. Fuel cells generally have relatively high efficiency. Hydrogen (PEM) fuel cells have no harmful emissions and low noise signatures [91].

b) High temperature fuel cells such as a MCFC and SOFC require significant start-up time to heat up the fuel cell and have relatively slow response time [91]. However, PEMFCs have better start up time. Fuel cells generally, have relatively low specific power and relatively high investment costs. Hydrocarbon fuels can be used in fuel cells; however it has to reformed, which is a complex and expensive process [16].

c) For high power demand the MCFC and SOFC are more suitable and for lower power demand the PEMFC is more promising [16]. The high temperature MCFC (650-700°C) and SOFC (500-1000°C) can run on different fuels. Whereas the low temperature (60-85°C) PEMFC is only suitable for operating on purified hydrogen [91]. Fuel cells have the potential to be a supplementary technology to batteries and IC engines. Some high temperature fuel cells have the capability to run on hydrocarbon fuels. They can also operate directly on natural gas by converting methane into hydrogen with internal reformation [16].

d) Fuel cells are not yet extensively used in maritime transportation. However, they have the potential to replace diesel engines on the long term. PEMFC have been demonstrated on small passenger ferries for propulsion such as NEMO H_2 (60-70 kW) [91]. Concepts of road ferries with hydrogen (PEM) fuel cells are being developed [26].

C. Fuels

This appendix describes the types of considered fuels. Section C.1 gives an overview of the types and the used description structure. The fuels are described in Section C.2 to Section C.9. The dataset with relevant performance data of the fuels is given in Section F.1.

C.1. Types and description structure

The described fuels are grouped as follows:

- Residual products and diesel fuels (Section C.2);
- Natural gas (Section C.3);
- Biofuels (Section C.4);
- Methanol (Section C.5);
- Liquefied Petroleum Gas (LPG) (Section C.6);
- Hydrogen (Section C.7);
- Ammonia (Section C.8);
- Other fuels (Electricity, Wind & Solar Energy) (Section C.9).

Description structure

The fuels are described in a uniform way and the following features are described in more detail.

a) Alternative specification, production, storage and advantages.

b) Off-design performance and limitations such as ship-design impacts, costs, etc.

c) Compatibility (inclusive, exclusive, redundant) or interactions with other alternatives.

d) Demonstrations on road ferries, workboats or other ship types.

Fuel concepts with large space requirements can result in a loss of payload capacity and consequently a loss of revenue and profitability of the vessel [57]. The energy density of fuels can be expressed by the volumetric energy density and by the gravimetric energy density (as shown in Figure C.1).

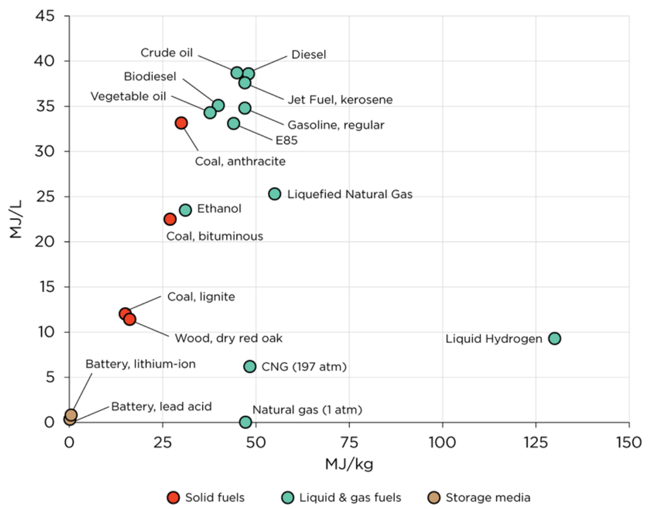


Figure C.1: Volumetric and gravimetric density of fuels and storage media. [40]

Influential decision-parameters
The choice of fuel is mostly an economic decision, however the emission (e.g. SO_x) requirements are leading to a forced shift in marine fuel types. There are many uncertainties in choosing the alternative fuel, such as the available fuel infrastructure and long-term availability of the fuels. It may be wise to reserve extra space for changing the fuel concept on board the ship to anticipate in the future on stricter emission requirements, technological developments and fuel prices. Modularity and flexibility in the ship design are therefore favourable to cope with future challenges or opportunities.

C.2. Residual products and diesel fuels

a) Residual products and diesel fuels are conventional (fossil-based) marine fuels. Distillates are the products of a refinery process of crude oil. Distillates can be gaseous fuels and diesel fuels such as Marine Diesel Oil (MDO) or Marine Gas Oil (MGO). Residual products (e.g. Heavy Fuel Oil (HFO)) contain products of what is left in the oil refining process [85]. There is a well-established infrastructure for conventional marine fuels. Furthermore, they are relatively low-in price and have high volumetric energy density as shown in Figure C.1.

b) The low-sulphur fuels have a higher price than high-sulphur fuels, due to the costs of the desulphurization process and increasing demand [64]. Although, when low-sulphur fuels are used in IC engines they still contribute to high (NO_x, PM, CO_2) emissions compared with alternative fuels.

c) To comply with the SO_x regulations it is possible to change or switch (see Section D.2) to low-sulfur fuels. Shipowners that want to operate on high-sulphur fuels need to install exhaust gas scrubbers (see Section D.11). Using conventional fuels in require NO_x-ECAs after-treatment technologies such as Selective Catalytic Reduction (SCR) (see Section D.10 to comply with Tier III requirements.

d) Residual products and diesel fuels are the most used fuel types in maritime shipping.

C.3. Natural gas

a) Natural gas (NG) contains mainly methane (CH_4) and other hydrocarbons [55], where the energy content depends on the composition. The energy density of NG can be increased and thereby reducing the volume, as shown in Figure C.1. This can be achieved by compressing (Compressed Natural Gas (CNG)), cooling (Liquefied Natural Gas (LNG)) or adsorb/dissolve NG in other media. Absorbed NG is produced to achieve the equivalent energy density of CNG and has the advantage that it requires less energy to cool or to hold pressure. LNG is stored as liquid at cryogenic temperature of - 162°C at atmospheric pressure. CNG is stored as a pressurised gas at high pressure of about 250 bars. NG has a low carbon content and contains practically zero sulphur (low SO_x emissions). Furthermore, the NO_x emissions are reduced compared to diesel fuel.

b) The challenges with NG are the required pressure, insulation and gas handling equipment, which can have a significant design impact and significant investment costs [64]. Taking the space requirements of cylindrical LNG tanks into account, LNG tanks take up three times the volume of the equivalent amount of energy stored in diesel [26]. LNG has the potential risk of methane slip, which contributes to GHG effect. However, engines are developed, in which the methane slip is reduced [64].

c) Spark Ignition (SI) gas engines can be used for operating on NG. Dual Fuel (DF) engines can run on both conventional fuels and NG (by using a pilot fuel). The methane slip can be reduced by aftertreatment systems such as oxidation catalysts [77].

d) The LNG infrastructure is expanding [26]. The impact of LNG on space can be a challenge for the workboat and road ferry. There are some LNG-road ferries operating or being developed.

C.4. Biofuels

a) First generation biofuels can be produced from food crops or animal fats [55]. The second generation and third generation biofuels can be produced (e.g. Fischer-Tropsch) from various types of industrial waste and plant-based or animal-based biomass [55]. For example Hydrotreated Vegetable Oil (HVO) or Dimethyl Ether (DME). Engine manufacturers often certify their engines for use of biodiesel or blends (e.g. B20) [64], if it does not lead to too much fuel system degradation [64]. Biofuels typically have lower CO_2 emissions than conventional marine fuels.

b) The production of (first generation) biofuels can be in conflict with natural resources [64]. They can have high production costs ([64], [26]). Furthermore, thorough cleaning and gas freeing of fuel tanks are necessary when using high blends [55]. Biodiesel has a lower energy content than diesel [77] and it can lead to an increase of NO_x emissions [55].

c) Most biofuels are drop-in fuels or require minimal adjustments of the engine [55]. Biodiesels such as DME can be used in CI engines and DF engines [64]. Gaseous biofuels can be used in SI engines and DF engines. The NO_x emissions can be reduced by emission abatement options.

d) Ferry operators such as BC ferries are operating on blends of biofuel fleetwide.

C.5. Methanol

a) Methanol (CH_3OH) is an alcohol fuel and can be produced from various sources such as natural gas, coal, biomass (e.g. black liquor), CO_2 and hydrogen [26]. Currently, natural gas is the most important source of methanol [26]. Methanol is liquid at ambient temperatures at atmospheric pressure [91]. Methanol reduces CO_2 emissions and PM emissions can also be reduced [26].

b) The volumetric energy density of methanol is lower than diesel fuels. Methanol has a low calorific fuel and therefore the specific fuel consumption is significant compared to diesel fuel [36]. Methanol has a low flashpoint and therefore extra safety cautions need to be taken [26]. Methanol raises the possibility of corrosion [46].

c) Methanol has a high hydrogen content and can be used as hydrogen carrier for fuel cells [26]. The expected NO_x reductions in gas engines are significant, but for Tier III and therefore have to be combined with abatement options [26].

d) Methanol has been demonstrated on a large cruise ferry equipped with a dual fuel engine [64]. Methanol has also been demonstrated in fuel cells.

C.6. Liquefied Petroleum Gas (LPG)

a) Liquefied Petroleum Gas (LPG) includes mixes of propane (C_3H_8) and butane (C_4H_{10}) in liquid form. LPG is a by-product of oil production/refinery [26]. LPG is gaseous under ambient conditions and can be stored as liquid at 8.4 bar [26]. LPG contains no sulphur and the combustion results in lower CO_2 emissions. Furthermore, the PM emissions and technology-related NO_x emissions can be reduced.

b) Safety cautions need to be taken, because propane is heavier than air and presents an explosive safety hazard if it is accumulated [64]. Potential LPG slip needs to be considered, because propane and butane have three to four times higher global warming potential than CO_2 emissions [26].

c) A four stroke gas engine using LPG is expected to reduce the NO_x emissions and to be in compliance with Tier III requirements [26]

d) LPG requires high equipment costs and fuel-infrastructure (bunkering facility) needs to grow.

C.7. Hydrogen

a) Hydrogen (H_2) can be produced (on board) by electrolysis of water or reforming of natural gas or various other hydrogen carriers [64]. Electrolysis uses electricity to split water into hydrogen and oxygen, reforming is a chemical synthesis for producing hydrogen. Hydrogen can be stored liquid, compressed or in metal hydrides and chemical compounds [91]. Liquid Hydrogen (LH_2) requires cryogenic storage at - 253°C at atmospheric pressure [64]. Hydrogen can also be stored pressurised at 350 or 700 bar [91]. For long ranges, hydrogen (fuel cells) may provide a good alternative. Hydrogen in fuel cells has no harmful emissions, however, if it is used in IC engines it still can lead to NO_x emissions

b) Hydrogen produced from natural gas has a large (upstream) carbon footprint ([26], [36]). Hydrogen is costly to produce, transport and store [64]. Hydrogen has a low volumetric storage density. Hydrogen tanks need to be very well insulated and safety cautions need to be taken [64].

c) Hydrogen can be used in IC engines and fuel cells.

d) Concepts of hydrogen powered road ferries are being developed [26]. However, hydrogen power is less suitable for the workboats, due to limited space and endurance requirements.

