# Low carbon shipping

## A decision support tool for the implementation of $CO_2$ reducing measures

Seb van den Berg

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TNO

TU Delft

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## A decision support tool for the implementation of $CO_2$ reducing measures

by

Seb van den Berg

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# Preface

This thesis is the result of my graduation project for the completion of the Master's program Marine Technology at Delft University of Technology. The project has been carried out on behalf of TNO at which I have been a graduation intern at the Sustainable Transport and Logistics department. I was engaged in researching and writing this thesis from March to November 2018.

I am proud of the result and very satisfied about the process towards this. The type of work I did for my research was very well aligned with my interests and goals I had for a graduation project, which has kept me motivated and enthusiastic during the past months. The support I got from my daily supervisors - Austin Kana and Jorrit Harmsen - has contributed enormously to the result. Austin, I would like to thank you for your extensive involvement in the project during which you provided me guidance when I most needed it and valuable feedback on the work I did. Your honest and to the point approach and your experience on the topic helped me a lot in overcoming the obstacles I faced and to successfully finish this research. Jorrit, I would like to thank you for your important role in drawing the link between theory and practice, in which you taught me a lot on what aspects matter in maritime logistics and how I could use this in the interpretation of my results. I highly appreciate the freedom you gave me in carrying out my research, but more importantly, your availability at all times when I needed your opinion or feedback on my work. Also, I would like to thank professor Hans Hopman for his feedback and supervision during the progress meetings we had. Lastly, I want to thank the Head Operations of the company I did my case study for, for providing me the data I needed and gathering your colleagues involved with the vessel to have a discussion about the results. You provided me the opportunity to apply the tool on the case of a real vessel which was a valuable addition to the research and which I enjoyed a lot.

Finishing this project is a personal milestone marking the end of six amazing years of studying in Delft. My deepest gratitude goes to my parents who have always supported me during this time. Your continuous support helped me making the right decisions and taking the opportunities which has made my study time the amazing time it was. Thank you for everything.

*Seb van den Berg*
*Delft, November 1, 2018*

# Abstract

In April 2018, the International Maritime Organization (IMO) agreed upon the target to reduce the $CO_2$ emissions from international shipping in 2050 by 50 percent with respect to 2008 levels. The strategy to reach this target consists of the ambition to reduce $CO_2$ emissions per transport work, as an average accors international shipping, by at least 40% by 2030, compared to 2008 levels. However, due to uncertainties involved in the decision making on the implementation of $CO_2$ reducing measures, shipowners are uncertain which actions to take regarding their existing fleet in order to deal with those upcoming requirements.

For rail transport, road transport and inland waterway transport, TNO has developed the Multi-level Energy Optimization tool (MEO). For these modalities, MEO is capable of calculating the $CO_2$ emissions for a certain voyage and assessing the effect of $CO_2$ reducing measures on the carbon footprint of those voyages. The objective of the research presented in this report is to extend TNO's MEO tool with the maritime modality and develop a tool supporting shipowners in the decision making process regarding the pathway of implementing $CO_2$ reducing measures in sea-going vessels.

The tool presented in this report is developed to meet this objective and is based on a Markov Decision Processes (MDP) model. The MDP method has the ability of optimizing a time dependent decision policy in the face of uncertainty. In this case, the optimal policy resulting from the MDP model is optimized to obtain the highest cost savings by implementing $CO_2$ reducing measures. For the input of the model, the vessel has to be described by an operational profile and the vessel and engine specifics such as a speed-load curve and the propulsive efficiency. Also, the environment has to be described by fuel properties, economical parameters and a regulatory framework. With this input, the MDP method can assess the optimal policy regarding the implementation of a set of $CO_2$ reducing measures with the objective of minimizing costs. The output of the tool consists of the expected values of total costs, $CO_2$ emissions and $CO_2$ efficiency for when the optimal policy is followed, in comparison to maintain the business as usual.

To put this tool in practice, a case study has been carried out on a 93000 DWT bulk carrier of which operational data has been provided by the shipowner. A data analysis on the daily reports of the vessel has been done to obtain the values for the vessel input and literature has been used for the environment input. The optimal policy for a set of measures is assessed and the influence on the results by varying fuel prices, the regulatory framework and the dry dock schedule has been studied. The key result of the case study is that with the implementation of several fuel saving measures and a dual fuel engine the total costs with respect to maintaining the business as usual is expected to be reduced by 12%. Also, the total accumulated carbon emission reduction over 15 years is expected to be 29% and the $CO_2$ efficiency is improved by 45% without having to reduce the speed of the vessel.

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# 1

# Introduction

At the end of 2015, the *United Nations Climate Change Conference* - COP 21 - was held in Paris, France. This conference led to the Paris Agreement which is dealing with greenhouse gas emissions mitigation. One of the key elements of this agreement is the goal of keeping the increase in global average temperature to well below 2 degrees Celsius above pre-industrial levels. In April 2018, the members of IMO closed an agreement to cut $CO_2$ emissions from international shipping with 50% by the year of 2050, in order to contribute to the targets of the Paris Agreement. The exact policy related to these new targets are yet undefined, but it is inevitable the agreement will have consequences for this industry in the near future. Currently, the majority of ships are diesel powered and there is a large uncertainty in the best route to a considerable reduction in the emission of $CO_2$. Due to this uncertainty, shipowners are reluctant to act on short term. However, considering the long lifespan of vessels, it already is crucial at this moment to take potential changes and developments into account in the decision making on the requirements of new build and existing vessels.

In this report, a study which focuses on this problem is presented, which is the results of a project carried out at TNO and with the supervision of Delft University of Technology. In this chapter, the introduction of the research is given which starts with the problem background described in section 1.1. In section 1.2, the solution techniques for the problem which are currently used or available are described after which TNO's interest in the problem is elaborated on in section 1.3. Lastly, the research objective including the method proposal is to be found in section 1.4.

## 1.1. Problem background

The problem as described in the introduction of this chapter can be summarized in one problem statement, as to be seen below.

Problem statement:
*Shipowners are uncertain which actions to take in order to deal with future* $CO_2$ *emissions requirements for sea-going vessels.*

This problem statement contains some aspects which should be further defined in detail and therefore an elaboration will be made on some of its keywords in the following sections.

### 1.1.1. Stakeholders

In the problem statement, shipowners are defined as the subject experiencing the problem. However, there are several possible stakeholders who might be interested in or affected by the problem as described above, since solutions and actions taken by them or others could have consequences for these stakeholders. In the sections below, the parties with a possible interest in the problem are described, including the reasons why they might be interested.

**Shipowners**

A shipowner could be an individual or a company equipping and exploiting the vessel to ship cargo. Usually, the shipowner is not only responsible for the performance and financial aspects of the ship, but also for its maintenance and legal obligations. This includes the responsibility of the vessel being class-certified and meeting global and local regulations. Part of these regulations are the environmental requirements with respect to the maximum emissions of $CO_2$. These regulations will very likely become more strict in the future and, since maintenance programs are costly and time consuming, shipowners need to adapt to this sufficiently in advance of the moment these regulations come into force. Therefore, it is not only of interest for the shipowners what the current regulations are, but also the expected changes of these regulations in the foreseeable future. This could help them with deciding how to act to these changes and how to adapt their ship to meet these regulations. Possibilities for adaption to stricter $CO_2$ emission regulations are described in section 1.1.4.

### Ship operators

A ship operator is the person or party responsible for the operation of the ship owned by the shipowner. The shipowner and ship operator could be the same person or party, in which case the previous paragraph is applicable for the explanation of why this problem is of interest to the ship operator. However, the ship operator can also be a different party than the ship owner. In this case, the shipowner and ship operator have a contract transferring the rights of exploiting the ship from the shipowner to the ship operator in return for a certain price; a charterparty. There are three types of charters; the voyage charter, the time charter and the demise charter. A voyage charter is the hiring of a vessel between two ports and a time charter is the hiring of a vessel for a specific period of time. In both a voyage- and a time charter, the shipowner remains responsible for the emission requirements and maintenance activities of the vessel and therefore still is interested in the case, as described in the previous paragraph. The ship operator - or charterer - is in these cases not particularly interested in the actions to take to meet the emission requirements, but is interested in the consequences these actions have regarding the charter availability of the vessel. In other words, the ship operator of a voyage- or time charter is interested in knowing the maintenance and retrofit schedules of the vessel in order to match their shipping demand with the vessel charter availability. However, it is different for the case of a demise charter. In a demise charter agreement, all the rights and legal, financial and operating responsibilities are transferred from the shipowner to the ship operator. Therefore, the interests of the ship operator regarding the problem in the case of a demise charter are as those as described for the shipowner in the previous paragraph.

### Ship financiers

The problem described is also of interest to ship financiers. Ship financiers have to make an investment analysis for their financing activities regarding ships. Changing economical and technical environments could have consequences to the value of the ship and therefore it is important for them to evaluate the risks and opportunities involved in the investment. For instance, it has a substantial effect on the investment analysis when it is expected that a new build diesel powered ship requires a major retrofit after five years in order to meet future $CO_2$ emission regulations.

### Regulators

Regulating parties such as governments and the International Maritime Organization (IMO) could also have an interest in this problem, but in this case from an opposite point of view. If solutions would be found regarding to the actions to take by stakeholders with respect to meeting future $CO_2$ emission regulations, the adaptability of those stakeholders can be examined. For instance, a hypothetical outcome of stakeholders being able to adapt to a certain level of $CO_2$ emission reduction within a specific time frame could play a role in the decision making of regulators in terms of strictness of new regulations. Although the main motivation of stricter regulations would be to mitigate environmental damage, the knowledge of the adaptability of stakeholders could influence the terms of the regulations.

### Port Authorities

Responsibilities of port authorities include the facilitation of fuel bunkering and port access for ships. A port authority is interested in the problem since it needs to arrange the logistics of the fuel supply. If, for instance, LNG as a fuel gets broadly adopted, a port authority needs to adapt their supply chain in order to facilitate this sufficiently. Also, in the (questionable) case of Flettner rotors becoming the industry standard, the average height of ships will increase tremendously which has to be taken into account during the development of the port's infrastructure such as bridges and equipment such as gantry cranes.

#### Other stakeholders

Parties which could also have an interest in the problem, even though indirect, are shippers and third party logistic companies. They would be interested in the consequences the regulations will have on the freight rates. Also, nowadays it is more common for shippers to provide clients with the amount of $CO_2$ emitted by the shipping of their goods and trying to minimize those. However, since solving the problem as stated in the introduction of this chapter will not result in the consequences to the freight rates or client constraints, these stakeholders are not directly interested in the problem.

#### Stakeholders focused on in this thesis

The stakeholders included in this thesis are the ones responsible for the operational obligations; ship owners and demise charterers. These are the stakeholders which are directly affected by the problem and thus have the largest benefits of a solution. As described in the paragraphs above, operators of the other kind of charters have a more indirect relation to the problem and therefore are left out in this thesis in order to keep the approach focused and feasible. Since demise charter operators have in practice the same scope of work as ship owners, the stakeholders included in this thesis - shipowners and demise charterers - are from now on referred to as *shipowners*, for reasons of simplicity.

### 1.1.2. Carbon emission requirements

As mentioned before, stakeholders are uncertain which actions they should take in order to meet $CO_2$ emission requirements. In this section, an elaboration is made on $CO_2$ emission requirements; by which parties are these determined and what are the specifics of theses requirements, now and in the future?

#### Paris Agreement

From November 30, 2015 until December 12, 2015 the *2015 United Nations Climate Change Conference* - COP 21 - was held in Paris, France. This conference led to the Paris Agreement which is dealing with greenhouse gas (GHG) emissions mitigation. One of the key elements of this agreement is the goal of keeping the increase in global average temperature to well below 2 degrees Celsius above pre-industrial levels (United Nations, 2015). Although this is a legally valid and binding agreement, detailed consequences or direct legislation for the shipping industry is not included. Therefore, it is up to local governments and regulators to transform the elements of the agreement to goals and regulations for the shipping sector. This is, for instance, exactly what the European Commission did for the members of the European Union; they have set up objectives for the shipping sector which could be translated to binding legislation in the near future.

#### International Maritime Organization

The International Maritime Organization - IMO - is a specialized agency of the United Nations. IMO is the global standard-setting authority for the safety, security and environmental performance of international shipping. Its main role is to create a regulatory framework for the shipping industry that is fair and effective, universally adopted and universally implemented (IMO, 2018b). IMO has developed regulations and guidelines considering ship energy efficiency; the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Operational Indicator (EEOI) which are discussed in the paragraphs below.

The EEDI is a binding regulatory framework for the indication of the performance of the ship (Bazari, 2016). The EEDI is an index calculated during the design stage of new build vessels and gives an output with the unit of grams $CO_2$ emitted per ton cargo per nautical mile ($gCO_2$/ton-nm). IMO has developed a set of reference lines for these values (phase 0) as a function of the DWT per ship type by assessing data of ships in the year 2013. The binding goal is to reduce these values for new ships in three phases: -10% for 2015-2020 (phase 1), -15% to -20% for 2020-2025 (phase 2) and -30% for 2025 and after (phase 3), see figure 1.1. Shortly said, this means that new build ships in the near future gradually should be designed in a more efficient, less $CO_2$ emitting way.

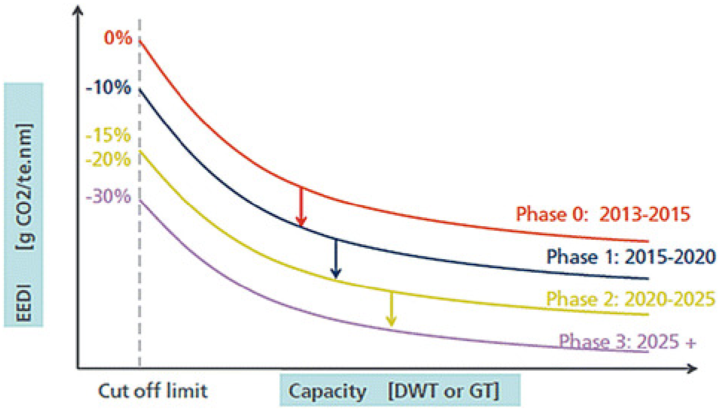

Figure 1.1: Energy Efficiency Design Index (EEDI) framework (Papanikolaou, 2016)

The EEOI is focused on the operational efficiency of ships and is, in contrary to the EEDI, not legally binding yet. The EEOI is an index with the purpose of monitoring and stimulating the improvement of $CO_2$ reduction by the effort in operation. Equally as for the EEDI, the EEOI is also defined as ($gCO_2$/ton-nm), but in this case calculated for one voyage or an average of a certain number of voyages. As mentioned, the EEOI is not legally binding and therefore there is no particular regulation stating to which value this should be decreased over time, but it could function as a valuable measurement method in combination with other regulations.

On April 13, 2018 IMO's Marine Environment Protection Committee (MEPC) signed an agreement in order to reduce $CO_2$ emissions from shipping. The agreement is in line with the goals of the Paris agreement and its vision is as follows: *IMO remains committed to reducing GHG emissions from international shipping and, as a matter of urgency, aims to phase them out as soon as possible in this century* (IMO, 2018a). The strategy consists of three ambitions:

1. Carbon intensity of the ship to decline through implementation of further phases of the energy efficiency design index (EEDI) for new ships to review with the aim to strengthen the energy efficiency design requirements for ships with the percentage improvement for each phase to be determined for each ship type, as appropriate;

2. Carbon intensity of international shipping to decline to reduce $CO_2$ emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008;

3. GHG emissions from international shipping to peak and decline to peak GHG emissions from international shipping as soon as possible and to reduce the total GHG emissions by at least 50% by 2050 compared to 2008.

### 1.1.3. Uncertainties

The problem in the introduction of this chapter states that shipowners are uncertain with respect to the actions to take in order to meet future $CO_2$ emission requirements. In this section, an elaboration will be made on the reasons for the shipowners to be uncertain and the factors influencing the decision making process.

#### Technologies

Currently, there are lots of $CO_2$ reducing technologies in development. Some of those technologies are in a late stage of development and will soon become, or already are, available to stakeholders. Other technologies are very promising but still in an early stage of development and need more time to become available to the market. Uncertainties come into play about the moment of availability of these technologies and their functionality at that moment. Also, existing technologies will be improved over time, but the rate of improving is uncertain and can only be speculated about. Another aspect is the practical impact on the $CO_2$ emission reduction; suppliers and researchers will claim a theoretical reduction to be obtained, but what is the real effect under installed and operating conditions? Another uncertain influence is the behaviour of competitors and other companies in the sector. Which technologies will get broadly adopted and experience an industry lock-in? This presumably would have a major effect on the availability and development rate of the technology, but is at the same time highly uncertain.

#### Regulations

While some targets and goals regarding $CO_2$ emissions are set, uncertainty still exist with respect to the translation to concrete regulations. What will be the limits of the regulations and when would they go into force? How much improvement is required in order to meet the regulations and what would be the consequence for the shipowner when these regulations are not met? These are all questions included in the uncertainty regarding regulations of $CO_2$ emissions.