C.8. Ammonia

a) Ammonia (NH_3) can be produced by the catalytic reaction between nitrogen and hydrogen (see Section C.7). Ammonia is liquid at temperature of -33 °C at atmospheric pressure [91]. An advantage of ammonia is that it can be used as a hydrogen carrier. Moreover, ammonia contains no carbon and therefore has no CO_2 emissions.

b) Ammonia has a relatively low volumetric energy density [91]. Another disadvantage of ammonia is the potential ammonia slip which is toxic to human and polluting to the environment [91].

c) Ammonia can be used in IC engines, either in Compression Ignition engine together with a diesel pilot fuel or in Spark Ignition engine. Furthermore, ammonia may be used in fuel cells such as SOFC.

d) Ammonia is not yet widely demonstrated and waits further technological developments.

C.9. Other fuels (electricity, wind energy, solar energy)

- Electricity is an energy carrier and can be supplied on board by generators powered by engines or supplied from Energy Storage Systems (ESS) (see Appendix B. The ESS can be charged with electricity generated on board of the ship or by charging electricity from the electricity grid in the port. The upstream emissions for producing the electricity can be significant.

- Wind energy is a 'free' renewable energy resource. Wind-assisted propulsion devices recover the wind energy and they are described in Section E.9.

- Solar Energy is a 'free' renewable energy resource. Solar panels extract solar energy and they are described in Section E.10

D. Emission-reducing options

This appendix describes the emission-reducing options. Section D.1 gives an overview of the types and the used description structure. The emission-reducing options are described in the Section D.2 to Section D.13. The dataset with relevant performance data is given in Section F.1.

D.1. Types and description structure

The emission-reducing options are grouped by the three main strategies as recognised by CIMAC Exhaust Emission Control [85] to reduce and control the exhaust emissions. Furthermore, measures are given to reduce Underwater Radiated Noise (URN) (Section D.13).

- Fuel related (Section D.2 and Section D.3).
- Primary methods (related to engine modifications):
  - Modification of combustion (Section D.4);
  - Modification of air intake conditions, e.g. Humid Air Motor (HAM) (Section D.5);
  - Water injection into the cylinder, e.g. Direct Water Injection (DWI) (Section D.6);
  - Exhaust Gas Recirculation (EGR) (Section D.7).
- Secondary methods (aftertreatment systems):
  - Diesel Oxidation Catalyst (DOC (see Section D.8)
  - Particle filters, e.g. Diesel-Particulate Filter (DPF) (Section D.9);
  - Selective Catalytic Reduction (SCR) (Section D.10);
  - Exhaust Gas Scrubbers (EGS) (see Section D.11);
  - Carbon Capture System (CCS) (Section D.12).

Description structure

The following features of the abatement options are described:

a) Alternative specification, operational aspects, application and advantages.

b) Off-design performance and limitations such as ship-design impacts, costs, etc.

c) Compatibility (inclusive, exclusive, redundant) or interactions with other alternatives.

d) Demonstrations on road ferries, workboats or other ship types.

D.2. Alternative fuel or multiple fuels

a) Changing the fuel concept to alternative fuels (as described in Appendix C) forms an abatement option. To reduce fuel costs, a ship with an operational area that covers non-SECA and SECA can operate on multiple fuels (on low-sulphur (0.1 %S) compliant fuel and a global (0.5 %S) complaint fuel. If multiple fuels are considered, two methods can be applied, change-over of the fuels or segregated tanks.

b) A disadvantage of the change-over method is that enough time is needed to flush out all the high sulphur fuel [102]. Fuel changeover must be controlled and requires a certain fuel viscosity, which can be achieved by controlling the temperature of the fuel.

c) Fuel switches between high-sulphur fuels to low-sulphur fuels can lead to problems in engines normally operating on high-sulphur fuels. However due to global sulphur cap, this difference in sulphur content in the fuel and associated effects are reduced.

d) Fuel change-over or segregated tanks are not relevant for the considered vessels, because the road ferry and the workboat operate in one operational area (with one strict sulphur limit).

D.3. Fuel water emulsion

a) In Fuel Water Emulsion (FWE) is the fuel mixed with accurately dosed (distilled) water (e.g. 30%) prior to injection into the combustion chamber [77]. FWE leads a better distribution of fuel in the chamber, and more complete combustion [77]. FWE technology reduces NO_x and PM emissions.

b) A drawback of FWE systems is that corrosion can occur in the fuel systems, the severity of this corrosion depends on water to fuel ratio [77]. Furthermore, the fuel consumption is increased [99].

c) FWE is not useful to combine with other abatement options that add water to the combustion.

d) FWE can be applied in any type of engine, however it is not often used.

D.4. Internal Engine Modifications (IEM)

a) Internal Engine Modifications (IEM) involve changes to the combustion processes. It includes measures such as slide valves and other advanced modifications. These IEM measures can be intended to increase energy efficiency and/or to reduce exhaust emissions. Miller cycle is an cycle implemented in the combustion cycle with either early or late intake valve closing during the compression stroke [46]. It improves the reduction of NO_x emissions and at the same time has a high cycle efficiency [99].

b) There are various trade-offs such as the diesel dilemma (see subsection 2.2.2), so either a reduction of NO_x emissions leading to an increase of PM emissions or vice versa.

c) Due to the variety of modifications, these modifications have to be determined engine specific.

d) These types of modifications are often incorporated into the new engine designs by the engine manufacturer [77]. Therefore, this measure is not further considered relevant for the selection tool.

D.5. Modification of air-intake conditions

a) The Humid Air Motor (HAM) system uses a humidifier to modify the air-intake conditions. A HAM can use water and it allows the absorption of heat generated in the compression chamber. Thereby it reduces the combustion air temperature and the thermal NO_x formation [77].

b) A HAM may under-perform at low load, if there may be not enough heat to evaporate the required volume of water [77]. It can also be difficult to control the humidity under varying loads of the engine [77]. Is not able to reduce the NO_x emissions to Tier III level.

c) HAM is a good alternative to DWI, it is not affected by the sulphur content of fuel [77].

d) The humidifier requires a large space on board of the vessel.

D.6. Water injection into the cylinder

a) Direct Water Injection (DWI) injects water directly into the combustion chamber via a separate nozzle [46]. The DWI can reduce the combustion temperature and decreases the NO_x emissions [46].

b) The DWI system reduces the engine efficiency and increases the fuel consumption.

c) Water injection can be combined with the EGR to comply with Tier III NO_x emissions [77]. Water-addition methods such as DWI and HAM are a set of redundant abatement options [5].

d) The DWI does not require much extra space and is therefore suitable for smaller engines [46]. However, there are better alternatives to reduce NO_x emissions.

D.7. Exhaust Gas Re-circulation (EGR)

a) The EGR is a modification of the diesel engine. In the EGR, a portion (often 20% [38]) of the exhaust gases is (filtered,) cooled and recirculated into the charge air of the engine [77]. The cooling can be done by the compressed airflow [85]. The EGR process decreases the cylinder (peak) temperature and thereby reduces the amount of NO_x emissions. The EGR is relatively compact compared with other NO_x reducing measures such as the SCR.

b) A side effect of EGR is that the engine works less efficient, which increases fuel consumption and generates more soot (PM) emissions [77].

c) The EGR can only be used with low sulphur (less than 0.2 %) fuels. High-sulphur fuels (e.g. HFO) lead to problems with fouling and corrosion of the engine components. Unless a SO_x scrubber is installed [55] before the EGR. The EGR can be combined with a SCR or a DPF to reduce PM emissions.

d) The EGR is suitable to apply on high speed marine diesel engines.

D.8. Diesel Oxidation Catalyst (DOC)

a) A Diesel Oxidation Catalyst (DOC) oxides hazardous pollutants (carbon monoxide (CO) and hydrocarbons) into CO_2 and H_2O [38]. The DOC also reduces PM emissions, through the oxidation of soluble substances [38]. It oxides nitric oxide (NO) to nitrogen dioxide (NO_2).

b) A DOC can increase backpressure on the engine and thereby increase energy consumption.

c) The NO_2 is increased by the DOC, which supports the performance of other aftertreatment systems such as the SCR and DPF. The DOC, is however, only appropriate for diesel with low sulphur content, because the oxidation reaction can create sulfate particulates (PM).

d) The DOC can be combined with other aftertreatment systems.

D.9. Diesel Particulate Filter (DPF)

a) A Diesel Particle Filter (DPF) is efficient in the filtering and collection of PM from the exhaust gasses. The DPF periodically burns PM off during the filter regeneration process [77]. There are two types of DPF: either active or passive. Active DPF use fuel burners for the regeneration and passive DPF use catalysts to regenerate [77].

b) A drawback is that the collected diesel particulate must periodically burned to prevent filter clogging and increase in backpressure on the engine [77].

c) The DPF is often combined with a DOC, where the DOC optimises the exhaust gasses for the DPF. DPF are effective only on engines using low sulphur fuel and most efficient when the fuel sulphur content is less than 0.05% ([77], [38]).

d) DPF are applied in diesel vehicles [38] and in inland waterway vessels [55].

D.10. Selective Catalytic Reduction (SCR)

a) Selective Catalytic Reduction (SCR) uses a catalyst to convert NO_x emissions into nitrogen (N_2) and water (H_2O) by injecting an additive. The additive can be ammonia (NH_3) or urea ($CO(NH_2)_2$) or a mix of water and urea (Adblue) [77]. Urea is generally more practically to store on board. The reactor of the SCR houses the catalyst elements and this catalyst can be made from various ceramic materials. The additive is accurately dosed to improve the NO_x reduction ([77], [38]). The SCR is modern Tier II diesel engines the most promising method to meet the strict Tier III limit [38].

b) A potential drawback of SCR is ammonia slip, if not all ammonia (NH_3) can react, ammonia slips occurs [77]. Furthermore, significant space is required for the catalyst elements, storage tanks for the additives (ammonia and urea). There are also relatively high consumable costs for the additives such as urea [85]. Furthermore, the efficiency of the catalyst decreases with time, due to thermal load and declining amount of catalyst [55].

The additive is fed through a catalytic converter at temperatures between 300 to 350 °C [77]. The temperature range is needed to avoid clogging by the formation of ammonium sulphate [99].

c) The lifetime of the catalysts depends on the sulphur (S) content of the fuel and can vary from 5 year to longer periods and the other components can range from 15-25 years [55]. The catalytic converter of the SCR can be placed between the engine and turbocharger to ensure that the temperature is high enough for the required temperature window [77]. The SCR is sometimes combined with an Ammonia Slip Catalyst (ASC) after the SCR, that can reduce the NH_3 slip and the CO emissions [38].

d) SCR is a viable abatement option to achieve Tier III NO_x requirements ([77], [46]).

D.11. Exhaust Gas Scrubber (EGS)

a) An Exhaust Gas Scrubber (EGS) reduces SO_x (and PM) emissions. It scrubs the exhaust gas stream by exposing it to an medium/absorber, either water (with or without additives) or a dry chemical [77]. There are two main types of SO_x scrubbers: either wet scrubbers or dry scrubbers. Wet-scrubbers can use seawater or freshwater and dry scrubbers uses a dry chemical. Wet scrubber configurations can be divided into closed loop, open loop or hybrid systems [55]. Seawater scrubbers utilises the alkalinity in the seawater to neutralise the sulphur oxides in the exhaust gases [55]. A closed loop scrubber uses an alkaline chemical such as as sodium hydroxide to neutralise the sulphur [55].

b) The effectiveness of an open loop scrubber depends on the alkalinity [46]. A drawback of a scrubber, is the generated sludge that needs to be stored. Furthermore, the (treated) washwater including acidic oxides may need to be stored or discharged, which can acidify the marine environment in sheltered waters [88]. In addition, some scrubbers may produce backpressure leading to higher fuel consumption [99]. The dimensions (volume and weight) of a scrubber can be significant [46].

c) Wet SO_x-scrubbers must be installed after a WHR, as the wet SO_x-scrubber cools the exhaust gasses [56]. Furthermore, it may require a re-heater if the wet scrubber is combined with a SCR [56].

d) Scrubbers are not applied on the considered road ferry and workboat. However, scrubbers can be useful for larger vessels operating on open seas and in SO_x-ECAs.

D.12. Carbon Capture System (CCS)

a) The Carbon Capture and Storage (CCS) system is able to capture CO_2 emissions. This CCS system consists of a separation part for separating the CO_2 from the exhaust gas and a liquefaction part for liquefying the CO_2 and requires cryogenic tanks for storage.

b) However, the CCS is very expensive and has a significant space impact on the vessel.

c) The CCS may be combined with other abatement options/ aftertreatment systems such as exhaust gas (SO_x) scrubbers.

d) Due to its dimensions and costs it is not considered relevant for the road ferry and workboat.

D.13. Underwater Radiated Noise (URN) mitigating measures

a) There are various measures that can help to reduce URN [41]. These measures are the following: selecting other energy systems with less noise, hull coatings and maintenance measures such as propeller polishing. Cavitation can be reduced by propeller optimisation or by installing Propulsor Improving Devices (PIDs). An air injection system can reduce cavitation erosion, or bubble curtains can reduce the propagation of sound [41]. Furthermore, the on-board machinery noise can be reduced by adapting the location or enclosing the equipment [41]. The engines can be elastic coupled or mounted on vibration isolators to the foundation [90].

b) An URN reducing measure can reduce the propeller efficiency, e.g. an air injection system [41].

c) The technical measures to reduce URN that are related to the propulsors may be redundant or have to be modelled and tested together.

d) Reduction of URN is gaining more attention, for example in the road ferry sector [41].

E. Energy-efficient options

This appendix describes the energy-efficient options. Section E.1 provides an overview of the types of energy-efficient options and the used description structure. These alternatives are described in Section E.2 to Section E.12. The dataset with the relevant performance data is given in Section F.1.

E.1. Types and description structure

This section gives an overview of the abatement options that have a reduction effect on the energy consumption of different energy systems. The energy-efficient options are grouped as follows:

- Ship design (Section E.2, Section E.3, Section E.4, Section E.5;
- Power and propulsion system (Section D.4, Section E.6, Section E.7, Section E.8);
- Alternative energy sources (Section E.9, Section E.10);
- Other technical measures (Section E.11);
- Operational measures (Section E.12).

Description structure

The energy-efficient options are described in a uniform way and the following features of the energy-efficient options are described:

a) Alternative specification, operational aspects, application and advantages.

b) Off-design performance and limitations such as ship-design impacts, costs, etc.

c) Compatibility (inclusive, exclusive, redundant) or interactions with other alternatives.

d) Demonstrations on road ferries, workboats or other ship types.

E.2. Lightweight construction

a) A lightweight construction (materials such as aluminium or composite) of the hull or superstructure can lead to a lighter displacement compared to a conventional steel construction. A lighter displacement enables higher speeds and contributes to a reduction of frictional resistance [1].

b) Lightweight constructions encounter generally more fabrication difficulties than ships with conventional materials and therefore entail higher construction costs.

c) Lightweight construction is compatible and, in some cases, favourable with other alternatives. The extra weight, e.g. using batteries, can lead to a desire to reduce the structural weight.

d) Many modern ferries (such as the road ferry M/F Ampere [34]) are made from aluminium.

E.3. Computational optimisation of hull form and superstructure

a) The hull form can be hydro-dynamically evaluated and optimised by doing Computational Fluid Dynamic (CFD) assessments or model tests [63]. In a CFD assessment, the hull can be optimised to reduce the ship's resistance (and energy consumption) for the design speed, but also for off-design conditions. Furthermore, the flow into the propeller can be optimised and the appendage drag can be reduced [63]. The aerodynamic resistance of the superstructure can be evaluated and optimised by doing CFD computations or wind tunnel tests.

b) CFD assessments are costly and the reduction depends on the vessel characteristics and profile.

c) Hydrodynamic optimisation is compatible with any other alternative, however the considered Propulsion Improving Devices (PID) must be taken into account in the CFD assessment.

d) CFD is done if the ship and operational profile is such that a potential reduction can be gained. For the double-ended ferry there is a trade-off for the flow performance between the stern and bow [63].

E.4. Hull coating

a) The hull surface can be treated with a hull coating that reduces corrosion and reduces fouling on the hull and thereby reduces frictional resistance [41]. There are various types of coatings and there has been forced shift towards non-toxic and non-biocide coatings. An advantage of reducing fouling is that it improves the water flow and it reduces turbulence-related URN [41].

b) The potential saving in fuel consumption is high for ships that have large wetted hull surfaces and sail long distances. The ship must be docked and re-coated every five year.

c) Hull coatings are compatible with any non-redundant alternative.

d) Hull coatings are essential for any vessel types with regard to hull maintenance.

E.5. Air cavity lubrication

a) An air cavity lubrication system creates an air cavity (chamber) over the flat bottom of the ship. Air lubrication reduces the wetted surface area and skin friction resistance [1] and it is especially interesting for ships with low Froude numbers [25]. Air lubrication can help to reduce fouling growth.

b) The air cavity lubrication system requires additional systems (such as pumps) and modifications to the hull. The air cavity lubrication system is less effective at high speeds and rough waves. The stability of the air cavity then becomes difficult to maintain [1].

c) The air can flow into the propeller from the chamber and can negatively affect the efficiency and URN of the propeller ([1],[25]).

d) Air lubrication might be suitable for single-ended ferries.

E.6. Waste Heat Recovery (WHR) system

a) The thermal energy available from exhaust gasses can be partly recovered by a Waste Heat Recovery (WHR) system. It generally consists of exhaust gas boilers and turbo-generators [25]. The recovered thermal energy can be converted into electrical energy or mechanical energy.

b) The WHR system has a relatively low efficiency and its potential depends on the engine efficiency [25]. The WHR is an extra system on board and requires maintenance, however the fuel costs are slightly reduced due to increased energy efficiency.

c) The WHR is compatible with after-treatment systems such as Selective Catalytic Reduction (SCR) [56]. Wet-SO_x scrubbers, however, must be installed after the WHR [56], because the wet scrubber cools the exhaust gasses.

d) WHR systems are also being developed for engines with smaller engine power output. WHR systems are also installed on road ferries, e.g. LNG or battery-electric (MF/Ampere) configurations.

E.7. Propulsion Improving Devices (PIDs)

a) A Propulsion Improving Device (PID), also referred to as a Energy Saving Device (ESD) can be intended to improve wake inflow to the propeller or utilising the rotational energy behind the propeller. Thereby the PID can reduce the cavitation (and URN) or improve the propeller efficiency [25]. PIDs can be generally classified into devices located before the propeller (e.g. wake-equalising devices or pre-swirl devices), at the propeller (cap) and after the propeller (post-swirl devices).

b) Some PIDs are less effective at off-design or in the case of correct designed hulls ([1],[25]). CFD assessments are required to prevent additional resistance, structural and vibration problems [1].

c) Combinations of PIDs or hull form modifications have to be modelled or tested together [14].

d) PIDs are more relevant for ships that sail long distances at the same operational conditions.

E.8. Propeller optimisation

a) Propellers can be optimised in terms of efficiency and cavitation performance for off-design conditions and/or design speed. A higher efficiency can be achieved by larger propeller diameters with fewer blades operating at lower rotational speed [1]. The cavitation performance (which affects URN) can be improved by reducing the load per propeller, e.g. by increasing the blade area.

b) There exists a trade-off between open water efficiency and cavitation performance ([47],[16]). Advanced propeller blade sections can provide high efficiency and good cavitation performance [41].

c) Optimisation of the propeller must be compatible with the considered PID and the ship hull. Therefore, they must be modelled and tested together.

d) Propeller optimisation and advanced propeller design can be suitable for existing container vessels that operate, e.g. at slow steaming conditions [24].

E.9. Wind energy recovery systems

a) The system types varies from sails, wings, kites to Flettner rotors. Flettner rotors, for example, can generate a propulsive force perpendicular to that of the wind [1]. Wind recovery systems can be used to assist the main engine and thereby reducing the energy consumption.

b) The fuel savings depend on the ship design, vessel speed, the operating envelope including wind conditions. Furthermore, these systems require enough deck space on board of the vessel [1].

c) Combinations of different types are often not effective, because they interact with each-other [1].

d) These systems are generally more suitable for ships with sufficient space on deck and for ships with an operational profile that covers long distances with favourable wind conditions.

E.10. Solar panels

a) Photovoltaic cells extract the solar energy and convert it directly into electricity [73]. Solar cells can contribute for a relatively small part to the total energy consumption and are mainly useful for supplementing auxiliary loads such as HVAC [1]. The efficiency is improved, and the costs of solar cells are reduced, making them more attractive for use on ships with limited space [73].

b) The energy yield by solar panels is rather small. Therefore, the applicability of solar panels is limited by the available space on board of the ship.

c) Solar radiation is very variable and therefore batteries can be useful to store the energy during supply peaks. This stored energy can then be used later when needed.

d) Solar panels are applied to road ferries with a closed superstructure, which normally have ample space for solar panels. For example, the TESO-ferry, as shown in Figure 8.2.