#### Fuel prices

An everlasting uncertainty is the development of fuel prices. One could only guess and speculate about the price it is going to be tomorrow. However, fuel prices could have a major influence in the decision making when costs and profits are important decision factors for stakeholders. Therefore, a way should be found dealing with this particular uncertainty in a proper manner.

#### Economy

What is the economy expected to be tomorrow, the day after and the during upcoming future? Will there be a positive or a negative growth? As for the case of the fuel prices, the development of the economy is hardly to be predicted and highly uncertain. Still, the economy has a substantial influence on the freight rates and trading demand. If, for instance, the amount of $CO_2$ emission per transport work can be decreased with 25%, but the trading demand doubles, the net result is that the amount of $CO_2$ emitted is increased and that would be an unsatisfactory outcome in terms of total $CO_2$ reduction. Also, the economy affects the discount rate used by companies, which is an important factor in investment analyses.

### 1.1.4. Actions

In this section, an elaboration will be made on what is meant by actions to be taken by shipowners and what these could be exactly. Actions to be taken by shipowners should lead to a reduction in the ship's $CO_2$ emissions in order to meet the stricter regulations of the future. These actions can be distinguished by the moment in time they have to be taken; the ones to be taken today, the ones to be taken tomorrow and the ones to be taken at any time during the remaining lifetime of the vessel. These actions could be in the form of technical- or operational measures to the ship or possibly even changes in the business strategy. Mentioned measures will be explained in further detail in the following sections.

#### Technical measures

A technical measure is meant to be an improvement, overhaul, expansion or a complete exchange of a specific system or set of systems in the ship. These technical measures can be distinguished in roughly four categories: alternative fuel, alternative power source, energy saving devices and efficiency improvements. Those four categories will be described in the paragraphs below.

Currently, the major part of the vessels are powered by oil-based fuel engines such as heavy fuel oil (HFO) and marine diesel oil (MDO). These types of fuel contain a large amount of carbon which gets emitted in the form of $CO_2$ when burned. One of the technical measures to be applied in order to reduce the $CO_2$ emissions of the ship is the transition to an alternative fuel with a lower rate of carbon. Examples of these alternative fuels are liquefied natural gas (LNG), hydrogen ($H_2$) or biofuel. LNG and $H_2$ both contain a lower rate of carbon than oil-based fuels and therefore could be promising as an alternative fuel in order to reduce the $CO_2$ emissions (Faber et al., 2017; Momirlan and Veziroglu, 2005). Biofuels are, in contrast to oil-based fuels and LNG, produced through contemporary biological processes. Therefore, their carbon cycle is short and the net $CO_2$ emission by burning biofuels will be smaller comparing to diesel oil (Coronado et al., 2009). In other words, for all alternative fuels it applies that technical measures have to be made to the ship in order to facilitate the use of it. For instance, this could be an overhaul or exchange of the engine, new types of fuel tanks or additional safety measures.

Using alternative power sources could also lead to a reduction in $CO_2$ emissions (Bouman et al., 2017). Instead of obtaining energy from fuels, energy could be obtained from, for instance, batteries and fuel cells or renewable energy sources such as wind-, solar- or hydro power. To achieve this, technical improvements to the ship has to be made in order to be able to harvest energy from these sources.

Needless to say, energy saving devices lead to a reduction in energy consumption and therefore fuel consumption. A decrease of the amount of fuel burnt directly results in a decrease in $CO_2$ emissions. There are several examples of energy saving devices which could be either be applied on new build vessels or on existing vessels by means of a retrofit. Examples of systems which, in certain operational profiles, could function as energy saving devices are contra-rotating propellers, ducted propellers, waste heat recovery systems and air lubrication systems (Bouman et al., 2017).

While most of the $CO_2$ reduction with respect to efficiency improvement is expected to be found in the operational efficiency (see paragraph below), there are some technical options to be implemented in order to improve the ship's efficiency. For instance, an upgrade of the autopilot software or the ballasting software could result in a more efficient way to use the power systems on board (GloMEEP and DNV-GL, 2018).

#### Operational measures

By operational measures is meant that the way of operating and maintaining the ship is adjusted in order to obtain a decreased energy consumption per nautical mile. Operational measures have an impact on the EEOI of the ship, which is measured as emitted mas of $CO_2$ per transport work. An example for this is slow steaming, operation the vessel on a lower speed. In general, decreasing the sailing speed results in a decrease of fuel consumption per nautical mile. Also, weather routing could be an effective operational measure, since avoiding rough weather and heavy seas results in a reduction of the average power required during a trip and therefore the amount of $CO_2$ emitted.

Optimization of the maintenance schedules and policy of the ship is an operational measure which also could contribute to the decrease of fuel consumption. Included in this maintenance, a special focus could be to the cleaning and coating of the hull and the polishing of the propeller. When this schedule is optimized, it leads to a better overall efficiency of the ship.

#### Business strategy

Different shipowners could have different priorities in decision making factors (section 1.1.6). Dependent on these priorities, stakeholders could decide to change their business strategy instead of applying changes to the ship. For instance, for a shipowner it is very likely that profit optimization is the most important. It could be possible that retrofitting and operating the ship for the rest of its lifespan is less profitable than selling it directly. In that case a decision of the shipowner could be to sell the ship and buy a new one which already meets the requirements.

### 1.1.5. Vessels

This sections describes which types of vessels are to be distinguished and which ones are interesting to be studied. In a very broad view, there are two cases to be considered with respect to vessels. A vessel could either be an already existing vessel which has to maintain meeting the legislation or it could be a new build vessel in the form of a design or technical requirements. As mentioned, an already existing vessel has to be kept up to date with respect to new regulations and it might be possible that the ship in its original state is not able to achieve that. This would result in a case where the existing systems in a ship have to be either improved, expanded or exchanged by performing minor adaptions or a complete retrofit. In this case, the changing capabilities of the ship, such as reduced capacity or alternative maximum speed, have to be taken into account, as well as the feasibility of these changes. For new-build vessels, the case is different. Since the ship is yet only existing on paper, changes to the design have less consequences and are less costly to implement. However, due to the reason that there is no operational data available, it is more complicated to estimate the real emission performance of the ship.

The world's merchant fleet consists of a large variation of ships and the problem - and therefore the possible solutions - are different for every individual ship. However, in order to find solutions in an efficient way, ships could be classified by type and size and those in the same category are very comparable in properties and therefore solutions.

Ship types mainly are defined by the functionality of the ship and examples are container ships, oil tankers, bulk carriers and general cargo vessels. Sizes are classified according to appropriate ranges dependent on the ship type and therefore differ per type. However, container ships, oil tankers and bulk carriers are categorized in standardized ranges, such as Panamax, Suezmax and Capesize. In this report, the combination of ship type and ship size define the ship segment and those segments are defined as presented in figure 1.2.

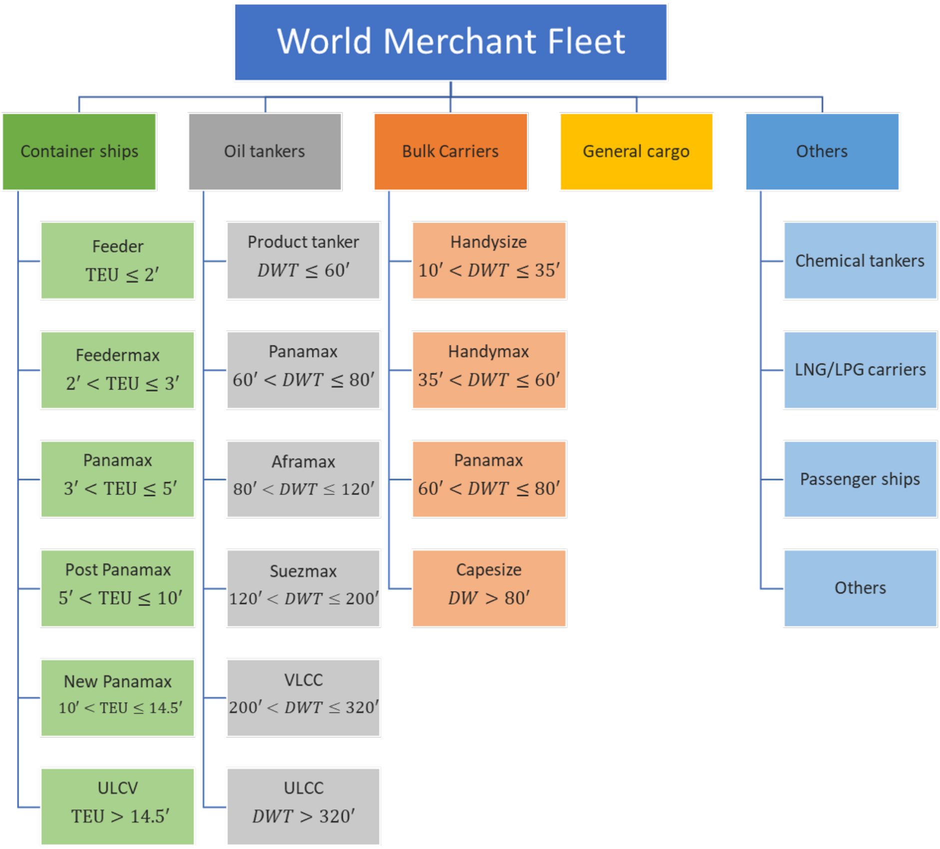

Figure 1.2: The world's merchant fleet distinguished by ship segments

According to the data of the United Nations Conference on Trade and Development (UNCTAD, 2018), the world's merchant sea-going fleet consisted in 2017 of a total amount of 93 161 vessels with a size equal or greater than 100 GT. In terms of deadweight tonnage (DWT), the total size of this fleet equals approximately 1.9 billion tonnes. In figure 1.3, the share of number of ships by ship type is presented and this is done for the share of DWT in figure 1.4. The ship types are divided in container ships, bulk carriers, oil tankers, general cargo and others, where the latter contains all other types such as - but not limited to - RoRo vessels, offshore supply vessels and passenger ships. It should be noted that UNCTAD's figures excludes fishing vessels, military vessels, yachts, and offshore fixed and mobile platforms and barges.

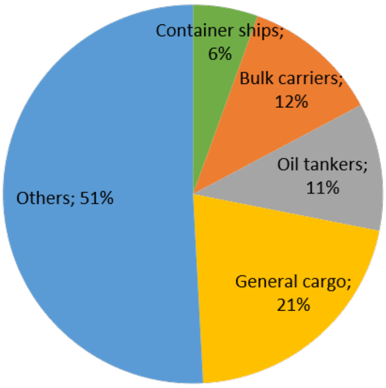

Figure 1.3: Share of world merchant fleet by number of ships on January 1, 2017 (UNCTAD, 2018)

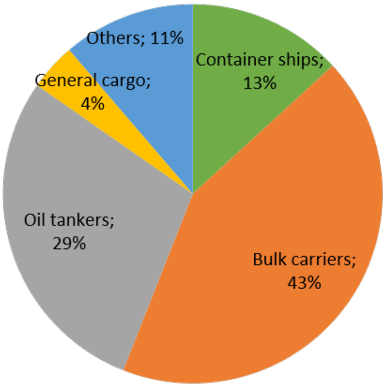

Figure 1.4: Share of world merchant fleet by DWT on January 1, 2017 (UNCTAD, 2018)

When comparing these shares, it is to be noted that 29% of the ships - namely container ships, bulk carriers and oil tankers - are accountable for 85% of the total deadweight of the fleet. This means that the average size of those vessels are substantially larger than that of the general cargo vessels and the ships in the category *other*. Figure 1.5 shows the average DWT per ship type, calculated by dividing the total DWT per ship type by the total number of vessels of that type.

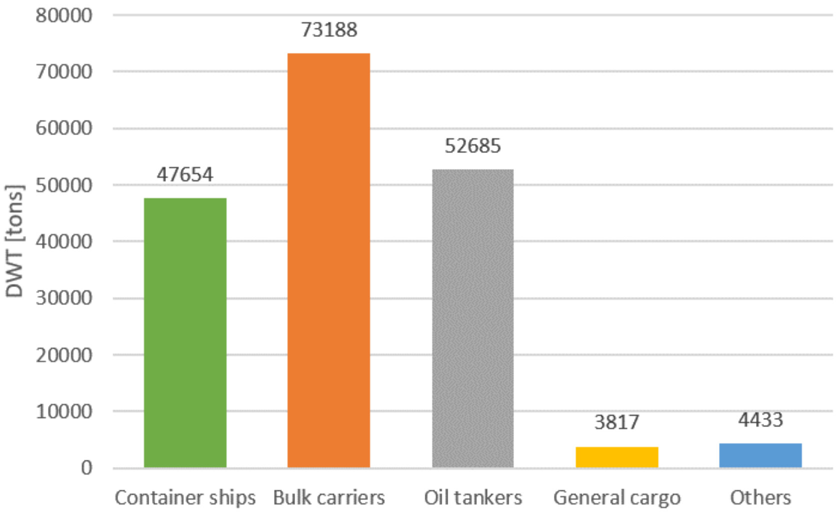

Figure 1.5: Average DWT per ship type

The International Council on Clean Transportation carried out a research on the GHG emissions from global shipping during the period of 2013-2015 (Olmer et al., 2017). One of the findings of this study is the share by ship type of the total $CO_2$ emissions due to global shipping during 2013-2015, see figure 1.6. In this figure it can be seen that 55% of the $CO_2$ emissions are accountable for the three biggest ship types mentioned before. Although these findings are based on the fleet in different years than 2017, the change in composition of the fleet between 2013 and 2017 is negligible small for the analysis made in this section. Also important to notice is the fact that the ship types excluded in the UNCTAD data is included in the data of the ICCT report, which means that the three biggest ship types are accountable for even more than 55% of the total $CO_2$ emissions by global shipping, in case the same ship types are excluded as in the UNCTAD data. In summary, the data presented above shows that 29% of the ships carry 85% of the total DWT and are accountable for more than 55% of the total $CO_2$ emissions of global shipping.

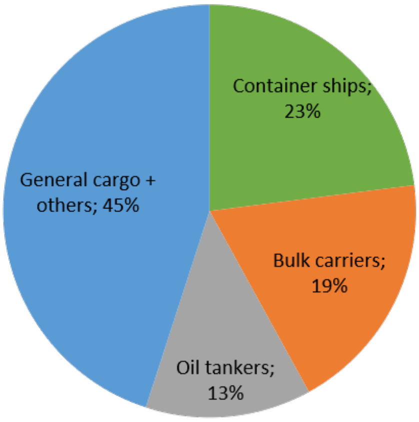

Figure 1.6: Share of total $CO_2$ emissions between 2013-2015 per ship type (Olmer et al., 2017)

As a consequence of changing economics and world shipping demand, the composition of the world fleet could change. For instance, there is a possibility that the number of oil tankers will drop in the future due to the transition to green energy supply and the decrease of oil demand. Although the possibility of a varying fleet composition is noticed in this study, the starting point for the research is the fleet composition as presented in this section.

### 1.1.6. Decision factors

Decision factors are the factors which are important for the shipowner and thus drive the decisions to be taken by him. Dependent on the person, company or other stakeholder, these decision factors could differ and priorities are in a different order. In the following sections, some of these possible decision factors are discussed.

#### Monetary

The majority of companies involved in the shipping industry are profit-driven. The main objective is to transport cargo or facilitate a service in order to earn money and make a profit. With this objective in mind, revenues and costs are the main decision factors of those companies. In other words, if a certain action is not expected to be profitable, or there are other possibilities with a higher potential, it would not be tempting to take this action in terms of the maximization of profits.

#### Technical development

Besides the aspect of uncertainty, the technical development of measures is also a important decision factor in the sense of market knowledge. For instance, a relatively new technology which is not yet widely adopted in the industry is difficult to maintain or operate due to the lack of experts. If regular maintenance on a measure can only be carried out in just a few places around the world, it might effect the profits the measure. The same goes for finding suitable personnel for the operation or on board maintenance of the measure.

#### Funding potential

For shipowners it is important that it is realistic to obtain funding for the measures they take. This could be either out of own equity for smaller measures or from other (financing) parties for large improvements. No matter how it gets funded, the potential for funding is an important decision factor for shipowners in the consideration of taking a certain action.

#### Continuation of operations

For shipping companies the continuation of their operational activities are of high importance. Taking certain actions could affect their ability of carrying out their usual operations and this effect would certainly be taken into account for the decision whether to take that action or not. For instance, if the transition to LNG would be considered and it turns out that it is not possible to bunker LNG at the ports the company ships to, it is unlikely that action would be taken. However, it is not required that exactly the same kind of operations should be able to be carried out. In the end it is important that the vessel can be operated in a market in which is sufficient demand, even though this is a different one. The vessel should be sufficiently flexible in order to account for these changes.

**Environmental**
Other decision factors, which nowadays are important, are environmental reasons. Shipowners, or at least a part of them, are well-aware of their environmental responsibilities and the importance of mitigating the burden to nature by their company activities. Depending on the shipowner, environmental decision factors could be lower or higher on the agenda and could be connected to monetary decision factors.

**Reputation and ethics**
Reputation and business values could be important for companies and therefore it is very likely it influences their decisions. A part of this is the message the company sends to the world with respect to their environmental beliefs and another part is the values of the company which relates to the question *'Am I doing the right thing?'*. A company could make the decision, for instance, to become completely $CO_2$ neutral, even if this would lead to lower (short-term) profits. It could function as a marketing strategy in order to gain good publicity and as a result of that attract more business.