E.11. Other technical measures (e.g. lighting and control strategies)

Energy-efficient light (LED) systems can be applied to reduce the auxiliary energy consumption. Energy-saving lighting is increasingly adopted at new ships [75]. Furthermore, hybridisation/electrification can lead to a reduction of total ship fuel consumption. It is suitable for vessels with large fluctuations in power demand [24]. The potential of hybridisation depends on the vessel operational profile, power requirements, etc. There are various control strategies for different power and propulsion systems [35].

E.12. Operational measures

The operational measures are not taken into account in the selection tool as they are less relevant for the ship design. For example, speed reduction can reduce the fuel consumption, because the fuel consumption increases a cubic function of vessel speed [24]. Furthermore, operational measures such as autopilot adjustments, weather routing or maintenance measures are not considered. If the work boat has DP and if accuracy is not necessary, green Dynamic Positioning (DP) can be used, as this can lead to a reduction in energy consumption. In case of the double-ended ferry with a CPP the appendage drag can be reduced by feathering the forward CPP [63]. In case of double-ended ferry with a FFP, the drag of the forward FPP can be reduced by turning the FPP with small revolutions [63].

F. Datasets

The selection tool consists of two separate Excel datasets. One dataset contains the relevant data of predefined combinations of energy systems (ES) and reference fuels. The other dataset contains the relevant data of abatement options (AO) including fuels. First the data structure and data sources are given in Section F.1. Thereafter, the datasets of the energy systems and the abatement options are presented. Finally, Section F.2 describes the consideration of various decision parameters.

F.1. Data structure and data sources

The dataset of the energy systems are first presented. This sheet contains data of the six predefined engine-fuel combinations and other type of energy systems relevant for the selection tool. This dataset contains columns that read out the system specific data supplemented by the user in the user-interface. Thereafter the dataset of the abatement options is given. This sheet is divided into the following categories of abatement options as stated in the third column. The first group is fuel. The second group includes emission-reducing (er) options (including Primary methods (PM), Secondary methods (SM) and Underwater Radiated Noise (URN) related measures). The third group includes energy efficient (ee) options (Ship Design (SD) and Propulsion Improving Devices (PID)).

The dataset structure for the energy systems and the abatement options is broadly as follows.

- Alternative applicable to workboat and/or road ferry;
- Measure applicable to emission source: main (m), auxiliary(a) or all power supply(all);
- Technology Readiness Level (TRL);
- Environmental performance for the emissions (NO_x, SO_x, PM, VOC, CO_2, URN);
- Fuel costs, investment costs and maintenance costs of alternatives.

Data sources

Studies on technologies and fuels have been reviewed in this thesis in order to gain knowledge and to collect data for the selection tool. The data in the datasets are obtained from various studies on abatement options (e.g. [1], [11], [12], [25], [55])). The costs in the dataset are based on numbers for engines with smaller power, which have relatively higher unit costs due to costs which are similar/fixed for other power ranges.

- Energy systems
  - Costs and emission factors: [12], [55], [86], [87], [95].
- Fuels:
  - Costs and emission factor or reduction effects: [26], [29], [36], [55], [82], [92].
- Abatement options:
  - Emission reduction effects and costs: [6], [24], [46], [52], [55], [86], [101], [99], [102].

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	**Energy systems and compatibility with ships**											**Engine emission factors**							
2	**Type Energy System**	**Category Energy System**	**Emissions defined for reference fuel:**	**TRL**	**Electric ferry: applicabl e? [0/1]**	**Workbo at: applicab le? [0/1]**	**Applicable to ship and TRL**	**Total capacity of system [value]**	**Capacit y [unit]**	**System selected in 'Input'**	**Load factor [%]**	**SFC [g/kWh]**	**NO_x per [g/kg fuel] or [kg/ton]**	**NO_x spe [g/kWh]**	**%S content [%m/m]**	**SO_x per [g/kg]**	**SO_x spe [g/kWh]**	**PM per [g/kg]**	**PM spe [g/kWh]**
3	**HS-4s Diesel (CI) engine (Tier II)**	Main engine	LSMGO	9	0	1	1	1410	kW	1	25%	208.0	34.6	7.2	0.1	2	0.42	7	1.5
4	**HS-4s Diesel (CI) engine (Tier II)**	Main engine	LSMGO	9	0	1	1	1410	kW	1	50%	203.0	26.1	5.3	0.1	2	0.41	5	1.0
5	**HS-4s Diesel (CI) engine (Tier II)**	Main engine	LSMGO	9	0	1	1	1410	kW	1	75%	201.0	26.4	5.3	0.1	2	0.40	1.5	0.3
6	**HS-4s Diesel (CI) engine (Tier II)**	Main engine	LSMGO	9	0	1	1	1410	kW	1	100%	209.0	24.9	5.2	0.1	2	0.42	3	0.6
7	**HS-4s Gas (SI) engine**	Main engine	LNG	9	0	1	1	1410	kW	0	25%	172.6	6.2	1.1	0.0015	0.03	0.01	0.7	0.1
8	**HS-4s Gas (SI) engine**	Main engine	LNG	9	0	1	1	1410	kW	0	50%	168.5	4.7	0.8	0.0015	0.03	0.01	0.5	0.1
9	**HS-4s Gas (SI) engine**	Main engine	LNG	9	0	1	1	1410	kW	0	75%	166.8	4.7	0.8	0.0015	0.03	0.01	0.15	0.0
10	**HS-4s Gas (SI) engine**	Main engine	LNG	9	0	1	1	1410	kW	0	100%	173.5	4.5	0.8	0.0015	0.03	0.01	0.3	0.1
11	**HS-4s Dual fuel (DF) engine**	Main engine	LNG & pf MDO	7	0	0	0	1410	kW	0	25%	176.8	33.6	5.9	0.1	2	0.35	2.8	0.5
12	**HS-4s Dual fuel (DF) engine**	Main engine	LNG & pf MDO	7	0	0	0	1410	kW	0	50%	172.6	25.3	4.4	0.1	2	0.35	2	0.3
13	**HS-4s Dual fuel (DF) engine**	Main engine	LNG & pf MDO	7	0	0	0	1410	kW	0	75%	170.9	25.6	4.4	0.1	2	0.34	0.6	0.1
14	**HS-4s Dual fuel (DF) engine**	Main engine	LNG & pf MDO	7	0	0	0	1410	kW	0	100%	177.7	24.1	4.3	0.1	2	0.36	1.2	0.2
15	**MS-4s Diesel (CI) engine (Tier II)**	Main engine	LSMGO	9	0	0	0	1410	kW	0	25%	215.0	36.0	7.7	0.1	2	0.43	9	1.9
16	**MS-4s Diesel (CI) engine (Tier II)**	Main engine	LSMGO	9	0	0	0	1410	kW	0	50%	200.0	28.1	5.6	0.1	2	0.40	6	1.2
17	**MS-4s Diesel (CI) engine (Tier II)**	Main engine	LSMGO	9	0	0	0	1410	kW	0	75%	189.0	28.4	5.4	0.1	2	0.38	1.5	0.3
18	**MS-4s Diesel (CI) engine (Tier II)**	Main engine	LSMGO	9	0	0	0	1410	kW	0	100%	193.0	26.9	5.2	0.1	2	0.39	3	0.6
19	**MS-4s Gas (SI) engine**	Main engine	LNG	9	0	0	0	1410	kW	0	25%	178.5	6.5	1.2	0.0015	0.03	0.01	0.9	0.2
20	**MS-4s Gas (SI) engine**	Main engine	LNG	9	0	0	0	1410	kW	0	50%	166.0	5.1	0.8	0.0015	0.03	0.00	0.6	0.1
21	**MS-4s Gas (SI) engine**	Main engine	LNG	9	0	0	0	1410	kW	0	75%	156.9	5.1	0.8	0.0015	0.03	0.00	0.15	0.0
22	**MS-4s Gas (SI) engine**	Main engine	LNG	9	0	0	0	1410	kW	0	100%	160.2	4.8	0.8	0.0015	0.03	0.00	0.3	0.0
23	**MS-4s Dual fuel (DF) engine**	Main engine	LNG & pf MDO	9	0	0	0	1410	kW	0	25%	180.6	34.9	6.3	0.1	2	0.36	3.6	0.7
24	**MS-4s Dual fuel (DF) engine**	Main engine	LNG & pf MDO	9	0	0	0	1410	kW	0	50%	168.0	27.3	4.6	0.1	2	0.34	2.4	0.4
25	**MS-4s Dual fuel (DF) engine**	Main engine	LNG & pf MDO	9	0	0	0	1410	kW	0	75%	158.8	27.5	4.4	0.1	2	0.32	0.6	0.1
26	**MS-4s Dual fuel (DF) engine**	Main engine	LNG & pf MDO	9	0	0	0	1410	kW	0	100%	162.1	26.1	4.2	0.1	2	0.32	1.2	0.2
27	**Batteries (lithium-ion)**	Energy Storage Syste	Electricity[mix]	8	1	0	0	4000	kWh	0			0	0	0.0%	0	0	0	0
28	**Batteries (lead acid)**	Energy Storage Syste	Electricity[mix]	9	1	0	0	4000	kWh	0			0	0	0.0%	0	0	0	0
29	**Flywheel**	Energy Storage Syste	Electricity[mix]	3	1	0	0	4000	kWh	0			0	0	0.0%	0	0	0	0
30	**Ultracapacitors/Supercapacitors**	Energy Storage Syste	Electricity[mix]	6	1	0	0	4000	kWh	0			0	0	0.0%	0	0	0	0
31	**Hydrogen fuel cell (LT-PEMFC)**	Fuel cell	Hydrogen[CH4]	6	1	0	0	1300	kW	0			0	0	0.0%	0	0	0	0
32	**Gearbox**	Propulsion system		9	0	1	1	375	kW	0			0	0	0.0%	0	0	0	0.000
33	**Electric Motor**	Propulsion system		9	0	1	1	375	kW	0			0	0	0.0%	0	0	0	0.000
34	**Propeller (FPP/CPP) - rudder**	Propulsion system		9	0	1	1	375	kW	0			0	0	0.0%	0	0	0	0
35	**Azimuth thruster (FPP/CPP)**	Propulsion system		9	0	1	1	375	kW	0			0	0	0	0	0	0	0