## 1.2. Solution techniques

The problem of facing uncertain future requirements is nothing new for shipowners. Facing new requirements such as sulphur emission limits, safety regulations and ballast treatment requirements are some examples of legislation shipowners have to deal with every day. Generally said, the responsibilities of shipowners are to secure a financial healthy company and take the applicable risks into account. Considering the future $CO_2$ regulations, there are many uncertainties to be considered and there seems to be a general practical method which is used right now. Very basically said, for the decision to take $CO_2$ reducing measures at this moment, a few questions have to be answered by the shipowner. First of all, is it required to take measures in order to meet existing or soon to come in force regulations? Secondly, is it required to take measures in order to maintain a certain reputation or to meet client's requirements? Furthermore, what would be the expected costs and revenues of the measures and is it worth it feasible to invest in them considering the risks involved? Currently, in the majority of cases, all these questions are answered with *no* and therefore $CO_2$ reducing measures remain often unimplemented.

Trying to stimulate the process, lots of research is carried out regarding $CO_2$ emission mitigation in the international shipping industry. For instance, (Smith et al., 2014b) carried out the *Third IMO GHG Study* which focused on the current and expected status of $CO_2$ emissions regarding international shipping and possible reduction targets. In this report, a projection of different plausible future scenarios and their contributing $CO_2$ emissions by the shipping industry is presented. The study mainly focus on the current and expected situation and to a lesser extend on the specific actions to take in order to reduce the emissions from the shipping industry.

Also, (Smith et al., 2014a) studied the individual components of the global shipping system in order to guide the development of technologies and operation strategies for the reduction of shipping's $CO_2$ emissions. In this study, a system approach is applied in order to map the full carbon value chain of the shipping industry, including the ships themselves, ports and logistics and regulatory frameworks. Also included in this study are technologies and measures to be taken in order to reduce the $CO_2$ emission of ships. However, these technologies and measures are studied using a rather general approach which lacks to connection to specific ships or ship types in order for shipowners to make a use of it.

A study which provides a more practical focus is carried out by (Bouman et al., 2017) and focuses on the state-of-the-art technologies, measures and potential for reducing GHG emissions from shipping, combining a set of around 150 studies on this topic. This study provides a very useful overview of the available actions to take by shipowners and their contributing expected impacts. Part of the results is the range of $CO_2$ emission reduction potential of a range of measures. For instance, converting from diesel fuels to LNG has a $CO_2$ emission reduction potential in the range of 8% - 32%, according to the studies included in this review. Although it provides a useful overview, it is difficult for shipowners to project the results on their own case, since all presented studies in this paper use diverse constraints and methods.

IMO takes a step further in the sense of a practical approach for shipowners. IMO's GloMEEP and DNV-GL developed the appraisal tool with which several $CO_2$ reducing measures can be assessed dependent on the ship type (GloMEEP and DNV-GL, 2018). With this tool, the expected impact and contributing costs, profits and payback time of measures can be estimated. Although this provides a very practical approach for shipowners, some assumptions regarding the operational profile are made in the tool which have a substantial influence on the reliability of the results. The tool has a fixed operational profile depending on the ship type and size which also included the operational speed of the vessel. This assumption of the operational profile is unknown for the user and therefore it is not known to the shipowner to which degree the results are applicable and reliable for his ship. Due to this uncertainty, the tool remains to be a general method for shipowners to explore the measures which could possibly be worth it to take and lacks the individual focus shipowners need.

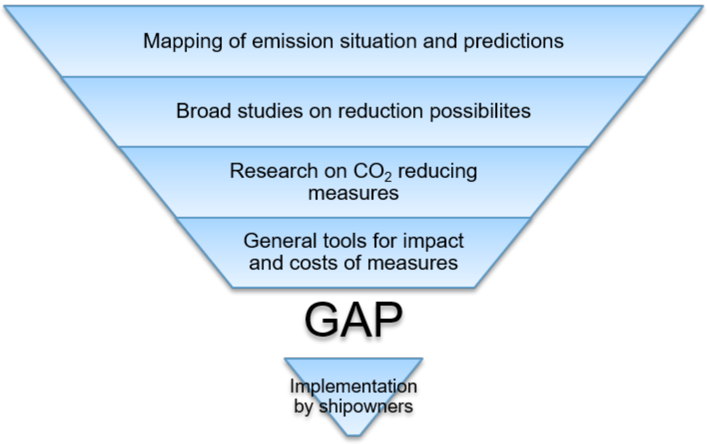

Figure 1.7: Solution techniques and knowledge gap with respect to solving the problem

In summary, there is lots of interest in the topic of $CO_2$ emission reduction, both by researchers and shipowners. Researchers are contributing by mapping the current and predicted $CO_2$ emissions due to shipping and also on mitigation measures and potentials to reach essential environmental targets. This research is of great importance for the final process of $CO_2$ emission reduction in vessels, but mainly focused on the fundamentals and broad scope. In general they lack the practical focus on specific cases in order for shipowners to make use of it. Therefore, it is challenging for shipowners to translate this research to practical actions and this contributes to the causes of reluctance described in the first paragraph (see figure 1.7). The study presented in this report tries to fill mentioned knowledge gap. The way this is done is described later on in this chapter (section 1.4), but first TNO's relation to the problem is described in the next section.

## 1.3. TNO's MEO tool

TNO has developed a tool to assess the environmental impact of several modes of transport: the Multi-level Energy Optimization tool - abbreviated as MEO. The modalities included in MEO so far are rail transport, road transport and inland waterway transport. For these modes of transport, the energy consumption for one voyage or several voyages can be determined and with a certain fuel mix the $CO_2$ emissions related to those voyages can be calculated. These results provided by the MEO tool are based on deterministic calculations and time independent.

For the rail transport modality, a mission profile describing a voyage of the train is required as an input. In MEO, this mission profile consists of a time step in seconds, the acceleration of the train per time step, the velocity and the length of the wagon combination, which is used to approximate its total weight. Additional to the mission profile, an engine model is required; what is the amount of energy required to carry out this mission profile and which fuel type (e.g. diesel or electricity) is used to deliver this energy? With an engine efficiency included in the engine model, the amount of fuel required for the voyage can be calculated and subsequently the $CO_2$ emissions of the train during that voyage.

Figure 1.8: The MEO tool supports fuel consumption analyses on road transport, rail transport and inland waterway transport

A mission profile is also required as an input for the road transport modality, in MEO included as trucks. A mission profile of a truck is - as for a train - also described by its acceleration and velocity over time. The weight, however, is determined by the load factor of the truck and another additional aspect which is important for the energy consumption of a truck is the angle of inclination (slope) of the road. Together with the engine model of the specific truck, the energy consumption and $CO_2$ emissions during the voyage can be calculated. An additional feature in MEO for the road transport modality is the possibility to asses the effects of technical measures taken to improve the performance of the truck. Examples of technical measures could be fuel saving measures such as drag reducing spoilers or fuel changing measures such as LNG engines rather than diesel engines. MEO offers the possibility to assess the impact on the $CO_2$ emissions of the truck over a certain voyage by implementing those measures.

The appropriate term for the mission profile of a inland ship is an operational profile. Although the purpose is the same, the aspects included in an operational profile for an inland ship are different than those for train and trucks since the energy consumption is dependent on different physical phenomena. For the operational profile of an inland ship, MEO requires the sailing speed, the load factor, the water current and the depth and width of the applicable waterway. With an engine model applicable for the specific ship, the energy and fuel consumption can be calculated, as well as the $CO_2$ emissions. As for the road transport modality, MEO has also the possibility to asses the effects on the $CO_2$ emissions of the ship by implementing technical measures. For inland ships, these technical measures are limited to changes in the drive train, such as a retrofit from diesel engine to diesel electric power supply or an LNG engine.

The input and output parameters of the MEO model for the road, rail and inland waterway transport modalities are schematically illustrated in figure 1.9.

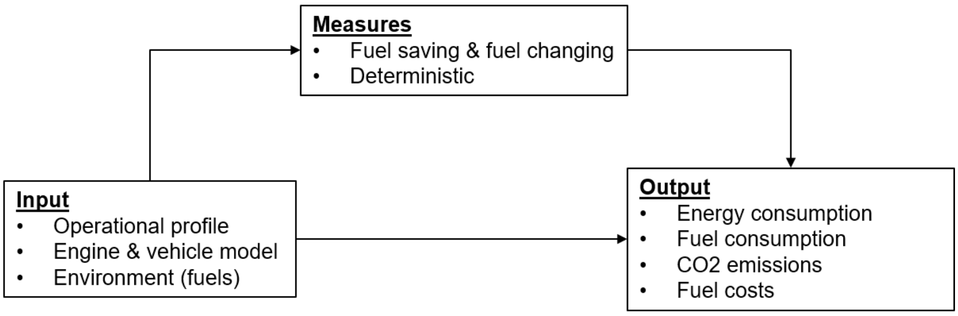

Figure 1.9: A schematic representation of the input and output parameters of the MEO model

Maritime transport is a widely used modality for both people and cargo transportation, but is not yet included in the MEO tool. Although shipping cargo by vessels is - in comparison to the other modalities - a relatively clean transportation alternative, international shipping is a large contributor to global $CO_2$ emissions (Smith et al., 2014b). Also, due to the long lifetime of vessels - as described before - the uptake of new $CO_2$ reducing measures in the shipping industry goes fairly slow in comparison to other sectors. As a result from this slow uptake, research, development and especially results on the impact of these measures are limited available and the true impact of these measures are uncertain (see section 1.1.3). TNO desires the addition of the maritime transport modality in the MEO tool which is able to asses the environmental performance of seagoing vessels and the impact of $CO_2$ reducing measures taken to the vessel.

## 1.4. Research objective

In section 1.2, several approaches are described which are used in order to deal with the problem of reaching low carbon emissions in sea-going vessels. As summarized in figure 1.7, the environmental impact by international shipping is mapped and studies are available on $CO_2$ reduction opportunities. Also, research is done on the development of specific $CO_2$ reducing measures and the impact of these measures can be theoretical tested for certain ship segments by various tools. However, due to unknown and important assumptions taken in these tools, it is difficult to get results focused on a specific ship and due to this uncertainty actions by shipowners remain untaken. The objective of this research is to fill this gap by offering shipowners an approach which is more custom made by translating the literature to a specific ship and dealing with uncertainties shipowners are experiencing.

An important aspect in dealing with uncertainties regarding the investment in $CO_2$ reducing measures is the time aspect. Since the maritime environment (e.g. fuel prices, regulations) is dynamic and changing every year, the costs and benefits - both financially and environmentally - of those measures are dynamic as well. Where currently existing tools generally are time independent, it is believed that shipowners benefit from a tool which can take these changes over time into account in order to gain a more complete view of the risks and benefits involved.

The proposed method which is able to deal with both uncertainties and a time aspect is Markov Decision Processes (MDP). The MDP method has the ability of optimizing a time dependent decision policy in the face of uncertainties and probabilities. Using a MDP framework, the decision maker - in this case the shipowner - is assumed to take those actions in order to maximize its utility. In other words, every time step the shipowner can decide to implement one or more measures which leads to the greatest costs savings during the analysis period. The MDP is modeled to be memoryless, which means that decisions are only based on the situation at that moment and the opportunities of the future from that moment on. A representative application of this method is provided by (Kana et al., 2015), in which MDP is used for the analysis of temporal design and decision pathways involving the impact of evolving emission control areas on the design and operation considerations of a container ship. That study shows that the MDP method can be used to assist in making investment decisions in the maritime environment considering regulations, uncertainties and a time aspect. More relevant applications of the MDP method are described in section 2.1. Combining the information presented in this chapter, the thesis objective can be defined as below:

Thesis objective:
*Develop an extension of TNO's Multi-level Energy Optimization tool supporting shipowners in the decision making process regarding the pathway of implementing $CO_2$ reducing measures in sea-going vessels in the face of uncertainty, using Markov Decision Processes.*

To fulfill the thesis objective and focus on the knowledge gap, TNO's MEO tool (see section 1.3) is expanded with the maritime modality. First of all, the maritime extension should work with the same types of input requirements and output values as the other MEO modalities in order to be consistent. Additionally, the maritime extension will be based on the MDP method, which provide the opportunity to include the probability and time aspect. When the addition of the MDP method is proved to be valuable, TNO considers to implement this method for the other modalities as well. However, the implementation of the MDP method within the road, rail and inland waterway transport modalities is beyond the scope of this research. The relation of the maritime model to the already existing MEO tool is schematically shown in figure 1.10.

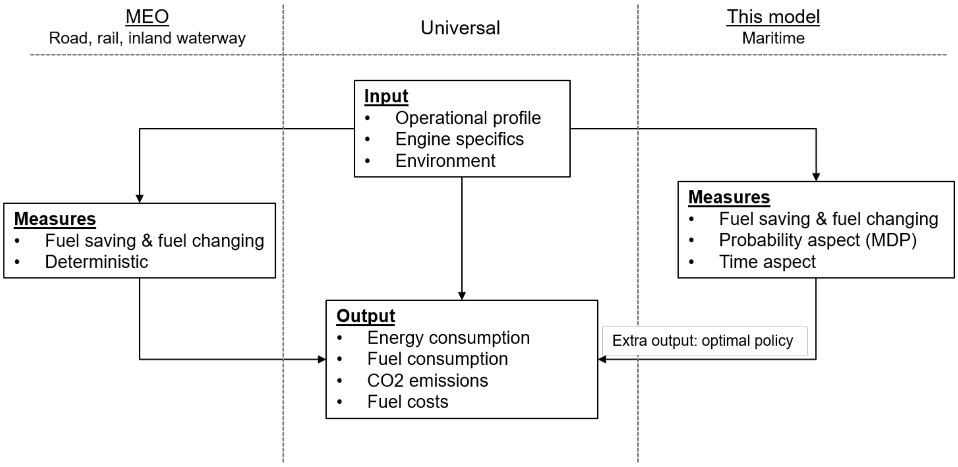

Figure 1.10: A schematic representation of the input and output parameters of the MEO maritime expansion

In order to fulfill the thesis objective considering the problem background described earlier in this chapter, the requirements of the tool are as listed below.

The tool should:

- be based on a framework which could be applied to the most relevant ship segments of the world's merchant fleet; container vessel, oil tankers and bulk carriers;
- be based on input data which is generally available to shipowners;
- be able to analyze both individual measures and sets of combined measures;
- deal with uncertainties regarding the impact of $CO_2$ reducing measures and upcoming regulations;
- determine the best moment of implementing measures in order to minimize total costs;
- determine the expected and extreme values of the impact on the ship's $CO_2$ efficiency and the accumulated $CO_2$ reduction in accordance with the output of the other modalities included in MEO;
- determine the expected and extreme values of the accumulated costs and savings with respect to the business as usual in accordance with the output of the other modalities included in MEO;
- determine the expected payback time of individual measures and the break-even year of combined investments.

# 2

# Markov Decision Processes

In this chapter, the theory of Markov Decision Processes (MDP) is described. This theory will function as a foundation of the model which is described in chapter 3. In section 2.1, earlier relevant applications of MDP in the maritime environment are described. Thereafter, a general description of the MDP theory is given in section 2.2. At last, an example case is described in section 2.3, which shows the theory applied on a similar problem proving the validity of the method.

## 2.1. Earlier applications

Prior to this research, MDPs has been used in several other studies in the maritime environment. In this section, a few of those studies are listed and elaborated on. Note that this is just a selection of MDP applied in the maritime environment and does not give a complete outline.

- *Ship design evaluation subject to carbon emission policymaking using a Markov decision process framework* (Niese et al., 2015). This study uses MDP to evaluate the flexibility of ship designs with respect to meeting future EEDI regulations. The study shows the possibility of using MDPs for dealing with optimal design decisions in the face of uncertain policy making.
- *A decision-making framework for planning lifecycle ballast water treatment compliance* (Kana et al., 2016). This study focuses on the policy making regarding the implementation of ballast water treatment systems. The MDP method is used to optimize for the financially most favorable systems, which are undergoing uncertain technological development throughout time.
- *A Markov Decision Process Framework for Analyzing LNG as Fuel in the Face of Uncertainty* (Kana et al., 2015). In this study, the conversion from a diesel engine to a LNG dual fuel engine of a container ship is analyzed. Using MDP, the most profitable policy regarding the retrofit decision making is explored, considering several kinds of uncertainties such as fuel prices, fuel supply chain risks, regulatory framework and more.

The studies listed above all make use of the MDP method in the maritime environment and are in some way all linked to the kind of problem in this study. It shows that MDPs are suitable to use when dealing with complex ship design and retrofit decisions under uncertain circumstances.

## 2.2. MDP theory

Before diving into the theory of Markov Decision Processes, a step back will be taken to the underlying basis of this method: the Markov chain. A Markov chain is capable of dealing with stochastic state changes within a system and a definition is given by (Sheskin, 2016):

> *A Markov chain is an indexed collection of random variables used to model a sequence of dependent events such that the probability of the next event depends only on the present event. In other words, a Markov chain assumes that, given the present event, the probability of the next event is independent of the past events.*

The Markov chain describes a stochastic process which is observed at equally spaced points in time called epochs. At each epoch, the system is observed to be in one of the finite number of states in the system. At each period - the time step between two epochs - the system can move to another state dependent on the transition probabilities corresponding to the initial state. According to this, a Markov chain is defined by a set of states and a set of transition probabilities which is clarified below by means of an example.

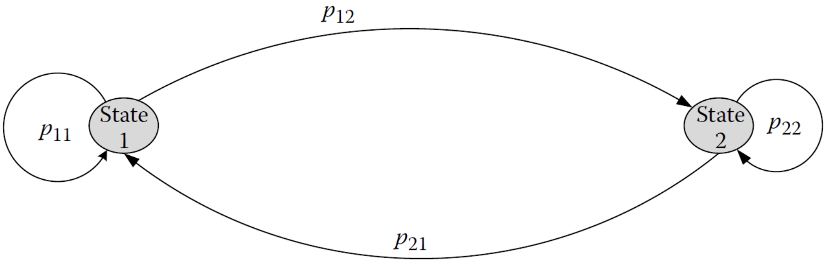

Figure 2.1: Representation of a simple two-state Markov chain (Sheskin, 2016)

A representation of a simple two-state Markov chain is shown in figure 2.1. According to this setup, the states can be defined in a state vector **S** (equation 2.1) and the transition probabilities of moving from one state - $s_n$ - to the next one - $s'_n$ - in a transition matrix $M$ (equation 2.2).

$$\mathbf{S} = \begin{pmatrix} s_1 & s_2 \end{pmatrix} \tag{2.1}$$

$$M(s'|s) = \begin{array}{c c} & \begin{array}{cc} s'_1 & s'_2 \end{array} \\ \begin{array}{c} s_1 \\ s_2 \end{array} & \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \end{array} \tag{2.2}$$

Now, the probabilities of the system being in a certain state at any moment in time - epoch n - can be calculated according to equation 2.3. In this equation, $\mathbf{S}_{n+1}$ is calculated by multiplying the state vector during the epoch before with its corresponding transition matrix.

$$\mathbf{S}_{n+1} = \mathbf{S}_n\, M_n \tag{2.3}$$

A Markov Decision Process (MDP) is an extension of Markov chains in which - besides the state vector and transition matrix - also rewards and actions are included. MDP is a method for solving dynamic and sequential decision-making problems in a stochastic environment (Puterman, 2014) and a short description is also given by (Sheskin, 2016):

> *A Markov decision process is a sequential decision process for which the decisions produce a sequence of Markov chains with rewards. (...) A MDP generates a sequence of states and an associated sequence of rewards as it evolves over time from state to state, governed by both its transition probabilities and the series of decisions made.*

Besides the set of states included in a Markov chain, MDP also consists of a set of actions to be taken in each state $A(s)$, a reward function $R(s)$ and an expanded transition matrix $P(s'|s,a)$ (Russell and Norvig, 2016). This means that at any epoch a decision can be made which affects the transition probabilities to states in the following epoch and that entering a state results in a reward of a certain kind. Over a specific time period with N epochs, the obtained rewards can be translated to a obtained utility of a state sequence, $U_h$, using discounted rewards, as to be seen in equation 2.4.

$$U_h([s_0, s_1, s_2, \ldots, s_N]) = R(s_0) + \gamma R(s_1) + \gamma^2 R(s_2) + \cdots + \gamma^N R(s_N) \tag{2.4}$$

In the equation above, $\gamma$ is the discount factor which is a number between 0 and 1. The discount factor accounts for the preference of current rewards rather then future rewards. A real life example where current rewards are preferred over future rewards is during financial net present value calculations, where money earned today is of higher value than money earned tomorrow.

The utility function as presented in equation 2.4 is for a fixed time period with N epochs. The analysis of a fixed number of epochs makes the MDP a finite horizon for decision making which means that the analysis is only based on this time frame N, after which nothing matters. During this time frame, the expected utility for each state at any epoch is calculated by the Bellman Equation, presented in equation 2.5. The Bellman Equation defines the utility of a state as the immediate reward for that state plus the expected discounted utility of the next state, assuming that the optimal action is taken (Puterman, 2014; Russell and Norvig, 2016).

$$U(s) = R(s) + \gamma \max_{a \in A(s)} \sum_{s'} P(s'|s,a)U(s') \tag{2.5}$$

To goal of a MDP is to maximize the utility function and in order to this, the action at state $s$ is taken which maximizes the utility of the next state, $s'$. These optimal actions, combined in an optimal decision policy $\pi(s)$, can be obtained by taking the argument of the max operator of the Bellman Equation, as shown in equation 2.6.

$$\pi(s) = \arg\max_{a} \sum_{s'} P(s'|s,a)U(s') \tag{2.6}$$

For finite horizon MDPs, the optimal policy can be found by solving equation 2.6 via backward induction (Puterman, 2014). This method start solving the problem at the end of the period - at epoch N - and works its way back to the starting state in order to find the optimal action for each state in any epoch.

The MDP theory described in this section will be clarified by means of a example presented in section 2.3, where MDP is used to solve a representative problem for this study in order to proof its functionality.

## 2.3. Proof of concept

In this section, the way of modelling the Markov Decision Process of this research is clarified and the method is proved to work for the intended application of this research. This is done by carrying out a fictional and simplified case study related to the real objective of this study. Based on the methodology described in 2.2, the MDP input values and results of this example are determined.

Note that this is an test case with the purpose of showing the technique behind MDP and the results coming from it. It is an example which can prove the trustworthiness of the method before it gets more complex by expanding the model. The real MDP to be modelled will be more extensive and include more aspects, as described in chapter 3.

### Problem description

This is a test case for one measure to be studied over a time frame of 20 years, or 20 epochs. Assume the $CO_2$ reducing measure to be studied is Trim/Draft Optimization Software, hereafter called TDOS. An analysis is made regarding the optimal policy regarding the implementation of TDOS and the resulting expected utility following from that policy. Note that all values in this example are fictional and merely for the purpose of clarifying the implementation of the MDP method.

First of all, the states and actions of the MDP model are defined as shown in equations 2.7 and 2.8 respectively. An important simplification made here with respect to the real model is that regulations and the costs of not meeting them are not taken into account. The purpose of this is to keep the example simple in order to be able to clarify the technique behind the MDP method.

$$\mathbf{S} = \begin{pmatrix} s_1 \\ s_2 \\ s_3 \\ s_4 \end{pmatrix} = \begin{pmatrix} \text{Not implemented} \\ \text{Implemented, minimal impact on fuel consumption} \\ \text{Implemented, average impact on fuel consumption} \\ \text{Implemented, maximum impact on fuel consumption} \end{pmatrix} \tag{2.7}$$

$$\mathbf{A} = \begin{pmatrix} a_1 \\ a_2 \end{pmatrix} = \begin{pmatrix} \text{Do nothing} \\ \text{Implement TDOS} \end{pmatrix} \tag{2.8}$$

### Reward matrix

The reward in this problem is total costs and, as opposed to the theory described in section 2.2, the objective is to minimize the utility function resulting from those rewards. The total costs is a combination of fuel costs, additional operational costs when TDOS is implemented (e.g. software updates) and investment costs of TDOS. Fuel costs and operational costs are dependent on the MDP state and the investment costs are dependent on the MDP action, as to be seen in equation 2.9.

$$\min R(s,a) = C(s)_{fuel} + C(s)_{operational} + C(a)_{investment} \tag{2.9}$$

Important to realize is that the fuel costs are dependent on the MDP states from equation 2.7. The relationship between the state and the fuel costs are due to the fact that the change in state means a change in the vessel's fuel consumption which means a change in fuel costs, assuming all other variables remain unchanged. For simplicity reasons, the fuel costs in this example case are assumed to be 5M dollars for the state without TDOS implemented. Minimal impact when implemented ($s_2$) results in a fuel consumption reduction of 2%, average impact ($s_3$) in a reduction of 4% and maximum impact ($s_4$) in a reduction of 6%. This results in the fuel costs vector as shown in equation 2.10.

$$\mathbf{C}(s)_{fuel} = \begin{pmatrix} 5.0 \cdot 10^6 \\ 4.9 \cdot 10^6 \\ 4.8 \cdot 10^6 \\ 4.7 \cdot 10^6 \end{pmatrix} \tag{2.10}$$

Operational costs are set to be 5000 dollars per year when TDOS is implemented, so for states $s_2$, $s_3$, and $s_4$. This results in the operational cost vector as shown in equation 2.11.

$$\mathbf{C}(s)_{operational} = \begin{pmatrix} 0 \\ 5000 \\ 5000 \\ 5000 \end{pmatrix} \tag{2.11}$$

Investment costs of the TDOS software, to be paid when action *"implement TDOS"* is taken, are set to be 300 000 dollars. This results in the action dependent investment costs vector as shown in equation 2.12.

$$\mathbf{C}(a)_{investment} = \begin{pmatrix} 0 \\ 0.3 \cdot 10^6 \end{pmatrix} \tag{2.12}$$

When combining these cost matrices, the total reward matrix results to be as the one in equation 2.13. This reward matrix is one of the inputs of the MDP algorithm.

$$R(s,a) = \begin{array}{c} \\ s_1 \\ s_2 \\ s_3 \\ s_4 \end{array} \begin{array}{c} \begin{array}{cc} a_1 & a_2 \end{array} \\ \begin{pmatrix} 5.000 & 5.300 \\ 4.905 & 5.205 \\ 4.805 & 5.105 \\ 4.705 & 5.005 \end{pmatrix} \end{array} \cdot 10^6 \tag{2.13}$$

## Transition matrix

One of the other inputs of the MDP algorithm is the transition matrix $P(s'|s,a)$, which is shown in equations 2.14 and 2.15. The meaning of the transition matrix is as follows:

For action $a_1$, *"Do nothing"*, the state remains unchanged during the transition to the next epoch. For the action $a_2$, *Implement TDOS*, the probability equals 1/3 each to reach the state of minimum, average or maximum impact. When TDOS is already implemented, this action just leads to the original state which means that a further decrease of the fuel consumption is not possible.

$$P(s'|s,a_1) = \begin{array}{c} \\ s_1 \\ s_2 \\ s_3 \\ s_4 \end{array} \begin{array}{c} \begin{array}{cccc} s'_1 & s'_2 & s'_3 & s'_4 \end{array} \\ \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{array} \tag{2.14}$$

$$P(s'|s,a_2) = \begin{array}{c} \\ s_1 \\ s_2 \\ s_3 \\ s_4 \end{array} \begin{array}{c} \begin{array}{cccc} s'_1 & s'_2 & s'_3 & s'_4 \end{array} \\ \begin{pmatrix} 0 & 1/3 & 1/3 & 1/3 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{array} \tag{2.15}$$

## Results

This problem is a simple example and the expected result can be reasoned without using MDP. The expected payback period of the investment in TDOS can be calculated according equation 2.16.

$$\text{Payback time} = \frac{\text{Investment costs}}{\text{Fuel savings} - \text{Operational costs}} = \frac{0.3}{1/3 \cdot (0.1 + 0.2 + 0.3) - 0.005} = 2 \text{ years} \tag{2.16}$$

With the reward matrix and the transition matrix as an input, the Bellmann operator is solved for 20 years with a discount factor of $\gamma = 1$ (neglecting discounts on future rewards). The resulting optimal policy list is shown in table 2.1. It can be seen that when being in the state that TDOS is implemented ($s_2$, $s_3$ and $s_4$), the optimal action is to do nothing. This makes sense since it is not possible to improve its impact on the fuel consumption even more and therefore, investing (again) in the system is a loss of money. However, when being in state $s_1$ (TDOS not implemented), the optimal action for the first 18 years is to invest in TDOS. For the last two years of the analysis, the policy is not to make the investment. Again, this makes sense, since it is based on the payback period calculated in equation 2.16. It is simply too late to invest in TDOS in year 19 and 20, since the investment is not expected to be paid back within the end of the analysis period. For earlier years it is expected to be paid back and the sooner it is implemented, the lower the total accumulated costs are at epoch 20. Following the optimal policy, as shown in table 2.1, results in the expected utilities as shown in table 2.2. This table indicates the expected accumulated costs dependent on the year and the state the vessel is in.

Table 2.1: Resulting policy table ($a_1$ = do nothing, $a_2$ = implement TDOS)

| **Year** | **s₁** | **s₂** | **s₃** | **s₄** |
|---|---|---|---|---|
| **1** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **2** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **3** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **4** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **5** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **6** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **7** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **8** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **9** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **10** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **11** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **12** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **13** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **14** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **15** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **16** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **17** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **18** | $a_2$ | $a_1$ | $a_1$ | $a_1$ |
| **19** | $a_1$ | $a_1$ | $a_1$ | $a_1$ |
| **20** | $a_1$ | $a_1$ | $a_1$ | $a_1$ |

Table 2.2: Resulting expected utility table when optimal policy is carried out

| **Year** | **s₁** | **s₂** | **s₃** | **s₄** |
|---|---|---|---|---|
| **1** | 9.6595e+07 | 9.81e+07 | 9.61e+07 | 9.41e+07 |
| **2** | 9.179e+07 | 9.3195e+07 | 9.1295e+07 | 8.9395e+07 |
| **3** | 8.6985e+07 | 8.829e+07 | 8.649e+07 | 8.469e+07 |
| **4** | 8.218e+07 | 8.3385e+07 | 8.1685e+07 | 7.9985e+07 |
| **5** | 7.7375e+07 | 7.848e+07 | 7.688e+07 | 7.528e+07 |
| **6** | 7.257e+07 | 7.3575e+07 | 7.2075e+07 | 7.0575e+07 |
| **7** | 6.7765e+07 | 6.867e+07 | 6.727e+07 | 6.587e+07 |
| **8** | 6.296e+07 | 6.3765e+07 | 6.2465e+07 | 6.1165e+07 |
| **9** | 5.8155e+07 | 5.886e+07 | 5.766e+07 | 5.646e+07 |
| **10** | 5.335e+07 | 5.3955e+07 | 5.2855e+07 | 5.1755e+07 |
| **11** | 4.8545e+07 | 4.905e+07 | 4.805e+07 | 4.705e+07 |
| **12** | 4.374e+07 | 4.4145e+07 | 4.3245e+07 | 4.2345e+07 |
| **13** | 3.8935e+07 | 3.924e+07 | 3.844e+07 | 3.764e+07 |
| **14** | 3.413e+07 | 3.4335e+07 | 3.3635e+07 | 3.2935e+07 |
| **15** | 2.9325e+07 | 2.943e+07 | 2.883e+07 | 2.823e+07 |
| **16** | 2.452e+07 | 2.4525e+07 | 2.4025e+07 | 2.3525e+07 |
| **17** | 1.9715e+07 | 1.962e+07 | 1.922e+07 | 1.882e+07 |
| **18** | 1.491e+07 | 1.4715e+07 | 1.4415e+07 | 1.4115e+07 |
| **19** | 1e+07 | 9.81e+06 | 9.61e+06 | 9.41e+06 |
| **20** | 5e+06 | 4.905e+06 | 4.805e+06 | 4.705e+06 |

# 3

# Model description

In this chapter, the features and capabilities of the model created during this research are described. First of all, section 3.1 will focus on the required vessel input parameters. In section 3.2, the requirements and capabilities with respect to the $CO_2$ reducing measures to be analyzed are described and the environment input variables in section 3.3. Thereafter, in section 3.4, a description is made of the total cost function to be optimized in the analysis which all will lead to the translation to a MDP model as described in section 3.5. Lastly, the method to calculate the results and the data coming from the model are described in section 3.6, after which the computational memory limitations of the model are discussed in section 3.7.

## 3.1. Vessel input

The input for the model can be distinguished in two parts: a typical operational profile of the vessel and the base performance of the vessel. Both inputs will be discussed in the paragraphs below.

One of the inputs for the model is a typical operational profile of the vessel to be studied. This operational profile could cover one typical voyage which is made by the ship in general or one that covers a longer period with more than one voyage. The conditions for this input to be suitable for the model is that it covers a minimum of one voyage and a maximum of one year. This maximum is defined by the analysis interval - or the epoch duration in terms of MDP - which is defined to be one year (see section 3.5). The operational profile input must consists of four sets of data. First of all, the ship's speed and the deadweight tonnage loaded with respect to the maximum DWT capacity must be included. The speed of the vessel gives information about the distance sailed by the ship and the combination of speed and DWT can be translated to the required load of the main engine(s), which is discussed in the following paragraph. Another required set of data is the load of the auxiliary engine(s) with respect to the total installed auxiliary power in order to determine the auxiliary fuel consumption. The last data to be included is the cargo loaded in the ship, which is required to determine the $CO_2$ efficiency of the ship. A fictional example of an operational profile as input for the model is shown in figure 3.1. Furthermore, an operational factor has to be included in the input. This factor describes the amount of time the operational profile input is carried out by the vessel. The remaining time accounts for dry docking, maintenance and other unexpected events during which the vessel cannot be operational. Additionally, an optional dry docking schedule can be included in the input. This dry dock schedule could have an impact on the moments and costs related to the implementation of measures; scheduling an additional dry docking for implementing a measure will lead to an increase in costs related to this investment. The dry dock schedule is created by inserting the year of the next scheduled dry dock and the scheduled dry dock interval of the vessel.