	A	T	U	V	W	X	Y	Z	AA	AB	AC	AD	AE	AF	AG
1	**Energy systems and compatibility wit**					**Investment costs**					**Operational costs**				
2	**Type Energy System**	**VOC per (CH4) [g/kg]**	**VOC spe [g/kWh]**	**CO_2 per [g/kg]**	**CO_2 spe [g/kWh]**	**Investment costs: specific costs (equipment +installation - scrap value) [€/unit]**	**Investment costs: specific cost [unit {system}]**	**Investment costs: total costs (equipment + installation - crap value) (incl nr system) [total €]**	**Lifetime [yrs]**	**Annualised investment costs (capital/lifetime) [total €/y]**	**Operational costs: specific costs (consumable) [€/unit]**	**Operational costs: specific costs (maintenance) [€/unit]**	**Operational specific [unit {system}]**	**Energy delivered [MWh]**	**Operational costs: (consumables+maintenance) [€/year]**
3	**HS-4s Diesel (CI) engine (Tier II)**	2.6	0.5	3206	666.8	300	€/kW	€ 423,000	25	€ 16,920	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
4	**HS-4s Diesel (CI) engine (Tier II)**	2.0	0.4	3206	650.8	300	€/kW	€ 423,000	25	€ 16,920	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
5	**HS-4s Diesel (CI) engine (Tier II)**	1.0	0.2	3206	644.4	300	€/kW	€ 423,000	25	€ 16,920	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
6	**HS-4s Diesel (CI) engine (Tier II)**	1.0	0.2	3206	670.1	300	€/kW	€ 423,000	25	€ 16,920	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
7	**HS-4s Gas (SI) engine**	30.1	5.2	2750	474.8	600	€/kW	€ 846,000	25	€ 33,840	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
8	**HS-4s Gas (SI) engine**	23.1	3.9	2750	463.3	600	€/kW	€ 846,000	25	€ 33,840	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
9	**HS-4s Gas (SI) engine**	23.4	3.9	2750	458.8	600	€/kW	€ 846,000	25	€ 33,840	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
10	**HS-4s Gas (SI) engine**	22.5	3.9	2750	477.0	600	€/kW	€ 846,000	25	€ 33,840	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
11	**HS-4s Dual fuel (DF) engine**	56.6	10.0	2770	489.7	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
12	**HS-4s Dual fuel (DF) engine**	40.6	7.0	2770	478.0	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
13	**HS-4s Dual fuel (DF) engine**	41.0	7.0	2770	473.3	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
14	**HS-4s Dual fuel (DF) engine**	39.4	7.0	2770	492.1	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 2.00	€/MWh	3593.808	€ 7,188
15	**MS-4s Diesel (CI) engine (Tier II)**	6.6	1.4	3206	689.3	275	€/kW	€ 387,750	25	€ 15,510	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
16	**MS-4s Diesel (CI) engine (Tier II)**	5.0	1.0	3206	641.2	275	€/kW	€ 387,750	25	€ 15,510	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
17	**MS-4s Diesel (CI) engine (Tier II)**	2.4	0.5	3206	605.9	275	€/kW	€ 387,750	25	€ 15,510	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
18	**MS-4s Diesel (CI) engine (Tier II)**	2.0	0.4	3206	618.8	275	€/kW	€ 387,750	25	€ 15,510	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
19	**MS-4s Gas (SI) engine**	29.1	5.2	2750	490.7	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
20	**MS-4s Gas (SI) engine**	23.5	3.9	2750	456.5	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
21	**MS-4s Gas (SI) engine**	24.9	3.9	2750	431.4	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
22	**MS-4s Gas (SI) engine**	24.3	3.9	2750	440.5	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
23	**MS-4s Dual fuel (DF) engine**	56.6	10.0	2770	500.3	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
24	**MS-4s Dual fuel (DF) engine**	40.6	7.0	2770	465.4	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
25	**MS-4s Dual fuel (DF) engine**	41.0	7.0	2770	439.8	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
26	**MS-4s Dual fuel (DF) engine**	39.4	7.0	2770	449.1	575	€/kW	€ 810,750	25	€ 32,430	€ -	€ 3.00	€/MWh	3593.808	€ 10,781
27	**Batteries (lithium-ion)**	0	0	0	0	700	€/kWh	€ 2,800,000	10	€ 280,000	€ -	€ 1.00	€/MWh	5309.47	€ 5,309.47
28	**Batteries (lead acid)**	0	0	0	0	175	€/kWh	€ 700,000	10	€ 70,000	€ -	€ 1.00	€/MWh	5309.47	€ 5,309.47
29	**Flywheel**	0	0	0	0	800	€/kWh	€ 3,200,000	20	€ 160,000	€ -	€ 2.00	€/MWh	5309.47	€ 10,618.94
30	**Ultracapacitors/Supercapacitors**	0	0	0	0	10000	€/kWh	€ 40,000,000	12	€ 3,333,333	€ -	€ 2.00	€/MWh	5309.47	€ 10,618.94
31	**Hydrogen fuel cell (LT-PEMFC)**	0	0	0	0	3000	€/kW	€ 3,900,000	10	€ 390,000	€ -	€ 3.50	€/MWh		€ -
32	**Gearbox**	0	0	0	0	55	€/kW	€ 20,625	25	825	€ -	€ 1.00	€/MWh	3593.81	€ 3,593.81
33	**Electric Motor**	0	0	0	0	250	€/kW	€ 93,750	25	3750	€ -	€ 1.50	€/MWh	3593.81	€ 5,390.71
34	**Propeller (FPP/CPP) - rudder**	0	0	0	0	50	€/kW	€ 18,750	25	€ 750	€ -	€ 1.00	€/MWh	3593.81	€ 3,593.81
35	**Azimuth thruster (FPP/CPP)**	0	0	0	0	100	€/kW	€ 37,500.00	25	1500	€ -	€ 1.00	€/MWh	3593.808	€ 3,593.81