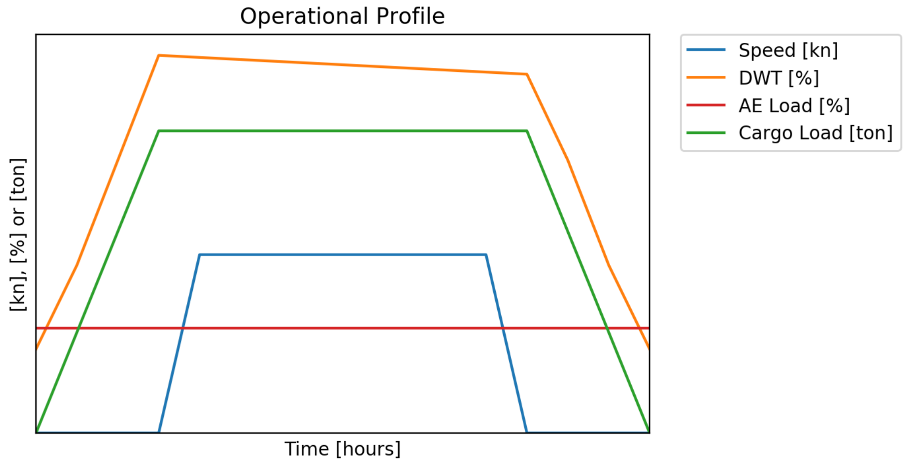

Figure 3.1: A fictional example of an operational profile as input for the model

The second part of the input are the base performance specifics of the vessel to be studied. These specifics describe the initial performance of the vessel based on a analysis of its operational data. The first specific is a constant describing the propulsive energy efficiency; what is the average ratio of energy supplied by the main engine and the energy consumed by the burning of fuels? Included in this constant are all mechanical, thermal and other losses between the fuel tank and the output of the engine. The second performance specific is a constant describing the auxiliary efficiency; what is the average ratio of energy supplied by the auxiliary engine(s) and the energy consumed by the burning of fuels? As for the propulsive efficiency, this constant also includes all losses between the fuel tank and the auxiliary engine output. Another input is a normalized vector which represents the share of fuel types burnt, in terms of kWh. For many ships nowadays, this would for instance be a share between HFO and MDO, but in the future this may swift to a share including other types of fuel such as LNG or biofuels. The last performance input is a table in which the average main engine load as a function of the speed and DWT of the vessel is given. A fictional example of such a table is shown in figure 3.2, where there is speed-load relation to the third power and a linear relation between DWT-load. Note, however, that obtaining this table from a data analysis would most probably not result in such a fluent and complete table and that interpolation would be required.

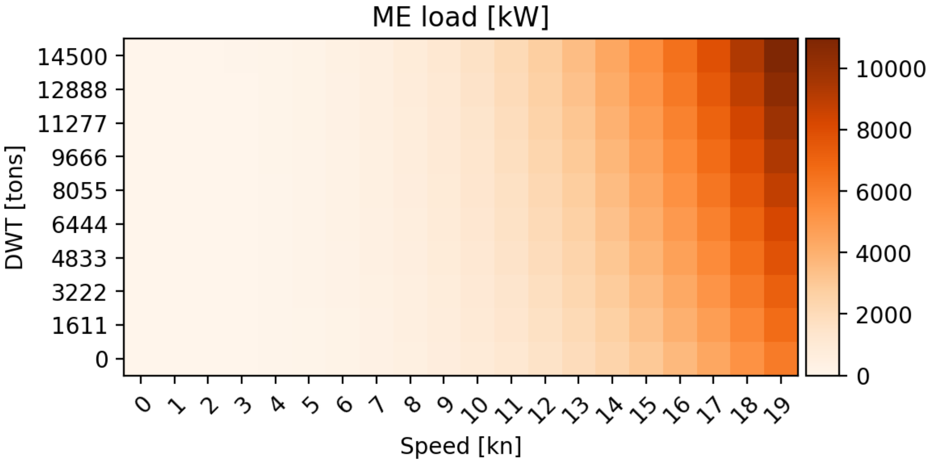

Figure 3.2: A fictional example of a ME load matrix as input for the model

Summarized, the input for the model consists of an operational profile including the speed, DWT, auxiliary engine load and cargo load as function of time and performance specifics including the propulsive- and auxiliary efficiencies, fuel share and main engine load table, as shown in table 3.1.

Table 3.1: Required input data for the model

| Operational profile | Data type | Performance specifics | Data type |
|---|---|---|---|
| Speed [kn] | Vector, $f$(time) | Propulsive efficiency [kWh$_{sup}$/kWh$_{cons}$] | Constant |
| DWT [%] | Vector, $f$(time) | Auxiliary efficiency [kWh$_{sup}$/kWh$_{cons}$] | Constant |
| AE Load [%] | Vector, $f$(time) | Fuel share [%] | Normalized vector |
| Cargo load [ton] | Vector, $f$(time) | ME load table [kW] | Matrix, $f$(speed, DWT) |
| Operational factor [-] | Constant | | |
| Dry dock schedule | Vector, $f$(time) | | |

## 3.2. Measures input

The next input required for the model is the description of one or more $CO_2$ reducing measures to be analyzed. The measures are modeled by several fundamental measure variables as described in table 3.2. This table shows only the variables included in the model; the method of taking these variables into account in the calculations of the model is described starting from section 3.4.

Table 3.2: Required measure variables as an input for the model

| Measure variable | Description |
|---|---|
| Name | The name or description of the measure which will be used in the output figures created by the model. |
| Type | Fuel changing or fuel saving measure. A fuel changing measure affects the fuel share used by the vessel (e.g. dual fuel engine) and a fuel saving measure decreases the energy consumption required for carrying out the same operational profile (e.g. anti fouling hull coating). |
| Fuel saving impact | The rate of decreasing impact of the measure on the fuel consumption of the vessel in percents. This variable is split up in three parts: the minimal expected impact, average expected impact and maximum expected impact. Only applicable for fuel saving measures. |
| Probability distribution | The probabilities of ending up in each of the fuel savings impacts (min, average, max) as described in the line above. |
| Effect on fuel share | The change of the fuel share used by the vessel after implementing a fuel changing measure. Only applicable for fuel changing measures. |
| Availability probability | The probability of the availability of the new fuel after implementing a fuel changing measure. This accounts for the lack of port facilities regarding fuel bunkering and combines the ’old’ fuel share and the ’new’ fuel share according to this factor. Only applicable for fuel changing measures. |
| Investment costs | The investment costs of making the measure operational (e.g. installation, testing, training). This measure does not include the costs of a regular scheduled dry dock, but should only included possible additional costs assuming the costs for the regular dry dock accounts for the maintenance expenses of the vessel. |
| Operational costs | The yearly additional costs of keeping the measure operational (e.g. additional maintenance costs, extra energy use). |
| Additional dry dock costs | This variable accounts for the additional investment costs when the implementation of the measure is not carried out during an already scheduled dry dock, but during an additional dry dock scheduled for the implementation. |

## 3.3. Environment input

Besides the vessel- and measure input, the environment the vessel is operating in has to be modeled. A selection of fundamental variables are required as an input in order to described this environment, shown and described in table 3.3. This table shows only the variables included in the model; the method of taking these variables into account in the calculations of the model is described starting from section 3.4.

Table 3.3: Required environment variables as an input for the model

| Environment variable | Description |
|---|---|
| Fuel properties | Properties of the fuels to be included in the model specifying the price per unit (e.g. ton or cubic meter), lower heating values and carbon contents of the fuels. |
| Discount rate | Discount rate used for the net present value calculations. |
| Regulation limits | The maximum acceptable $CO_2$ efficiency per year, determined by the current or expected regulations. |
| Charter day rate | The charter day rate of the vessel. This rate can be used to determine the potential loss of revenue when the vessel is not allowed to sail due to the regulations. |
| Carbon price | Carbon price per ton of $CO_2$ emitted. This price can be used to determine the fee of not meeting the regulations. |

## 3.4. Cost function

As to be read in the MDP theory described in chapter 2, the a MDP model is based on a reward function to be optimized. In this case, this reward function is a cost function which has to be minimized. The total costs is a sum of various cost elements; fuel costs, investment and operational costs of $CO_2$ reducing measures and costs due to not meeting $CO_2$ emission regulations (see equation 3.1). The calculations and determination of the values of the cost elements are described in the following subsections.

$$C_{total} = C_{fuel} + C_{investment} + C_{operational} + C_{regulation} \tag{3.1}$$

Due to the way the model and the cost function is setup, the problem should be qualified as an investment analysis. Therefore, it is important to account for today's value of money earned or spend in the future; the net present value (NPV). In the model, the total costs are subjected to a NPV calculation according to equation 3.2 (Investopedia, 2018).

$$\text{NPV } C_{total} = \sum_{n=1}^{N} \frac{C_n}{(1+r)^n} \tag{3.2}$$

Where: $C_n$ = net costs in year n;
$N$ = total number of years;
$r$ = discount rate.

### Fuel costs

The fuel costs can be calculated when the energy consumption and the fuel type(s) the vessel is burning are known. With the input data described in section 3.1, the total energy consumption over a certain time period can be calculated. This time period is modeled to be one year, for reasons which will become clear with the description of the MDP model in section 3.5. An important assumption which is made in the model is that the fuel share of the vessel is applicable to both the main engine and the auxiliary engines. This means that it is assumed that all engines run at the same fuel at any given moment.

First of all, the main engine load, $P_{ME}$ has to be determined at any given moment of the operational profile. For this, the right speed in the ME load matrix is selected without any interpolation; the speed should be an integer in the range of the maximum speed of the vessel. After this, the main engine load is calculated by linear interpolation between the two closest deadweight data points in the matrix. Now, both the main- and auxiliary engine loads are known, the energy consumption per operational profile cycle can be calculated, which is separated for the auxiliary engines and the main engine in equation 3.3 and equation 3.4 respectively. The output is a vector with the amount of energy consumed by burning fuel per fuel type.

$$\vec{E}_{AE} = \int_0^T P_{AE}\,dt \cdot \frac{1}{\eta_{AE}} \cdot \vec{F} \tag{3.3}$$

$$\vec{E}_{ME} = \int_0^T P_{ME}\,dt \cdot \frac{1}{\eta_{ME}} \cdot \vec{F} \tag{3.4}$$

Where: $\vec{E}$ = the AE/ME energy consumption per fuel type during one operational profile cycle in $[kWh]$;
$P$ = the power supplied by the auxiliary/main engine in $[kW]$;
$\eta$ = the propulsive/auxiliary energy efficiency;
$\vec{F}$ = the normalized vector of the fuel share;
$T$ = the duration of one operational profile cycle in [hours].

With the energy consumptions of the vessel known, the mass of fuel burnt can be calculated. To do this, the lower heating values (LHV) of the fuels are to be used. The LHV is a fuel specific property and is assumed to be constant in this model. In reality, these values could have a small variation due to different fuel qualities, but for this model the lower heating values are assumed to be constant as shown in table 3.4. Furthermore, the fuel consumption should be multiplied with a factor to convert the time span of the operational profile to a full year $\left(\frac{8760}{T}\right)$ and a factor to account for the nonoperational time $(\tau)$. With this information, the fuel consumption per type of fuel can be calculated as in equation 3.5.

$$\vec{M}_{fuel} = \frac{3600\,(\vec{E}_{AE} + \vec{E}_{ME})}{\overrightarrow{LHV}} \cdot \frac{8760\,\tau}{T} \tag{3.5}$$

Where: $\vec{M}_{fuel}$ = the accumulated amount of fuel burnt per fuel type during one operational year in [kg];
$\overrightarrow{LHV}$ = the lower heating values of fuels in [kJ/kg];
$\tau$ = the fraction of average operational time of the vessel in the range [0 1].

With the total fuel consumption per year known, the fuel costs can be calculated. The fuel costs can simply be obtained by multiplying the fuel consumption by the price per ton fuel, as in equation 3.6. The fuel prices are not set as a standard in this model since they are not suitable to be predicted in a reliable manner. Therefore, the fuel prices are part of the input for a case study and could for instance be varied for different scenarios.

$$C_{fuel} = \vec{M}_{fuel} \cdot \vec{P}_{fuel} \tag{3.6}$$

Where: $\vec{P}_{fuel}$ = Fuel prices in [US$/ton].

Table 3.4: Fuel properties for various marine fuel types

| Fuel type | LHV[1] [kJ/kg] | Carbon content[2] $[kg_C/kg_{fuel}]$ |
|---|---|---|
| HFO: Heavy Fuel Oil | 41000 | 0.85 |
| MDL: Low Sulphur Marine Diesel Oil | 44000 | 0.86 |

[1] (DNV-GL, 2018) [2] (Engineering ToolBox, 2009)

### Investment and operational costs

Another aspect of the cost function is the investment and operational costs of $CO_2$ reducing measures. These costs are measure dependent and part of the input values of the measures. The investment costs of a certain measure are to be paid once in the year the measure is implemented and therefore dependent on the action selected by the MDP (see chapter 2). The investment costs of a measure are modeled as all the costs to get the measure in operation (e.g. engineering, materials, personnel hours, testing), excluding dry docking costs. This arises from the assumption that a measure is installed during an already scheduled dry dock and therefore the dry docking costs are accounted to maintenance, instead of the measure's investment. The model provides the possibility to input a dry dock schedule and additional costs for when a measure is implemented beyond this schedule. The investment costs are calculated according equation 3.7. The operational costs of a measure are costs for using the measure such as additional maintenance or energy costs or personnel training costs. The operational costs are a direct input dependent on the measures to be implemented.

$$C_{investment} = C_{measure} + d \cdot C_{drydock} \tag{3.7}$$

Where: $C_{measure}$ = Investment costs of measure in US\$ ;
$C_{drydock}$ = Additional dry dock costs in US\$ ;
$d$ = 0 or 1, dependent on implementation within or beyond dry dock schedule.

### Regulation costs

The last element of the cost function is the regulation costs, which accounts for the costs when emission regulations are not met (see section 1.1.2). The price for not meeting the regulations differs per regulation framework and dependent on the case to be studied (see section 4.3), but the method to test if the case vessel meets the regulations is based on its $CO_2$ emissions and described below.

As opposed to the fuel costs, the $CO_2$ emissions due to the burning of fuels is perfectly to be determined since this is dependent on the chemical composition of the fuel. The $CO_2$ are directly related to the specific carbon content of the fuel and can be calculated according to equation 3.8. As for the lower heating value of fuels, the specific carbon content depends on the fuel quality and its chemical compositions and therefore small variations might occur. However, in this model the specific carbon content of the fuels is assumed to be constant and shown in table 3.4.

$$kgCO_2 = \vec{M}_{fuel} \cdot \vec{c}_f \cdot \frac{m_{CO2}}{m_C} \tag{3.8}$$

Where: $kgCO_2$ = the mass of $CO_2$ emissions per year in [kg];
$\vec{c}_f$ = the specific carbon content vector per fuel type in $[kg_C/kg_{fuel}]$;
$m_{CO2}$ = the molecular weight of $CO_2$ in [g/mole] = 44;
$m_C$ = the molecular weight of carbon in [g/mole] = 12.

The next step is the calculation of the average $CO_2$ efficiency during the particular year, which is a function of the total $CO_2$ emissions and the amount of cargo transported per nautical mile. The calculation method of the $CO_2$ efficiency is shown in equation 3.9.

$$CO_2 \text{ efficiency} = \frac{\text{Emitted mass of CO}_2}{\text{Transport work}} = \frac{\text{gCO}_2}{\text{ton} \cdot \text{nm}} \tag{3.9}$$

If the $CO_2$ efficiency of the vessel exceeds the limits of the regulations, it will create additional costs for the ship owner. The policy of this regulation costs is dependent on the government or regulator and could change per country or scenario. Examples of these regulation costs are the loss of potential revenue by not being allowed to sail with the vessel or by paying a price for every ton of $CO_2$ emitted by the ship. In the case study in this report, two policies are assessed regarding the costs of not meeting the regulations, see chapter 4.

## 3.5. MDP setup

As described in chapter 2, the MDP is described by a set of states, a set of actions, a reward function and a transition matrix. The way the MDP is setup for this model according to the input parameters described in the sections before are elaborated on in this section.

### Epoch duration

As described in section 2.2, the MDP for this tool will be modeled as a finite horizon MDP; there is an end of the analysis after which nothing happens. This is the case for analyzing a vessel, since it has an ending lifetime or an finite expected time of ownership by the shipowner. Thus, the most probable total analysis period would be maximum 25 to 30 years (or less), which is a common lifespan of a vessel. The older the ship to be analyzed, the shorter the analysis period. This period is split up by defining the amount of epochs included in the MDP. For this model, one epoch is considered to be one year. This means that every year, the utility of the system is calculated and a decision can be made. This epoch duration is considered to be sufficiently small to keep the results valuable, but also sufficiently large to keep the calculation time limited. A smaller epoch duration (e.g. a month) would result in higher detailed results, but is considered to be excessive for the conclusions which are desired to draw from the results.

### States

As explained in table 3.2, an implemented measure is modeled to have three possibilities with respect to affecting the fuel consumption; minimum, average and maximum. Considering the option that a measure can also be not implemented, there are four different states per measure in which the system can be: 1- not implemented, 2- implemented and minimum impact, 3- implemented and average impact and 4- implemented and maximum impact, as shown in equation 3.10.

$$\mathbf{S}_{\text{one measure}} = \begin{pmatrix} \text{Not implemented} \\ \text{Implemented and minimum impact} \\ \text{Implemented and average impact} \\ \text{Implemented and maximum impact} \end{pmatrix} \tag{3.10}$$

When multiple measures are included in the model, there is a combined state space in which all possible measure states have to be considered. This means that the state space grows exponentially with the amount of states defined by equation 3.11, in which the number of measures included is defined by $N$.

$$\text{Number of states} = 4^N \tag{3.11}$$

The combined state space **S** is created automatically by the model, dependent on the amount of measures included in the input.

### Actions

For each measure in the model, there are two actions to be taken; the shipowner can decide to not implement the model or to implement the measure, as shown in equation 3.12. Not implementing the action would lead to no change in the state space; after all, the shipowner is taking no action and the assumption is made that the impact of a measure does not change over time or by 'implementing it again'.

$$\mathbf{A}_{\text{one measure}} = \begin{pmatrix} \text{Do not implement} \\ \text{Implement} \end{pmatrix} \tag{3.12}$$

With multiple measures included, the shipowner could make the decision to implement multiple measures per year. Therefore, a combined action set is created which includes all combination of implementing or not implementing the included measures. As for the state space, this action vector is created automatically by the model, dependent on the amount of measures included in the input. The number of action to choose from are calculated as shown in equation 3.13, in which the number of measures included is defined by $N$.

$$\text{Number of actions} = 2^N \tag{3.13}$$

### Transition matrix

As described in chapter 2, the transition matrix is the link between the actions selected by the MDP - by means of an optimal policy - and the states the system is expected to be in. In other words, when it is decided to implement a certain measure, the state related to that measure moves from *not implemented* to one of the three other states. The probability of reaching each of the three *implemented* states are dependent on the impact probability given as an input (see table 3.2). The setups of this transition matrix for action $a_1$ - do nothing and action $a_2$ - implement measure are shown in equations 3.14 and 3.15 respectively (3D matrix shown as two 2D layers).

$$P(s'|s,a_1) = \begin{array}{c c} & \begin{array}{cccc} s'_1 & s'_2 & s'_3 & s'_4 \end{array} \\ \begin{array}{c} s_1 \\ s_2 \\ s_3 \\ s_4 \end{array} & \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{array} \tag{3.14}$$

$$P(s'|s,a_2) = \begin{array}{c c} & \begin{array}{cccc} s'_1 & s'_2 & s'_3 & s'_4 \end{array} \\ \begin{array}{c} s_1 \\ s_2 \\ s_3 \\ s_4 \end{array} & \begin{pmatrix} 0 & p_{min} & p_{avg} & p_{max} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \end{array} \tag{3.15}$$

As for the states and the actions, the transition matrix is dependent on the number of measures included in the model. The matrix is a 3D matrix of which two axes are dependent on the amount of states and one axis is dependent on the amount of actions. This means that the size of the matrix grows enormously with every measure included (number of elements = $2^{5N}$) of which the majority of matrix element equal zero. As for the state and action space, the transition matrix is created automatically by the model, including the proper combined probability values for the combinations of measures to include.

### Reward matrix

As described in section 3.4, the reward function is determined by the cost function. As described, the cost function is dependent on the investment costs of a measure, which is linked to taking an action in the MDP. Also, the cost function includes time dependent variables (e.g. fuel prices, regulatory framework). For these reasons, the reward function is not only dependent on the state the system is in, but also on the action taken and the MDP epoch $E$. According to the cost function explained in section 3.4, the reward function can be described as in equation 3.16.

$$\min R(s,a,E) = C(s,E)_{\text{fuel}} + C(a)_{\text{investment}} + C(s)_{\text{operational}} + C(s,E)_{\text{regulation}} \tag{3.16}$$

This reward function is calculated for all combinations of states, actions and epochs and stored in the 3D reward matrix, which forms an input for the MDP algorithm.

## 3.6. Model output

The objective of the MDP, as described in the previous section, is to minimize the total expected utility (total costs) by finding the optimal action policy. This policy is a table stating the optimal action dependent on the state the system is in in each epoch (see section 2.2). With the initial state of the system known - no measures are implemented in the vessel at the start of the analysis - the optimal policy can be translated to an action sequence of which an example is shown in figure 3.3. According to the MDP theory, the actions taken translate to the states accessed, shown in figure 3.4. In these figures, the color represents the likelihood of ending up at taking a certain action or in a certain state and is initiated by (Niese et al., 2015). The output graph of figure 3.4 shows a simplified state space in which the degrees of impact on the fuel consumption are not shown, since this is only relevant for the costs calculations behind it.

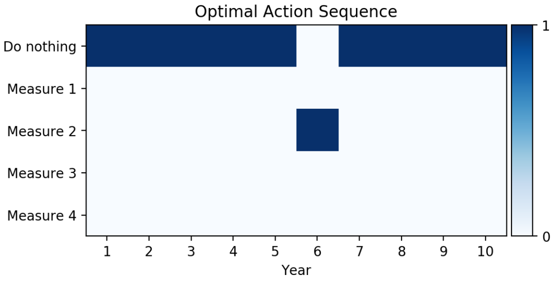

Figure 3.3: Example of optimal action sequence as an output from the model. The shading represents the likelihood of the action being optimal (Niese et al., 2015).

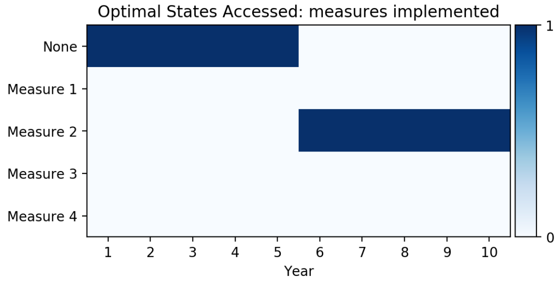

Figure 3.4: Example of states accessed following the optimal policy as an output from the model. The shading represents the likelihood of the system being in the specific state (Niese et al., 2015).

In this tool, the expected total fuel saving percentage of multiple implemented measures is modeled as being the sum of the expected fuel saving of the individual measures, as shown in equation 3.17. Although the possibility exists that certain combination of measures affect each others impact on the fuel consumption, the assumption has been made that this effect remains within the limits of the impact uncertainty range of those measures.

$$\text{Fuel savings}_{\text{total}}[\%] = \text{Fuel savings}_{\text{M1}} + \text{Fuel savings}_{\text{M2}} + \cdots + \text{Fuel savings}_{\text{M}N} \tag{3.17}$$

With the MDP results as presented in figures 3.3 and 3.4, the optimal policy costs can be calculated, combining the policy and the cost function as described before. Figure 3.4 shows a simplified visualization of the state space, but in reality, every measure has a probability of minimum, average or maximum impact on the fuel consumption. This is important for the calculation of the optimal policy costs and the expected value method will be used for this, where the probability of taking an action or the system being in a state is multiplied by its corresponding cost value. Since the probabilities of the system being in a state is described by the state vector and the probability of taking an action by the action vector, the total expected costs at a given year can be calculated according equation 3.18. The same method is used for the calculation of the expected $CO_2$ emissions and expected $CO_2$ efficiency.

$$\text{Expected costs} = \mathbf{S}\cdot\mathbf{C}_{\text{fuel}} + \mathbf{A}\cdot\mathbf{C}_{\text{investment}} + \mathbf{S}\cdot\mathbf{C}_{\text{operational}} + \mathbf{S}\cdot\mathbf{C}_{\text{regulation}} \tag{3.18}$$

Besides the expected values of the results (i.e. costs, $CO_2$ emissions and $CO_2$ efficiency), the extreme limits and one standard deviation range is calculated as well. For the extreme limits - or minimum and maximum - the total fuel savings as shown in equation 3.17 is defined by the sum of either all minimum or all maximum impact values of the individual measures. The mean and standard deviation of the total fuel saving impact is calculated by assuming that all possible fuel saving combinations regarding minimum, average and maximum impact of individual measures form a normal distributed value spread. From this normal distributed value spread, the mean and standard deviation is determined and the results regarding costs and $CO_2$ performance is calculated using these values.

## 3.7. Memory limitations

Due to the fact that the state space expands exponentially by the addition of each measure to be analyzed, the computer memory required for the calculations grows exponentially as well. Figure 3.5 shows a number of measurements carried out to analyze the required computer memory to run the model. It can be seen that an analysis of six measures requires almost 15 gigabytes of computer memory, which is the limit for most regular computers. The assessment of a seventh measure is expected to require approximately 60 gigabytes of memory which exceeds the resources available for this research. For this reason, the maximum amount of measures analyzed per run of the model is six, which takes approximately two minutes computer running time.

Although there is a practical maximum number of measures to be included in an analysis, there are several ways to work around this problem. First of all, different measure sets of six measures each could be created and analyzed separately. The results can be compared, patterns in the results identified and an overall conclusion can be drawn. This method is applied in the case study in this study, described in chapter 4. Also, the memory requirements of the model could be decreased by improving the coding. This solution is described in more detail in the proposed future work in chapter 8.

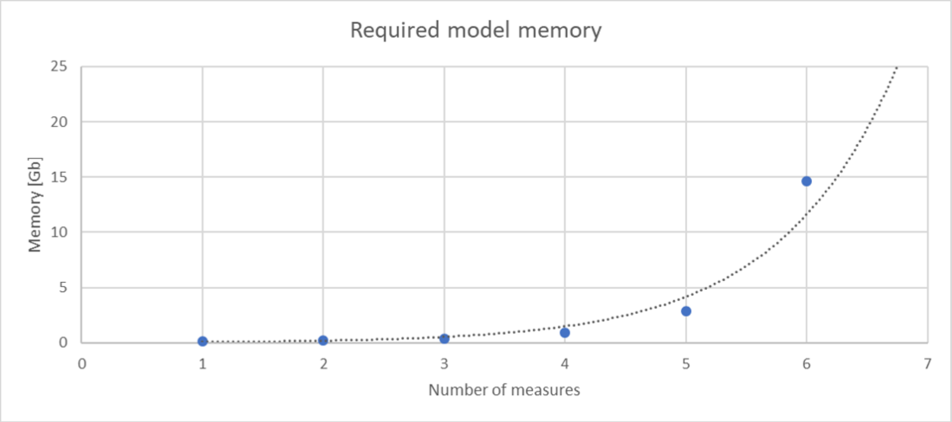

Figure 3.5: Computer memory required to run the model as function of the amount of measures included in the analysis

# 4

# Case study outline

In this chapter, the model is used for a case study analysis on an existing vessel in order to test the its functionality in a real life situation. The case study is performed on a 90000 DWT post-panamax bulk carrier owned by a Dutch shipping company. For legal reasons, the company's name and the vessel is not stated in this report and only referred to as 'the company' and 'the case study vessel'[1]. In section 4.1, the specifics of the case study vessel are described. Thereafter, in section 4.2, a data analysis is carried out in order to find the vessel input parameters for the model (see section 3.1 for a description of the vessel input parameters). In section 4.3, the baseline input parameters for the case study are described. These input parameters consist of a vessel input, based on results of the data analysis, and measure and environment input, both based on literature and other references. At last, in section 4.4, the scenarios are described for which the case study is carried out. The results of the case study are not presented in this chapter, but can be found in chapter 5.

## 4.1. Case study vessel

The company is an international shipping company of which the headquarters is located in The Netherlands. It operates and manages a diverse fleet of several dozens of vessels. Among other types, it owns container vessels, bulk carriers and product tankers. For this study, the company is approached to provide information and data of one of their vessels in order to use it as a case study. The company has responded positively to this request and has offered the case study vessel to perform a case study on. The case study vessel is (approximately) a 90000 DWT post-panamax bulk carrier built in 2012 and its main specifics are shown in table 4.1. An example of a post-panamax bulk carrier - but not the actual case study vessel - is shown in figure 4.1. Not only did the company provide valuable input by means of experience from its Head Operations and colleagues involved with the vessel, but it also made a dataset available which included operational data of the case study vessel. This dataset will be analyzed in order to find the input values for the model to be used in this case study (see section 4.2).

Figure 4.1: An example of a post-panamax sized bulk carrier used for this case study (SeaNews, 2014). Note that this is just an example and not the actual vessel used for this case study.

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[1] The company and the specific vessel are known by the author of this report and for questions regarding this matter the author can be contacted.

Table 4.1: Specifics of the case study vessel.

| Case study vessel | | | |
|---|---|---|---|
| Building Year | 2012 | Number of holds | 7 |
| Cargo type | Bulk Carrier | Max DWT | 90 000 [mT] |
| Size type | Post-Panamax | Max draft | 15 [m] |
| Length overall | 230 [m] | Main engine | Man B&W |
| Beam | 38 [m] | Installed engine power | 12 000 [kW] |
| Depth | 20 [m] | Generator power | 3 x 780 [kW] |

## 4.2. Data analysis

The dataset available contains operational data of the case study vessel which is based on four types of reports submitted by the chief engineer: noon reports, departure reports, arrival reports and special reports. When the vessel is at sea, a noon report is sent to shore on a daily basis. This report contains vessel conditions such as draft and displacement and system usage such as average engine load and generator energy consumption. Also, fuel consumption and bunker levels are included, as well as the location of the vessel and the distance sailed since the latest submitted report. It should be noted that, despite its name, a noon report does not necessarily contain the data of the situation at midday, but is drafted 24 hours after the last report. An arrival report is submitted when the vessel arrives at the pilot station of the port of destination and contains the same data elements as the noon report. A departure report is submitted when the vessel arrives at the pilot station of the port of departure. This report contains the fuel consumptions of the time between arrival at the pilot station and departure from the pilot station. Included in this period are the transits between the pilot station and the berth for (un)loading and the time at berth. Lastly, special reports are submitted when the ship has bunkered fuel and contains the amount of fuel received per fuel type. A visual representation of the parts of a voyage is included in each type of report is shown in figure 4.2.

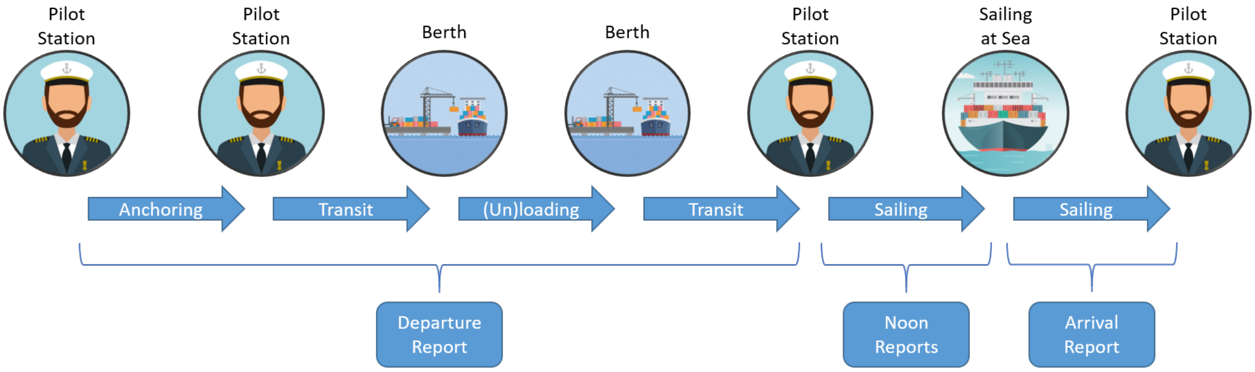


Figure 4.2: Each voyage is documented by one departure reports, one or multiple noon report(s) and an arrival report

The raw dataset contains 387 data points from the period between January 2017 and May 2018. In this case study, this dataset is split up into two parts; 2017 and 2018. The data of 2017, is analyzed in order to find the required input values for the model. In the following paragraphs, an analysis for the operational profile, the main engine load matrix and the energy efficiencies is carried out. It is important to note that the data consists of manually inserted values and therefore, it is very likely that - due to human mistakes - erroneous data points are included in the set. For each analysis in the following paragraphs, there are different criteria which make a data point erroneous and therefore, the cleaning of the dataset is described per paragraph. After this, the values found in the analysis are compared to the remaining part of the dataset (January - May 2018) for the sake of validation.

### 4.2.1. Operational profile

Part of each data point are the coordinates of the vessel at the moment of reporting. In order to gain an insight in the types of voyages the vessel makes and the seas it sails, these coordinates can be plotted on a map. Before doing this, the erroneous data points are deleted. The majority of those points are the ones stating the vessel's location is (0.0N, 0.0E). Although this location does exist - roughly 250 nautical miles south of Ghana, Africa - it is more likely this point is a default input by the reporting system rather than the actual position of the ship at the specific moment of reporting. After this first filter, the coordinates are plotted on the map and outlying points which are off-route are deleted as well. The resulting route of the case study vessel in 2017 is plotted in the map in figure 4.3.