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z	AA
1	Abatement options (AO) and compatibility with ships and energy systems																Emission reduction potential										
2	Type Abatement option	Abbreviation or	Category abatement option	Compatible with ES	Compatible with selected ES	TRL	Electric ferry: applicable? [0/1]	Workboat: applicable? [0/1]	AO applicable to selected ship, TRL and ES	AO red [Main, Aux, Tot]	Energy ratio [%]	AO number and size based on chosen energy system	Nr of AO	Capacity of specific component [value]	Capacity [unit]	Output MATLAB [0/1]	R_NO_x [%]	Fuels: %S content [%m/m]	Fuels R_S [%]	AO; R_SO_x [%]	R _PM [%]	R_VOC (CH4) [%]	Fuels: Carbon factor [kg/kg]	R_CO_2 [%]	Fuels: Lower Heating Value (LHV) fuel [MJ/kg]	Fuels: SFC [g/kWh] assuming same efficiency	Effect on energy consumption (FC) [%]
3	Marine Gas Oil 0.1%S (LSMGO) {CI}	LSMGO	Fuel	(CI)	1	9	0	1	1	Total	100%	Fuel	1			1	0	0.1	0%	0.00%	0%	0%	3.206	0.00%	42.65	183.50	0%
4	Marine Gas Oil 0.5%S (MGO) {CI}	MGO	Fuel	(CI)	1	9	0	1	1	Total	100%	Fuel	1			0	0	0.5	-400%	0%	-2%	0%	3.206	0.00%	42.65	183.50	0.0%
5	Marine Diesel Oil 0.1%S (MDO) {CI}	MDO	Fuel	(CI)	1	9	0	1	1	Total	100%	Fuel	1			0	0%	0.1	0%	0%	-1%	0%	3.206	0.00%	42.19	185.50	-1.1%
6	Low sulphur Heavy Fuel Oil 0.5%S (LSHFO) {CI}	LSHFO	Fuel	(CI)	1	9	0	0	0	Total	100%	Fuel	1			0	-3%	0.500	-400%	0%	0%	0%	3.114	3%	39	200.67	-9.4%
7	Heavy Fuel Oil 2.7%S (HFO) {CI}	HFO	Fuel	(CI)	1	9	0		0	Total	100%	Fuel	1			0	-3%	2.700	-2600%	0%	0%	0%	3.114	3%	40.5	193.24	-5.3%
8	Ultra Low Sulphur Diesel (ULSD) 0.001%S {CI}	ULSD	Fuel	(CI)	1	9	0	1	1	Total	100%	Fuel	1			0	3%	0.001	99%	0%	4%	0%	3.206	0%	42.8	182.85	0.4%
9	Biofuel (Biodiesel) (HVO) {CI}	Bio-HVO	Fuel	(CI)	1	8	0	1	1	Total	100%	Fuel	1			0	2%	0.001	99%	0%	5%	0%	2.700	16%	34.4	227.50	-24.0%
10	Biofuel (Biodiesel) (Dimethyl Ether (DME)) {CI}	Bio-DME	Fuel	(CI)	1	7	0	1	1	Total	100%	Fuel	1			0	2%	0.00	99%	0%	5%	0%	2.700	16%	28.70	272.69	-48.6%
11	Liquefied Natural Gas (LNG) {SI}	LNG	Fuel	(SI)	0	9	0	0	0	Total	100%	Fuel	1			0	0%	0.0015	0%	0.00%	0%	0%	2.750	0.00%	48.60	161.03	0%
12	Liquefied Petroleum Gas {SI}	LPG	Fuel	(SI)	0	6	0	0	0	Total	100%	Fuel	1			0	-66%	0.0000	100%	0%	0%	0%	3.015	-10%	45.50	172.00	-6.8%
13	Biogas (methane) Liquefied {SI}	Bio-LBM	Fuel	(SI)	0	9	0	0	0	Total	100%	Fuel	1			0	-84%	0.0000	100%	0%	-600%	0%	2.600	5%	20.00	391.30	-143.0%
14	Methanol [from methane] {SI}	MeOH	Fuel	(SI)	0	6	0	0	0	Total	100%	Fuel	1			0	-55%	0.0001	97%	0%	100%	100%	1.375	50%	20.00	391.30	-143.0%
15	Liquid Hydrogen (LH2) [from electrolysis water] {SI}	Hydrogen[ele	Fuel	(SI)	0	5	0	0	0	Total	100%	Fuel	1			0	11%	0.0005	67%	0%	100%	100%	0.000	100%	120.00	65.22	59.5%
16	Liquid Hydrogen (LH2) [from reforming methane] {SI}	Hydrogen[CH	Fuel	(SI)	0	5	0	0	0	Total	100%	Fuel	1			0	11%	0.0005	67%	0%	100%	100%	0.000	100%	120.00	65.22	59.5%
17	Liquefied Natural Gas (LNG) + pf MDO {DF}	LNG & pf MD	Fuel	(DF)	0	9	0	0	0	Total	100%	Fuel	1			0	0	0.1	0%	0.00%	0%	0%	2.770	0.00%	48.60	161.03	0%
18	Liquefied Petroleum Gas (LPG) + pf MDO {DF}	LPG & pf MD	Fuel	(DF)	0	6	0	0	0	Total	100%	Fuel	1			0	18%	0	100%	0%	0%	0%	3.015	-9%	45.50	172.00	-6.8%
19	Methanol + pf MDO [from methane] {DF}	MeOH & pf M	Fuel	(DF)	0	6	0	0	0	Total	100%	Fuel	1			0	-50%	5E-05	100%	0%	80%	80%	1.375	50%	20.00	391.30	-143.0%
20	Electricity [EU mix]	Electricity[mi	Fuel	Batteri	0	9	1	0	0	Total	100%	Fuel	1			0	0%	0	0.000	0%	0%	0%	0.000	0%	0	0.00	0%
21	Electricity [Renewable energy]	Electricity[Re	Fuel	Batteri	0	9	1	0	0	Total	100%	Fuel	1			0	0%	0	0.000	0%	0%	0%	0.000	0%	0	0.00	0%
22	Turbocharging (2-stage) and Miller cycle (IEM)	IEM	er-PM		1	9	0	0	0	Total	100%	Main engi	3	1410	kW	0	40%	0	0.000	0%	80%	50%		0%			2.0%
23	Humid Air Motors (HAM)	HAM	er-PM-wa		1	7	0	1	1	Total	100%	Main engi	3	1410	kW	0	35%	0	0.000	0%	20%	0%		0%			-1.0%
24	Fuel Water Emulsification (FWE or WIF)	FWE	er-PM-wa		1	8	0	1	1	Total	100%	Main engi	3	1410	kW	1	33%	0	0.000	0%	45%	0%		0%			0.0%
25	Direct Water Injection (DWI)	DWI	er-PM-wa		1	9	0	1	1	Total	100%	Main engi	3	1410	kW	0	38%	0	0.000	0%	50%	0%		0%			-2.0%
26	Exhaust Gas Recirculation (EGR)	EGR	er-PM		1	9	0	1	1	Total	100%	Main engi	3	1410	kW	0	43%	0	0.000	2%	-10%	0%		0%			-5.0%
27	Oxidation Catalyst (DOC)	DOC	er-PM		1	9	0	1	1	Total	100%	Main engi	3	1410	kW	0	0%	0	0.000	0%	25%	20%		0%			-0.5%
28	Diesel Particulate Filter (DPF)	DPF	er-SM		1	7	0	1	1	Total	100%	Main engi	3	1410	kW	0	0%	0	0.000	0%	80%	1%		0%			-1.0%
29	Selective Catalytic Reduction (fuel >1.5 %S) (SCR)	SCR	er-SM		1	9	0	0	0	Total	100%	Main engi	1	1410	kW	0	83%	0	0.000	0%	35%	0%		0%			-3.0%
30	Selective Catalytic Reduction (fuel <1.5 %S) (SCR)	SCR	er-SM		1	9	0	1	1	Total	100%	Main engi	1	1410	kW	1	83%	0	0.000	0%	35%	0%		0%			-3.0%
31	Wet scrubber - Open loop	WetScrubber	er-SM-sc		1	9	0	0	0	Total	100%	Main engi	1	1410	kW	0	0%	0	0.000	93%	78%	0%		0%			-1.5%
32	Wet scrubber - Closed loop	WetScrubber	er-SM-sc		1	9	0	0	0	Total	100%	Main engi	1	1410	kW	0	0%	0	0.000	90%	75%	0%		0%			-1.5%
33	Dry scrubber	DryScrubber	er-SM-sc		1	9	0	0	0	Total	100%	Main engi	1	1410	kW	0	0%	0	0.000	80%	70%	0%		0%			-1.5%
34	Carbon Capture and Storage (CCS)	CCS	er-SM		1	4	0	0	0	Total	100%	Main engi	1	1410	kW	0	0%	0	0.000	0%	0%	0%		90%			0.0%
35	Elastic mountings	ElasticMount	er-URN		1	7	0	1	1	Total	100%	Main engi	3	1410	kW	0	0%	0	0.000	0%	0%	0%		0%			-0.5%
36	Acoustic enclosing machinery	AcousticEncl	er-URN		1	8	0	1	1	Total	100%	Main engi	3	1410	kW	0	0%	0	0.000	0%	0%	0%		0%			0.0%
37	Structural reinforcements	StructuralRei	er-URN		1	8	0	1	1	Total	100%	Main engi	3	1410	kW	0	0%	0	0.000	0%	0%	0%		0%			0.0%
38	Air injection to propeller or bubble curtain	AirProp	er-URN		1	6	0	0	0	Main	50%		1	0	kW	0	0%	0	0.000	0%	0%	0%		0%			-2.0%
39	Lightweight hull construction	LightweightH	ee-SD		1	8	0	0	0	Main	50%		1	0	kW	0	0%	0	0.000	0%	0%	0%		0%			2.7%
40	Lightweight superstructure	LightweightS	ee-SD		1	8	0	0	0	Main	50%		1	0		0	0%	0	0.000	0%	0%	0%		0%			0.5%
41	Aerodynamic superstructure	CFD_Aero	ee-SD		1	9	1	0	0	Main	50%		1	0		0	0%	0	0.000	0%	0%	0%		0%			0.5%
42	Hydrodynamically optimised hull form +app.	CFD_Hydro	ee-SD		1	9	1	1	1	Main	50%		1	0		1	0%	0	0.000	0%	0%	0%		0%			2.7%
43	Hull coating	HullCoating	ee-SD		1	9	1	1	1	Main	50%		1	0		1	0%	0	0.000	0%	0%	0%		0%			1.5%
44	Air lubrication	Airlubrication	ee-SD		1	7	0	0	0	Main	50%		1	0		0	0%	0	0.000	0%	0%	0%		0%			1.5%
45	Appendages - Hull vane	HullVane	ee-SD		1	7	0	0	0	Main	50%		1	0		0	0%	0	0.000	0%	0%	0%		0%			0.0%
46	PID pre-swirl devices (fins, stators, ducts)	PIDpre	ee-PID		1	9	1	0	0	Main	50%		1	0	kW	0	0%	0	0.000	0%	0%	0%		0%			1.2%
47	PID - at propeller (propeller boss cap fins, nozzle)	PIDatProp	ee-PID		1	9	0	0	0	Main	50%		1	0	kW	0	0%	0	0.000	0%	0%	0%		0%			1.2%
48	PID - post swirl devices	PIDpost	ee-PID		1	9	0	0	0	Main	50%		1	0	kW	0	0%	0	0.000	0%	0%	0%		0%			1.2%
49	Propeller optimisation - Higher efficiency, higher URN	PropOptHigh	ee-PID-pr		1	9	1	1	1	Main	50%	Propulsor	1	0	kW	1	0%	0	0.000	0%	0%	0%		0%			1.5%
50	Propeller optimisation -Lower efficiency, lower URN	PropOptLow	ee-PID-pr		1	9	1	1	1	Main	50%	Propulsor	1	0	kW	0	0%	0	0.000	0%	0%	0%		0%			-1.0%
51	Waste Heat Recovery (WHR)	WHR	ee-Power		1	8	0	1	1	Total	100%	Main engi	1	1410	kW	1	0%	0	0.000	0%	0%	0%		0%			4.0%
52	Energy efficient light system	EfficientLight	ee-Power		1	9	1	1	1	Aux	50%		1	0	kW	1	0%	0	0.000	0%	0%	0%		0%			1.0%
53	Flettner rotors	FlettnerRoto	ee-REC		1	6	0	0	0	Main	50%		1	0	kW	0	0%	0	0.000	0%	0%	0%		0%			1.2%
54	Solar panels	SolarPanels	ee-REC		1	8	1	0	0	Total	100%	Main engi	1	30	kW	0	0%	0	0.000	0%	0%	0%		0%			1.0%

	A	B	AB	AC	AD	AE	AF	AG	AH	AI	AJ	AK	AL	AM	AN	AO	AP	AQ	AR
1	**Abatement options (AO) and compatibility with ships and energy sy**		**Emission**		**Investment costs**						**Operational costs**								
2	**Type Abatement option**	**Abbreviation or**	**Fuels: upstream (WTT) EF [gCO2eq/kWh] (fuel consumption)**	**URN reducing effect on category of URN source**	**Investment: variable costs (equipment+installation - scrap value) [€/unit]**	**Investment: specific cost [unit {system}]**	**Investment: constant costs (equipment + installation - scrap value) [total €/system]**	**total costs (equipment + installation - crap value) (incl nr system) [total €]**	**Lifetime [yrs]**	**Annualised investment costs: (depreciation=capital/lifetime) [total €/yrs]**	**Oper. (consumable) costs: specific costs [€/ton] or [€/MWh] electricity**	**Oper. (consumable) costs: specific costs [€/unit]**	**Operational (consumable) specific [unit {system}]**	**Fuel consumption [MWh/y]**	**Oper. (consumable) costs: total costs [€/unit]**	**Oper. (maintenance) costs: specific costs [€/unit]**	**Operational specific [unit {system}]**	**Energy delivered by engine [MWh/y]**	**Oper. (maintenance) costs: total costs [€/system]**
3	Marine Gas Oil 0.1%S (LSMGO) {CI}	LSMGO	43.20	_	€ -		€ -	€ -	1	€ -	€ 610	€ 51.49	€/MWh	7375	€ 379,726	€ -			€ -
4	**Marine Gas Oil 0.5%S (MGO) {CI}**	MGO	43.2	_	€ -		€ -	€ -	1	€ -	€ 585	€ 49.38	€/MWh	7375	€ 364,163	€ -			€ -
5	**Marine Diesel Oil 0.1%S (MDO) {CI}**	MDO	43.20	_	€ -		€ -	€ -	1	€ -	€ 592	€ 50.51	€/MWh	7375	€ 372,539	€ -			€ -
6	**Low sulphur Heavy Fuel Oil 0.5%S (LSHFO) {CI}**	LSHFO	43.20	_	€ -		€ -	€ -	1	€ -	€ 520	€ 48.00	€/MWh	7375	€ 353,996	€ -			€ -
7	**Heavy Fuel Oil 2.7%S (HFO) {CI}**	HFO	35.64	_	€ -		€ -	€ -	1	€ -	€ 350	€ 31.11	€/MWh	7375	€ 229,442	€ -			€ -
8	**Ultra Low Sulphur Diesel (ULSD) 0.001%S {CI}**	ULSD	50.4	_	€ -		€ -	€ -	1	€ -	€ 640	€ 53.83	€/MWh	7375	€ 397,005	€ -			€ -
9	**Biofuel (Biodiesel) (HVO) {CI}**	Bio-HVO	216.00	_	€ -		€ -	€ -	1	€ -	€ 670	€ 70.12	€/MWh	7375	€ 517,101	€ -			€ -
10	**Biofuel (Biodiesel) (Dimethyl Ether (DME)) {CI}**	Bio-DME	216.00	_	€ -		€ -	€ -	1	€ -	€ 670	€ 84.04	€/MWh	7375	€ 619,801	€ -			€ -
11	Liquefied Natural Gas (LNG) {SI}	LNG	36.00	_	€ -		€ -	€ -	1	€ -	€ 400	€ 29.63	€/MWh	7375	€ 218,516	€ -			€ -
12	**Liquefied Petroleum Gas {SI}**	LPG	18.00	_	€ -		€ -	€ -	1	€ -	€ 650	€ 51.43	€/MWh	7375	€ 379,281	€ -			€ -
13	**Biogas (methane) Liquefied {SI}**	Bio-LBM	72.00	_	€ -		€ -	€ -	1	€ -	€ 450	€ 81.00	€/MWh	7375	€ 597,368	€ -			€ -
14	**Methanol [from methane] {SI}**	MeOH	28.80	_	€ -		€ -	€ -	1	€ -	€ 500	€ 90.00	€/MWh	7375	€ 663,742	€ -			€ -
15	**Liquid Hydrogen (LH2) [from electrolysis water] {SI}**	Hydrogen[ele	7.20	_	€ -		€ -	€ -	1	€ -	€ 900	€ 27.00	€/MWh	7375	€ 199,123	€ -			€ -
16	**Liquid Hydrogen (LH2) [from reforming methane] {SI}**	Hydrogen[CH	324.00	_	€ -		€ -	€ -	1	€ -	€ 800	€ 24.00	€/MWh	7375	€ 176,998	€ -			€ -
17	Liquefied Natural Gas (LNG) + pf MDO {DF}	LNG & pf MD	36.00	_	€ -		€ -	€ -	1	€ -	€ 460	€ 34.07	€/MWh	7375	€ 251,293	€ -			€ -
18	**Liquefied Petroleum Gas (LPG) + pf MDO {DF}**	LPG & pf MD	18.00	_	€ -		€ -	€ -	1	€ -	€ 650	€ 51.43	€/MWh	7375	€ 379,281	€ -			€ -
19	**Methanol + pf MDO [from methane] {DF}**	MeOH & pf M	28.80	_	€ -		€ -	€ -	1	€ -	€ 530	€ 95.40	€/MWh	7375	€ 703,567	€ -			€ -
20	**Electricity [EU mix]**	Electricity[mi	468.00	_	€ -		€ -	€ -	1	€ -	€ 70	€ 70.00	€/MWh	Not applie	€ -	€ -			€ -
21	**Electricity [Renewable energy]**	Electricity[Re	324.00	_	€ -		€ -	€ -	1	€ -	€ 80	€ 80.00	€/MWh	Not applie	€ -	€ -			€ -
22	**Turbocharging (2-stage) and Miller cycle (IEM)**	IEM	0.00	_	€ 13	€/kW	€ 410.00	€ 18,740	2.5	€ 7,496		€ -			€ -	€ 9,800	€/yr		€ 9,800
23	**Humid Air Motors (HAM)**	HAM	0.00	_	€ 130	€/kW	€ -	€ 183,300	13	€ 14,100		€ -			€ -	€ 1,500	€/yr		€ 1,500
24	**Fuel Water Emulsification (FWE or WIF)**	FWE	0.00	_	€ 40	€/kW		€ 56,400	25	€ 2,256		€ -			€ -	€ 27,000	€/yr		€ 27,000
25	**Direct Water Injection (DWI)**	DWI	0.00	_	€ 37	€/kW	€ 27,000.00	€ 79,170	15	€ 5,278		€ -			€ -	€ 68,000	€/yr		€ 68,000
26	**Exhaust Gas Recirculation (EGR)**	EGR	0.00	_	€ 80	€/kW	€ -	€ 112,800	25	€ 4,512		€ -			€ -	€ 2.50	€/MWh	3594	€ 8,985
27	**Oxidation Catalyst (DOC)**	DOC	0.00	_	€ 10	€/kW	€ -	€ 14,100	3	€ 4,700		€ -			€ -	€ 10.00	€/kW-yr		€ 14,100
28	**Diesel Particulate Filter (DPF)**	DPF	0.00	_	€ 10	€/kW	€ -	€ 14,100	3	€ 4,700		€ -			€ -	€ 10.00	€/kW-yr		€ 14,100
29	**Selective Catalytic Reduction (fuel >1.5 %S) (SCR)**	SCR	0.00	URN_mach	€ 60	€/kW	€ -	€ 84,600	25	€ 3,384		€ -			€ -	€ 4.00	€/MWh	3594	€ 14,375
30	**Selective Catalytic Reduction (fuel <1.5 %S) (SCR)**	SCR	0.00	_	€ 60	€/kW	€ -	€ 84,600	25	€ 3,384		€ -			€ -	€ 4.00	€/MWh(	3594	€ 14,375
31	**Wet scrubber - Open loop**	WetScrubber	0.00	_	€ 150	€/kW	€ -	€ 211,500	25	€ 8,460		€ -			€ -	3% newbuild			€ -
32	**Wet scrubber - Closed loop**	WetScrubber	0.00	_	€ 150	€/kW	€ -	€ 211,500	25	€ 8,460		€ -			€ -	3% newbuild			€ -
33	**Dry scrubber**	DryScrubber	0.00	_	€ 150	€/kW	€ -	€ 211,500	25	€ 8,460		€ -			€ -	3% newbuild			€ -
34	**Carbon Capture and Storage (CCS)**	CCS	0.00	_	€ 2,600	€/kW {ME	€ -	€ 3,666,000	15	€ 244,400		€ -			€ -				€ -
35	**Elastic mountings**	ElasticMount	0.00	URN_mach	€ -		€ 100,000	€ 100,000	25	€ 100,000		€ -			€ -				€ -
36	**Acoustic enclosing machinery**	AcousticEncl	0.00	URN_mach	€ -		€ 100,000	€ 100,000	25	€ 100,000		€ -			€ -				€ -
37	**Structural reinforcements**	StructuralRei	0.00	URN_mach	€ -		€ 70,000	€ 70,000	25	€ 70,000		€ -			€ -				€ -
38	**Air injection to propeller or bubble curtain**	AirProp	0.00	URN_prop	€ -		€ 250,000	€ 250,000	15	€ 250,000		€ -			€ -				€ -
39	**Lightweight hull construction**	LightweightH	0.00	_	€ -			€ -	25	€ -		€ -			€ -				€ -
40	**Lightweight superstructure**	LightweightS	0.00	_	€ -			€ -	25	€ -		€ -			€ -				€ -
41	**Aerodynamic superstructure**	CFD_Aero	0.00	_	€ -	€	€ 200,000	€ 200,000	25	€ 8,000		€ -			€ -				€ -
42	**Hydrodynamically optimised hull form +app.**	CFD_Hydro	0.00	URN_hullD	€ -	€	€ 150,000	€ 150,000	25	€ 6,000		€ -			€ -				€ -
43	**Hull coating**	HullCoating	0.00	URN_foul	€ -	€	€ 30,000	€ 30,000	5	€ 6,000		€ -			€ -				€ -
44	**Air lubrication**	Airlubricatior	0.00	_	€ -	€	€ 400,000	€ 400,000	25	€ 16,000		€ -			€ -	€ 10,000			€ 10,000
45	**Appendages - Hull vane**	HullVane	0.00	_	€ -		€ 300,000	€ 300,000	10	€ 30,000		€ -			€ -				€ -
46	**PID pre-swirl devices (fins, stators, ducts)**	PIDpre	0.00	_	€ -	€	€ 200,000	€ 200,000	10	€ 20,000		€ -			€ -				€ -
47	**PID - at propeller (propeller boss cap fins, nozzle)**	PIDatProp	0.00	URN_prop	€ -	€	€ 100,000	€ 100,000	10	€ 10,000		€ -			€ -				€ -
48	**PID - post swirl devices**	PIDpost	0.00	_	€ -	€	€ 100,000	€ 100,000	10	€ 10,000		€ -			€ -				€ -
49	**Propeller optimisation - Higher efficiency, higher URN**	PropOptHigh	0.00	_	€ -	€	€ 250,000	€ 250,000	10	€ 25,000		€ -			€ -				€ -
50	**Propeller optimisation -Lower efficiency, lower URN**	PropOptLow	0.00	URN_prop	€ -	€	€ 200,000	€ 200,000	10	€ 20,000		€ -			€ -				€ -
51	**Waste Heat Recovery (WHR)**	WHR	0.00	_	€ 500	€/kW		€ 705,000	25	€ 28,200		€ -			€ -	€ 3.50	€/MWh	3594	€ 12,578
52	**Energy efficient light system**	EfficientLight	0.00	_		€	€ 100,000	€ 100,000	25	€ 4,000		€ -			€ -				€ -
53	**Flettner rotors**	FlettnerRoto	0.00	_			€ 500,000	€ 500,000	10	€ 50,000		€ -			€ -				€ -
54	**Solar panels**	SolarPanels	0.00	_	€ 2,500	€/kW		€ 75,000	10	€ 7,500		€ -			€ -				€ -

F.2. Consideration of decision parameters

This section describes various decision parameters that are taken into account in the selection tool.

TRL

The TRL of specific technologies are obtained from several studies. The scales that are used in other studies have also been translated into the TRL scale and are defined as follows. The scale used by Glomeep [24] is mature (TRL=9), semi-mature (TRL=7/8), not mature (TRL<=6). The scale by Symington [73] is mature when a technology is used for more than 10 years (TRL=9), commercialised and available for a period of less than 10 years (TRL=7/8) and otherwise developmental (TRL<=6).

Reduction effects

For each fuel in the long list it is indicated whether it is compatible with the energy system and whether it is a possible abatement option for the selected benchmark engine. Furthermore, the reduction potentials of fuels are dependent on the engine type in which the fuel will be used. In the dataset, the reduction potentials of fuels are defined with respect to the benchmark reference fuel. Furthermore, the reference basis of abatement options is considered: e.g. hull-coating has only a reduction effect on the propulsion part of energy consumption. Therefore, the reduction potential is multiplied by a relative factor for the power.

Specific fuel consumption

The specific fuel consumption (sfc) for an Internal Combustion (IC) engine is specified by the engine manufacturers usually for engines running on MDO [50]. If an engine runs on an fuel other than MDO, the specific fuel consumption is obtained by Equation F.1, where the lower heating value of the fuel is used.

$$sfc = \frac{3600000}{\eta_e \cdot h^L} \tag{F.1}$$

where:

η_e	Effective engine efficiency	[%]
h^L	Fuel-specific lower heating value (calorific value)	[MJ/kg]

Fuel costs

In the dataset, the fuel costs (C^{Fuel}) in [€/ton] are also expressed in the same unit [€/MWh] in order to compare different fuels such as diesel fuels and fuels such as electricity. The price of (conventional) fuels is often expressed in €/ton and can be converted to €/MWh according to Equation F.2 by using the lower heating value (h^L) of the fuel.

$$C^{Fuel}[\text{€/MWh}] = \frac{C^{Fuel}[\text{€/ton}]}{h^L[\text{MJ/kg}]} \cdot \frac{3.6 \cdot 10^6}{1 \cdot 10^6} \tag{F.2}$$

G. Structure of MATLAB files and selection tool

The structure of the MATLAB files is given in Section G.1 and the outline of the selection tool is given in Section G.2.