The route starts on January 14th from Mackay Harbour, Australia and it can be seen on the map that several relatively short voyages are made between Australia, Indonesia and South Eastern Asia. After this, the vessel departed eastbound and made via the west coast of the USA and Southern America a voyage across the globe to arrive back at South Eastern Asia at the end of 2017. The most important thing to learn from this plot is that there is a wide variation of distances and routes sailed by the vessel and therefore, a more in-depth analysis of the data should be carried out in order to draw conclusions about the operational profile to be used as an input for the model.

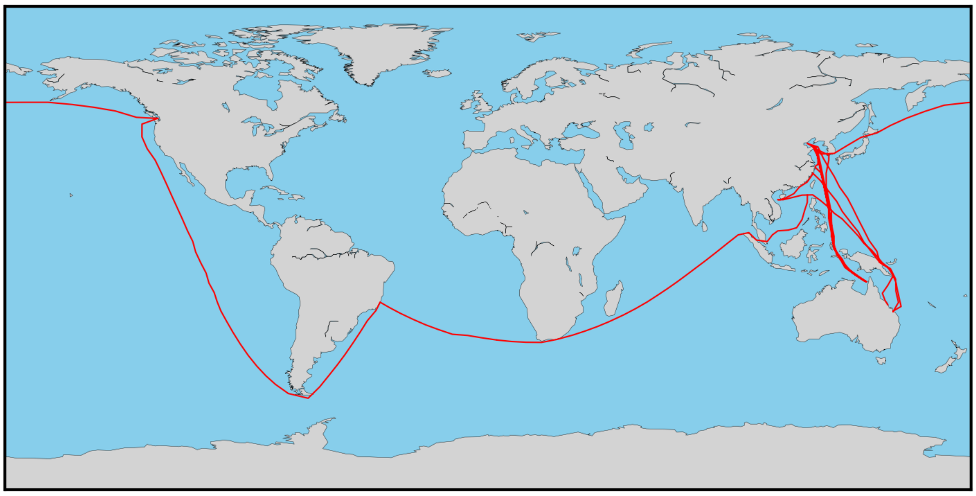


Figure 4.3: Route travelled by the case study vessel in 2017

To gain more insight in the operational profile of the case study vessel, the vessel's speed, deadweight tonnage on board and generator load is plotted over time. The average vessel speed is calculated by dividing the sailed distance since the latest report by the time since the latest report. Generally, this results in the average speed measured over one day (noon report) or less (arrival report). The DWT loaded on board is determined by subtracting the weight of the lightship from the reported displacement. Resulting data points containing negative values or values larger than the total DWT capacity of the vessel are considered erroneous and therefore deleted. The generator load is presented as the rate of total installed generator power and therefore consists of one line rather than three separate lines for each generator.

A part of the operational profile of the case study vessel is shown in figure 4.4. For the sake of clarity, only a period of two months is presented figure 4.4. The operational profile of the complete year of 2017 is to be found in appendix A. In the part of the operational profile below it can be seen that the vessel makes several cycles of sailing and (un)loading in port. In the operational profile of the complete year (see appendix A) these cycles go on with a variation in duration of the voyage and port times. Interesting to note in that figure is the out of service period between day 260 and 290 where the vessel underwent dry dock maintenance in Brazil.

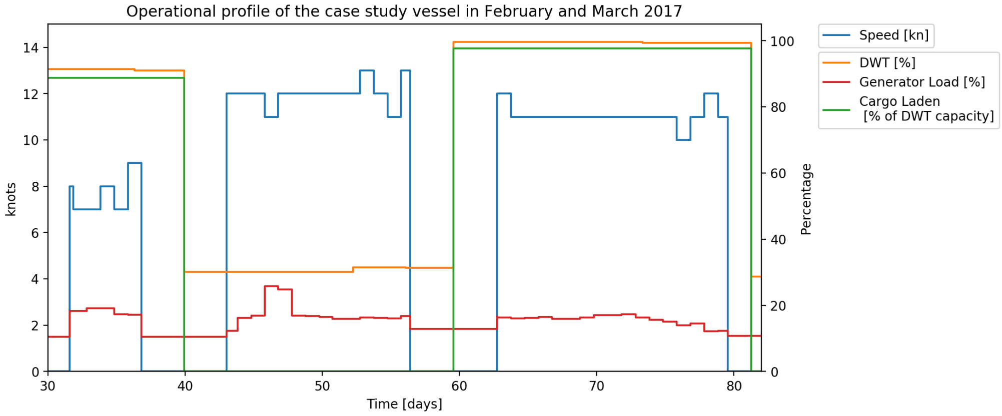


Figure 4.4: Operational profile of the case study vessel during February and March 2017

### 4.2.2. Main engine load

The main engine load matrix, as described in section 3.1, consists of the relation between the DWT on board and the sailing speed of the vessel. The DWT can be translated to the draft of a vessel as shown in figure 4.5. The reported data only consist the draft at the bow of the vessel and the draft at the stern of the vessel. In order to work with one draft in the model, the average of those two values are taken as a representation of the draft around midship.

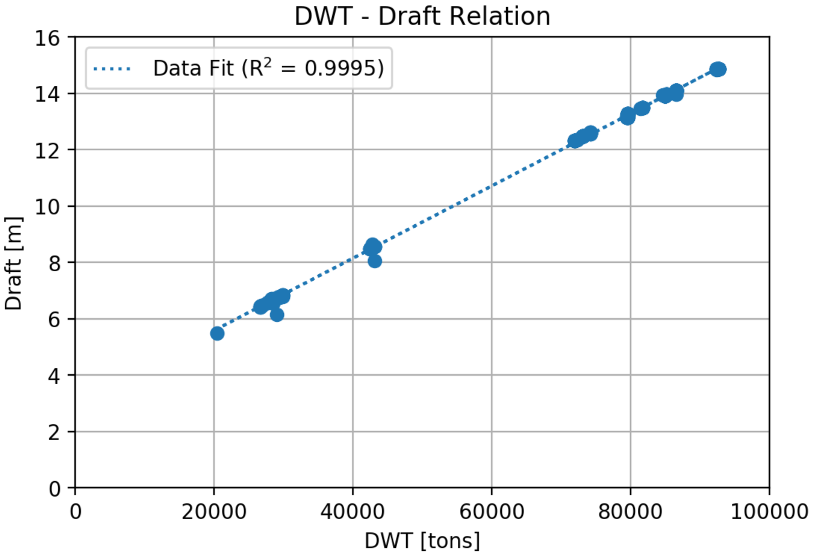


Figure 4.5: Linear relation between the DWT and speed of the case study vessel

In order to get an insight in the data points available, histograms of the draft and speed are shown in figure 4.6. For the draft, it can be seen that there are roughly two groups in the histogram. The first group is concentrated around a draft of 7 meters, which would be the distribution for the ballast draft. The second group is concentrated around a draft of 13 to 14 meters, which would be the distribution for the laden draft. For the speed, it can be seen that the majority of data points are concentrated between 11 and 13 knots, which is around the service speed of the vessel.

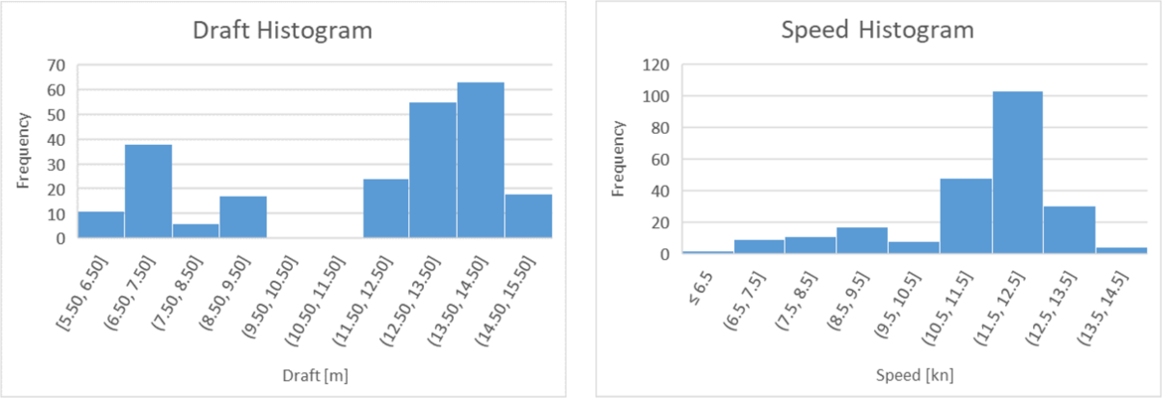


Figure 4.6: Histograms of draft and speed of the case study vessel during 2017

To create the main engine load matrix, the power at a specific draft and speed are rounded to the closest integer values of this draft and speed. Thereafter, the average of all power data points at the same draft and speed is calculated. This means that in the main engine load matrix, the value for $P(\text{draft, speed}) = P(7,12)$ is the average of all power values in the range $[6.5 \leq \text{draft} < 7.5;\ 11.5 \leq \text{speed} < 12.5]$. Following this procedure for each data point results in the main engine load matrix as shown in table 4.2.

The first thing to notice when analyzing the resulting main engine load matrix is the absence of data of many operational points. This was already to be expected after the presentation of the histograms in figure 4.6, since the frequency of many bins are less or equal than 10. The second thing to notice is the lack of influence of the draft on the power. It is to be expected that the draft does have an influence on the required power since the resistance increases with an increasing draft. However, this is not to be seen in the results and there are two possible explanations for this. First of all, the data of the power the matrix is based on includes external conditions such as current and waves. It is very likely that these external effects are of a greater influence on the vessel's resistance than its draft, especially due to the reason that many data points are measured over a time period of 24 hours (noon reports). The second possible explanation is the amount of data points at the foundation of the resulting main engine load matrix, which is shown in table 4.3. It can be seen that many many values in the main engine load matrix are based on less than 10 underlying data points. For this reason, individual data points have to much influence on the resulting average and therefore, the results cannot be trusted to be a credible representation of reality. In order to work with the limited data points available, an analysis of the engine power independent of the draft is made in the next paragraph.

Table 4.2: Main engine load matrix from first data analysis

| DWT [tons] | Draft [m] | P [kW] @ v = 7 kn | P [kW] @ v = 8 kn | P [kW] @ v = 9 kn | P [kW] @ v = 10 kn | P [kW] @ v = 11 kn | P [kW] @ v = 12 kn | P [kW] @ v = 13 kn | P [kW] @ v = 14 kn |
|---|---|---|---|---|---|---|---|---|---|
| 23260 | 6 | - | - | 2295 | 4982 | - | 6053 | 6419 | - |
| 31073 | 7 | - | - | 3182 | - | 5963 | 5867 | 5979 | 6120 |
| 38885 | 8 | - | - | - | - | - | 6047 | - | - |
| 46698 | 9 | - | 6487 | - | - | 6047 | 6377 | 6493 | 6610 |
| 54510 | 10 | - | - | - | - | - | - | - | - |
| 62323 | 11 | - | - | - | - | - | - | - | - |
| 70135 | 12 | - | - | - | - | 6083 | 6085 | 6100 | 6083 |
| 77948 | 13 | 4570 | 5998 | 5783 | - | 6244 | 6081 | 6079 | - |
| 85760 | 14 | 2883 | 3016 | 3534 | 5282 | 6378 | 6322 | - | 6120 |
| 93573 | 15 | - | - | - | 5851 | 6015 | 6071 | - | - |

Table 4.3: Number of data points at the foundation of the main engine load matrix in table 4.2

| DWT [tons] | Draft [m] | N @ v = 7 kn | N @ v = 8 kn | N @ v = 9 kn | N @ v = 10 kn | N @ v = 11 kn | N @ v = 12 kn | N @ v = 13 kn | N @ v = 14 kn |
|---|---|---|---|---|---|---|---|---|---|
| 23260 | 6 | - | - | 2 | 1 | - | 2 | 5 | - |
| 31073 | 7 | - | - | 1 | - | 5 | 23 | 8 | 1 |
| 38885 | 8 | - | - | - | - | - | 6 | - | - |
| 46698 | 9 | - | 1 | - | - | 2 | 4 | 9 | 1 |
| 54510 | 10 | - | - | - | - | - | - | - | - |
| 62323 | 11 | - | - | - | - | - | - | - | - |
| 70135 | 12 | - | - | - | - | 2 | 18 | 3 | 1 |
| 77948 | 13 | 3 | 1 | 4 | - | 13 | 27 | 6 | - |
| 85760 | 14 | 6 | 9 | 8 | 7 | 9 | 23 | - | 1 |
| 93573 | 15 | - | - | - | 2 | 14 | 2 | - | - |
| Total | | 9 | 11 | 15 | 10 | 45 | 105 | 31 | 4 |

As discussed in the previous paragraph, a correlation between the draft and the engine power cannot be found in the dataset available. Therefore, the main engine power is analyzed while only dependent on the speed of the vessel and a scatter plot is to be found in figure 4.7. As to be seen in the graph, the engine power required is very scattered along the different values for speed. However, looking to the graph from another perspective, combined with the information from the histogram in the same figure, a trend could be noticed. In the majority of cases, the main engine's load is set to be 6000 - 6250 [kW] (49% - 51%) which generally leads to a ship speed of about 11 - 13 knots. This trend is also to be noticed in the figure of the operational profile in appendix A. Discussing this observation with the shipowner resulted in the insight that the vessel's speed at this point would be approximately 12 knots when there is no current. The deviations are due to the operational situations where the vessel's speed is affected positively or negatively by the current at sea. Thinking about this conclusion from a captain's perspective it makes sense as well; the captain knows the engine and its best working point as no other and makes his decision from that perspective rather than an objective vessel speed. Also to be noticed in the figure is another common working point of the engine; setting the engine around 3000 [kW] (25%) results in a vessel speed of 7 - 10 knots.

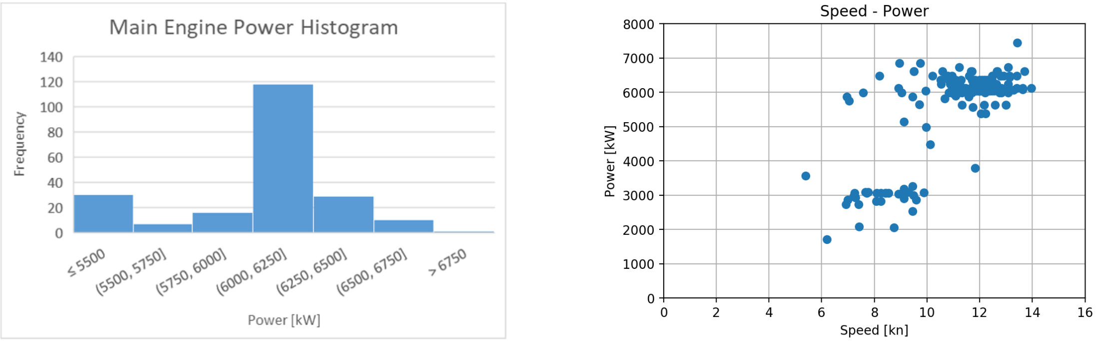


Figure 4.7: Left: Histogram of main engine power of the case study vessel during 2017. Right: Scatter plot of the vessel's main engine power as function of speed

To use the main engine characteristics as an input for the case study, the model is slightly adjusted with respect to the model description in chapter 3. As concluded in the previous paragraph, the vessel appears to be operated to set a specific engine load, rather than to opt for a specific speed. Therefore, the engine load is used as an input in the operational profile, instead of the vessel's speed. To translate this engine load to a speed - and thus a distance sailed - a speed-power curve is fitted through the data. This speed-power curve is a power line based on (speed, power) = (0, 0) and the two working points of 8.5 knots at 3000 [kW] and 12 knots at 6000 [kW]. The resulting speed-power curve which is used as an input for the model during this case study is to be seen in figure 4.8 (orange fitted curve). Undoubtedly, many operational data points are not exactly on this curve, but the validation described in section 4.2.4 confirms that the performance of the vessel is sufficiently described by this curve in order to be useful for this case study.