G.1. Structure of the MATLAB files

The optimisation part of the selection tool takes place in MATLAB (as shown in Figure 7.8). This section gives the structure of the MATLAB files specific programmed for the optimisation problem. The background of the NGPM files containing the algorithm (NSGA) functions can be read in the documentation of Song [58]. This section first describes the main script file for the pre-processing and post-processing part. Thereafter the function file for defining the optimisation problem is explained.

Structure of the script file
The main script is divided into the regions as specified below:

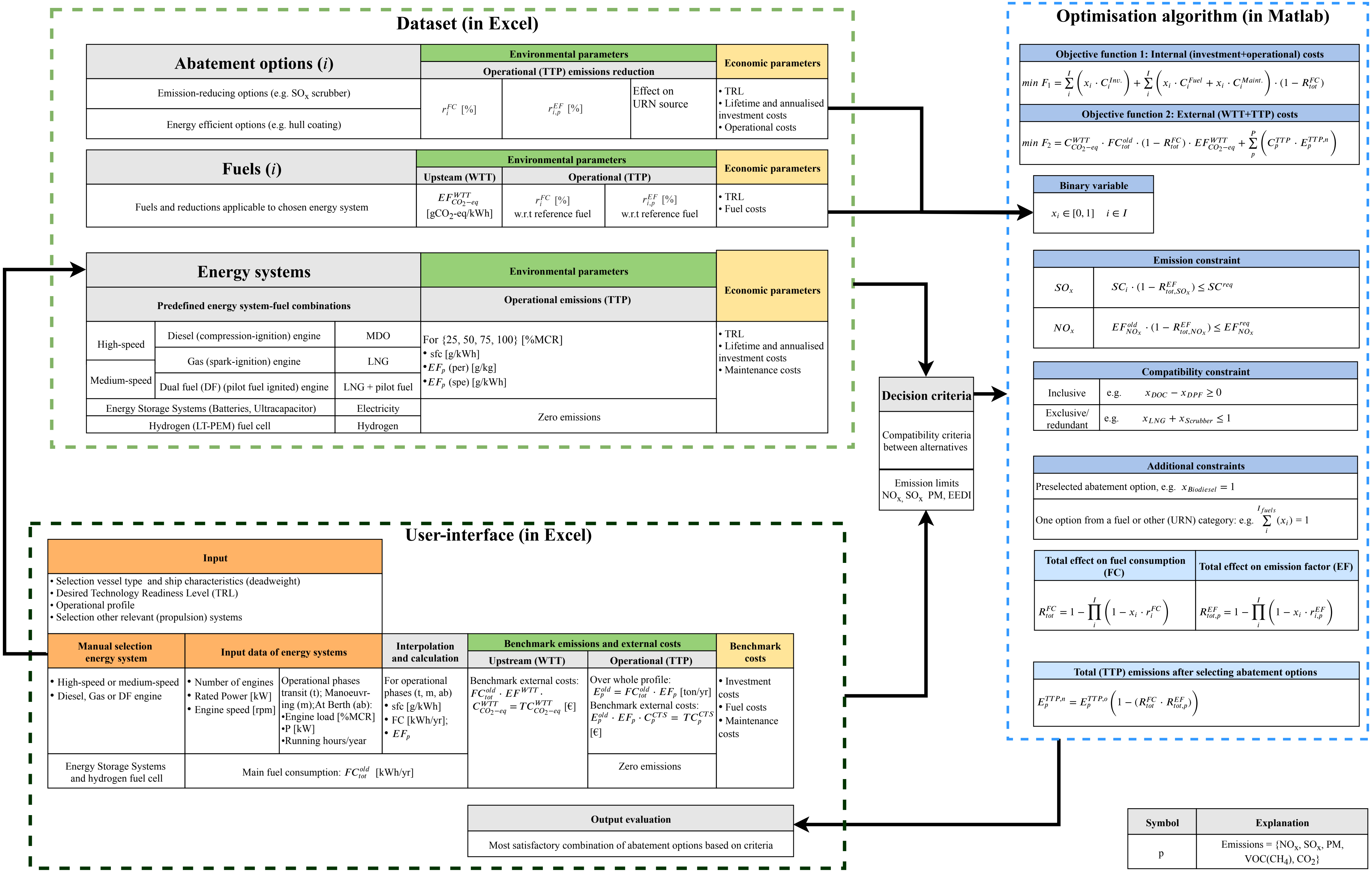
- region 1: Reading the necessary information and decision parameters of the applicable abatement options from the Excel sheets (user-interface and the dataset of abatement options).
- region 2: Defining the options of the optimisation algorithm (as described in subsection 7.3.3). The NSGA optimisation function can be invoked from the script file by supplementing the defined optimisation algorithm options and the decision parameters.
- region 3: Post-processing of the optimisation results and recalculate total reduction effects, emissions and (internal and external) costs. This calculation differs from the function file, because the products of reduction effects are determined stepwise in the function file. However, this recalculation in the script file offers an additional check.
- region 4: Displaying relevant optimisation information in MATLAB table and figure.
- region 5: Transferring the relevant information back to Excel.

Structure of the function file
The optimisation problem can be defined in the function file. This file is divided into the following regions:

- region 1: Allocating vector for objective function and number of constraints. This function uses the decision variable (x) and decision parameters as input and evaluates the objective values and constraint violations (cons). It returns these output values to the workspace of MATLAB [58].
- region 2: Objective 2 external costs of emissions influenced by the total reduction effects of combinations of abatement options.
- region 3: Objective 1 internal costs including annual investment costs and operational costs.
- region 4: Emission constraints

G.2. Outline of the selection tool

The outline of the selection tool is given on the following page.


Dataset (in Excel)
Abatement options (i)
Environmental parameters
Operational (TTP) emissions reduction
Economic parameters
Emission-reducing options (e.g. SO_x scrubber)
Energy efficient options (e.g. hull coating)
r_i^{FC} [%]
$r_{i,p}^{EF}$ [%]
Effect on URN source
• TRL
• Lifetime and annualised investment costs
• Operational costs
Fuels (i)
Environmental parameters
Upsteam (WTT)
Operational (TTP)
Economic parameters
Fuels and reductions applicable to chosen energy system
$EF_{CO_2-eq}^{WTT}$ [gCO_2-eq/kWh]
r_i^{FC} [%] w.r.t reference fuel
$r_{i,p}^{EF}$ [%] w.r.t reference fuel
• TRL
• Fuel costs
Energy systems
Environmental parameters
Economic parameters
Predefined energy system-fuel combinations
Operational emissions (TTP)
High-speed
Medium-speed
Diesel (compression-ignition) engine
MDO
Gas (spark-ignition) engine
LNG
Dual fuel (DF) (pilot fuel ignited) engine
LNG + pilot fuel
Energy Storage Systems (Batteries, Ultracapacitor)
Electricity
Hydrogen (LT-PEM) fuel cell
Hydrogen
For {25, 50, 75, 100} [%MCR]
• sfc [g/kWh]
• EF_p (per) [g/kg]
• EF_p (spe) [g/kWh]
Zero emissions
• TRL
• Lifetime and annualised investment costs
• Maintenance costs
Decision criteria
Compatibility criteria between alternatives
Emission limits NO_x, SO_x PM, EEDI
Optimisation algorithm (in Matlab)
Objective function 1: Internal (investment+operational) costs
$min\ F_1 = \sum_i^I \left(x_i \cdot C_i^{Inv.}\right) + \sum_i^I \left(x_i \cdot C_i^{Fuel} + x_i \cdot C_i^{Maint.}\right) \cdot (1 - R_{tot}^{FC})$
Objective function 2: External (WTT+TTP) costs
$min\ F_2 = C_{CO_2-eq}^{WTT} \cdot FC_{tot}^{old} \cdot (1 - R_{tot}^{FC}) \cdot EF_{CO_2-eq}^{WTT} + \sum_p^P \left(C_p^{TTP} \cdot E_p^{TTP,n}\right)$
Binary variable
$x_i \in [0,1] \quad i \in I$
Emission constraint
SO_x
$SC_i \cdot (1 - R_{tot,SO_x}^{EF}) \leq SC^{req}$
NO_x
$EF_{NO_x}^{old} \cdot (1 - R_{tot,NO_x}^{EF}) \leq EF_{NO_x}^{req}$
Compatibility constraint
Inclusive
e.g. $x_{DOC} - x_{DPF} \geq 0$
Exclusive/ redundant
e.g. $x_{LNG} + x_{Scrubber} \leq 1$
Additional constraints
Preselected abatement option, e.g. $x_{Biodiesel} = 1$
One option from a fuel or other (URN) category: e.g. $\sum_i^{I_{fuels}} (x_i) = 1$
Total effect on fuel consumption (FC)
Total effect on emission factor (EF)
$R_{tot}^{FC} = 1 - \prod_i^I \left(1 - x_i \cdot r_i^{FC}\right)$
$R_{tot,p}^{EF} = 1 - \prod_i^I \left(1 - x_i \cdot r_{i,p}^{EF}\right)$
Total (TTP) emissions after selecting abatement options
$E_p^{TTP,n} = E_p^{TTP,o}\left(1 - (R_{tot}^{FC} \cdot R_{tot,p}^{EF})\right)$
User-interface (in Excel)
Input
• Selection vessel type and ship characteristics (deadweight)
• Desired Technology Readiness Level (TRL)
• Operational profile
• Selection other relevant (propulsion) systems
Manual selection energy system
Input data of energy systems
Interpolation and calculation
Benchmark emissions and external costs
Upstream (WTT)
Operational (TTP)
Benchmark costs
• High-speed or medium-speed
• Diesel, Gas or DF engine
• Number of engines
• Rated Power [kW]
• Engine speed [rpm]
Operational phases transit (t); Manoeuvring (m);At Berth (ab):
•Engine load [%MCR]
•P [kW]
•Running hours/year
For operational phases (t, m, ab)
• sfc [g/kWh]
• FC [kWh/yr];
• EF_p
Benchmark external costs:
$FC_{tot}^{old} \cdot EF^{WTT} \cdot C_{CO_2-eq}^{WTT} = TC_{CO_2-eq}^{WTT}$ [€]
Over whole profile:
$E_p^{old} = FC_{tot}^{old} \cdot EF_p$ [ton/yr]
Benchmark external costs:
$E_p^{old} \cdot EF_p \cdot C_p^{CTS} = TC_p^{CTS}$ [€]
• Investment costs
• Fuel costs
• Maintenance costs
Energy Storage Systems and hydrogen fuel cell
Main fuel consumption: FC_{tot}^{old} [kWh/yr]
Zero emissions
Output evaluation
Most satisfactory combination of abatement options based on criteria
Symbol
Explanation
p
Emissions = {NO_x, SO_x, PM, VOC(CH_4), CO_2}