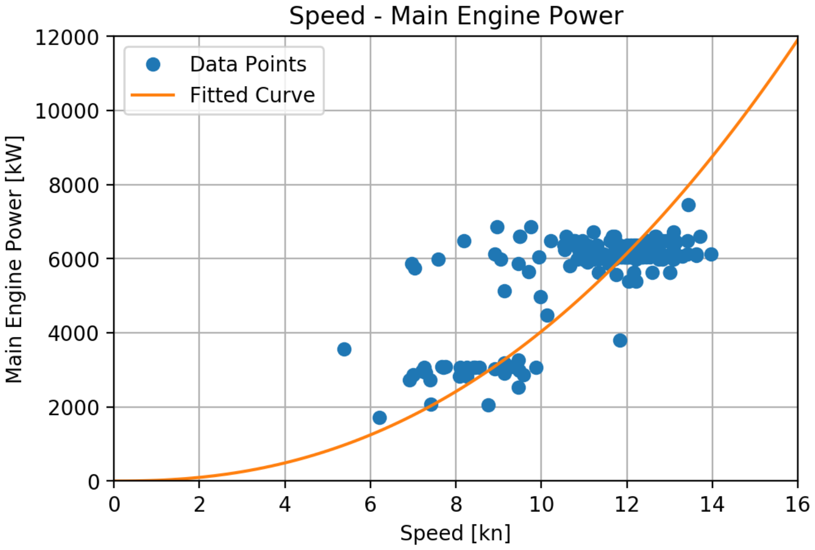


Figure 4.8: Vessel speed and main engine load relation. The fitted curve is used as an input for the model

### 4.2.3. Energy efficiencies

The model requires two inputs regarding efficiencies; the propulsive efficiency and the auxiliary efficiency. The propulsive efficiency is the efficiency between the fuel tank and the power output of the main engine and the auxiliary efficiency indicates the performance between fuel tank and auxiliary power output (see section 3.1). Per data point in the available dataset, the efficiencies are calculated according to equations 4.1 and 4.2.

$$\text{Propulsive efficiency} = \frac{\text{Energy supplied}}{\text{Energy burnt}} = \frac{P_{ME} \cdot [\%] \cdot t}{\sum_i (F_{prop})_i \cdot LHV_i \cdot \frac{1000}{3600}} \tag{4.1}$$

$$\text{Auxiliary efficiency} = \frac{\text{Energy supplied}}{\text{Energy burnt}} = \frac{\sum P_{gens} \cdot [\%] \cdot t}{\sum_i (F_{gens})_i \cdot LHV_i \cdot \frac{1000}{3600}} \tag{4.2}$$

$$\begin{aligned} \text{Where:} \quad i &= [HFO, MDL]; \\ P_{ME} &= \text{Installed main engine power in [kW];} \\ \sum P_{gens} &= \text{Sum of installed generator power in [kW];} \\ [\%] &= \text{Engine/generator load in [\%];} \\ t &= \text{Steaming hours of engine/generators;} \\ F_{prop} &= \text{Fuel consumption for propulsion in [mT];} \\ F_{gens} &= \text{Fuel consumption for generators in [mT];} \\ LHV &= \text{Lower Heating Value in [kJ/kg] (see table 3.4).} \end{aligned}$$

The result of these calculations is a set of propulsive efficiencies and a set of auxiliary efficiencies of the case study vessel during 2017. This is raw data and should be filtered for erroneous data points. First of all, all data points equal to zero can be deleted from both sets, since this indicates that no power is delivered by the engine or generators at those specific data points. Also, since the main engine is known, an upper limit for the propulsive efficiency can be determined. The main engine project guide (MAN Diesel and Turbo SE, 2014) informs that in the most optimistic case the specific fuel consumption of the engine is SFOC = 162 [g/kWh]. Considering a lower heating value of HFO of $LHV = 41000$ [kJ/kg] (see table 3.4), the most optimistic engine efficiency is equal to 54%. This value still excludes other losses in for instance piping or supporting systems, but avoiding speculation for these values, only values greater than 54% in the propulsive dataset can be considered erroneous and therefore are deleted.

Now, the remaining, filtered, datasets can be analyzed by visualizing them in histograms, see figure 4.9. As can be seen in the figure, the values of the propulsive efficiency are distributed along a broad range without a clear probability distribution to be recognized. From an engineering perspective, it is known that the efficiency of a marine engine depends on the engine load. Therefore, the propulsive efficiency is plotted against the main engine load in figure 4.10. Again, as in figure 4.7, the data concentration at the engine loads of 3000 [kW] and 6000 [kW] are to be recognized. Also, as expected, it is to be noticed that a slight positive correlation between the propulsive efficiency and the main engine power exists in the range of the data shown. The same correlation of the auxiliary efficiency is not explored, since the data is a sum of three generators and therefore it is unknown what the individual generator loads are behind the data.

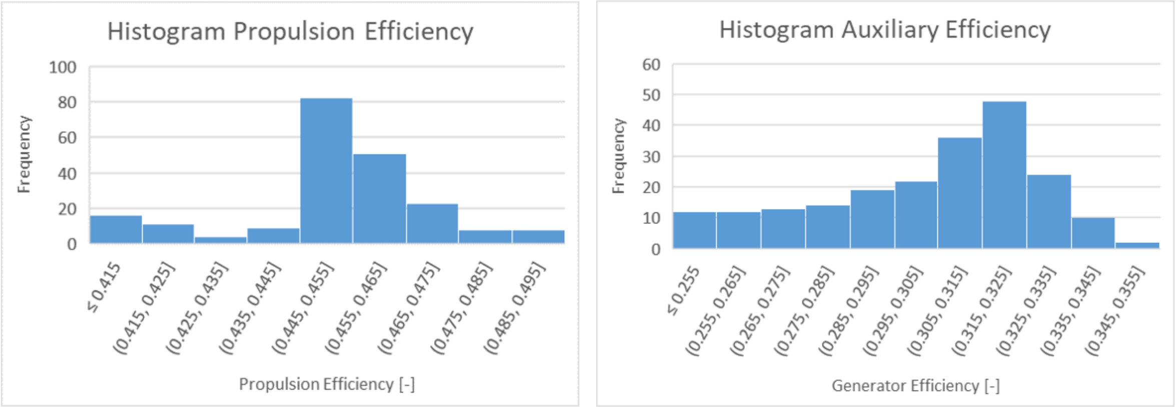


Figure 4.9: Histograms of propulsive and generator efficiencies

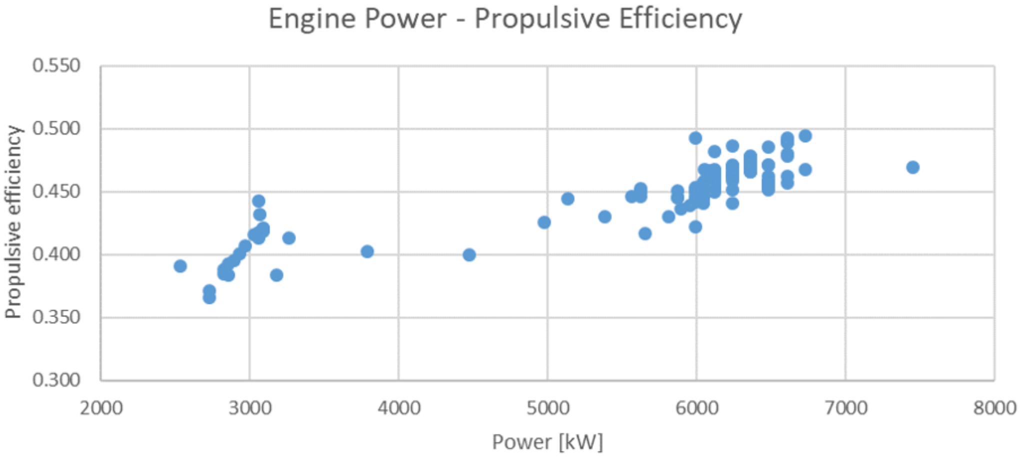


Figure 4.10: Main engine power versus propulsive efficiency of the case study vessel during 2017

The visualize and analyze the data, the efficiencies are presented by means of box plots. For the auxiliary efficiency, the data is presented as a whole, as discussed in the previous paragraph. For the propulsive efficiency, the box plots are made for the two operational points of 25% en 50% engine load. For 50% engine load, efficiency values are considered which correspond to the main engine power range of $6000 \leq P_{me}[kW] < 6250$. For the 25% engine load, a larger range is taken in order to include more values in the box plot: $2800 \leq P_{me}[kW] < 3200$. The resulting box plots are to be found in figure 4.11 and their corresponding data in table 4.4. The value of the propulsive efficiency for the input for this case study is composed by the weighted average of the propulsive efficiencies at the two operational points, according to equation 4.3. For the auxiliary efficiency, the median value resulting from the box plot is used as the input for the model, which means $\eta_{aux} = 0.311$.

$$\eta_{prop} = \frac{118 \cdot 0.454 + 20 \cdot 0.415}{118 + 20} = 0.448 \tag{4.3}$$

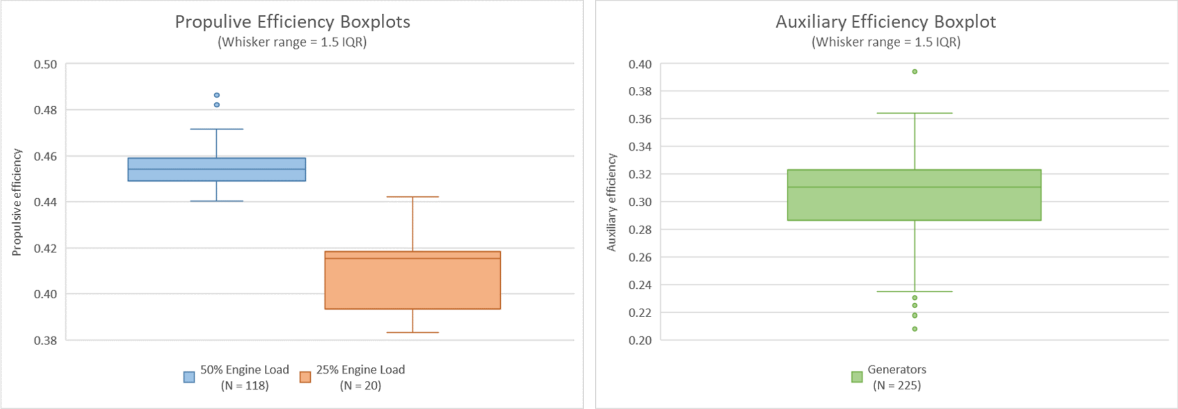


Figure 4.11: Box Plots of propulsive and auxiliary efficiencies

Besides the main engine fuel consumption for propulsive and the generator fuel consumption for auxiliary power, there are two other fuel consuming activities which are important to take into account: maneuvering and powering the ship's boiler. Since this data is logged in combined form in the departure reports, it is not suited for a detailed analysis as with the propulsive and auxiliary efficiency. However, the time in port and the energy consumption for maneuvering and powering the boiler during that time is known, which makes it possible to analyze the average power required. The combined values are presented in figure 4.12 and just as for the auxiliary efficiency, the median value resulting from the box plot is used as the *port power* input for the model, which means $P_{port} = 878$ [kW]. The validation described in section 4.2.4 confirms that the efficiencies and port power used in the case study is sufficiently accurate to model the fuel consumption of the vessel.

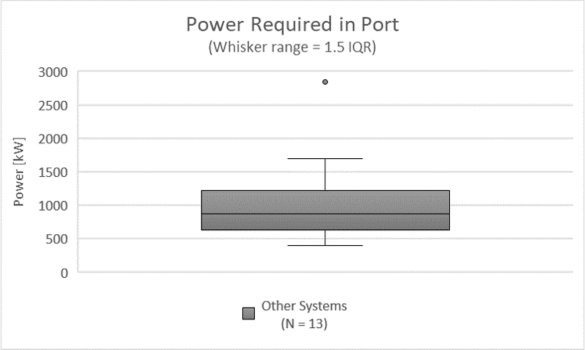


Figure 4.12: Box Plot of energy used by maneuvering and boiler per hour in port

Table 4.4: Box plot values of data analysis in figure 4.11 and 4.12

| Component | N | Q1 | Median | Q3 |
|---|---|---|---|---|
| Propulsive efficiency @ 50% engine load [-] | 118 | 0.449 | 0.454 | 0.459 |
| Propulsive efficiency @ 25% engine load [-] | 20 | 0.393 | 0.415 | 0.418 |
| Propulsive efficiency weighted [-] | 138 | - | 0.448 | - |
| Auxiliary efficiency [-] | 225 | 0.287 | 0.311 | 0.323 |
| Other Systems Power in Port [kW] | 13 | 632 | 878 | 1216 |

### 4.2.4. Validation

In order to validate the values found in section 4.2.2 and 4.2.3, the model is ran with these values for the operational part of the months in 2018. By doing this, it could be determined if the values representing the data of 2017 also would be valid for the operational profile of 2018. If this is the case, it means that the model is able to not only represent 2017, but also other years which will be done in the case study described in chapter 4.

After running the model, the fuel consumption of the vessel can be set out against the time. This is done in figure 4.13, in which also the operational profile of 2018 is shown. Presenting this in one graph gives an insight whether the moments of slow or rapid fuel increase makes sense. As can be seen in the figure, the HFO consumption increases rapidly when the vessel is sailing at sea and is less when at port, which is the logical outcome. Another aspect to notice is the extremely low MDL consumption (barely to be seen in the figure). This is the result of the way of modeling the HFO:MDL share of the vessel; it is modeled as 99:1 and therefore the HFO consumption is substantially larger.

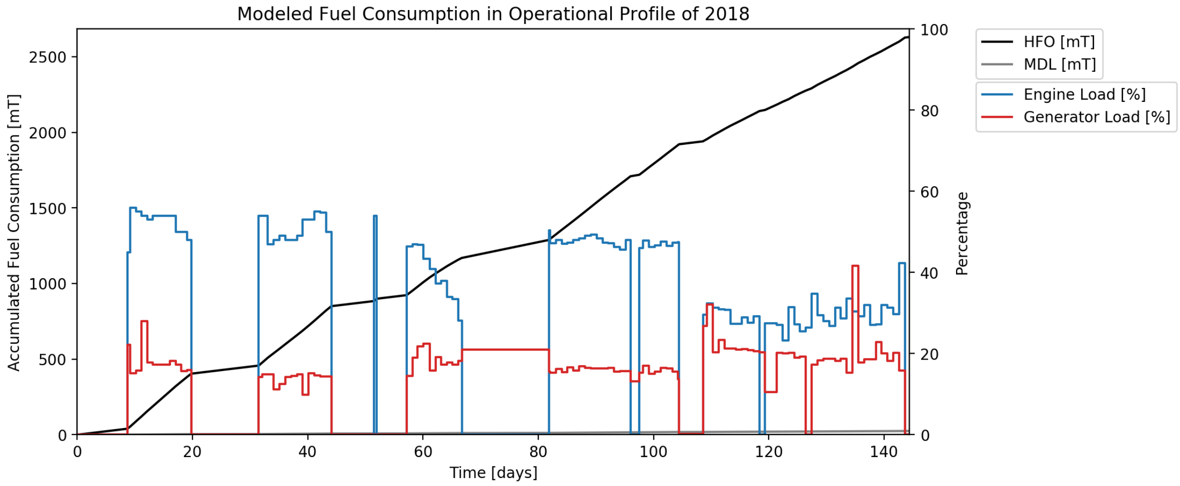


Figure 4.13: Operational profile of case study vessel during January - May 2018 with modeled fuel consumption

After the visual check described in the previous paragraph, the modeled fuel consumption and the real fuel consumption - obtained by the data analysis - can be compared. In figure 4.14, the modeled HFO consumption and the real HFO consumption are compared. The data points of the submitted fuel consumption by the vessel's crew are visualized by a dot in the graphs; these are the points where the modeled values and real values can be compared. In the graph presenting the deviation between both lines, it can be seen that the deviation starts with a high value and then quickly converges in the direction of a small negative value of smaller than 4%. This is explained by the fact that the consumption is cumulative and therefore the relative error decreases every time step. This method is valid since the model calculates the fuel consumption for a full year and therefore, it is acceptable to have larger small scale variations as long as the deviation curve converges in the direction of zero and does not have a structural positive or negative error. As said before, the deviation curve from figure 4.14 is slightly negative and the reason for this is explained later with the comparison of energy consumptions.

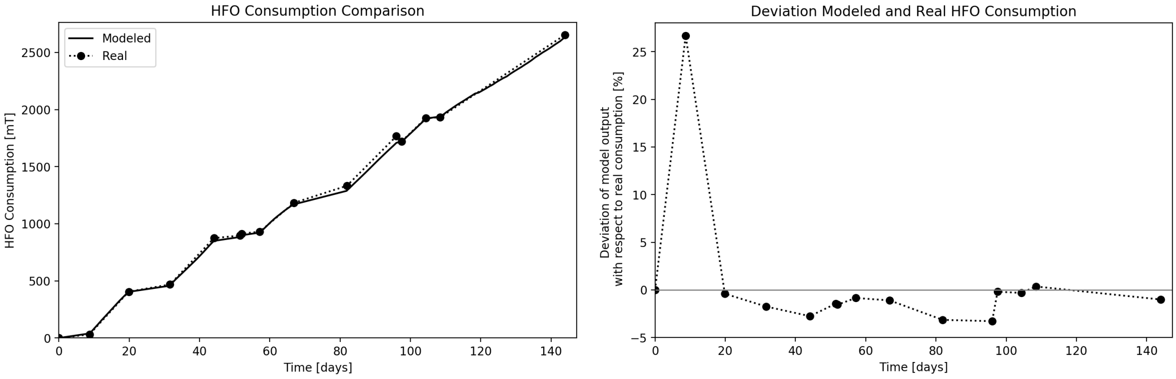


Figure 4.14: Comparison of modeled HFO consumption and real HFO consumption

Comparing the MDL consumption using the same method as the HFO comparison leads to the results as shown in figure 4.15. As opposed to the HFO consumption, there are huge differences to be seen between the modeled and real consumptions. In general, the modeled MDL consumption is way larger than the real MDL consumption. There are two explanations to be given for this observation. First of all, the amount of MDL consumed is roughly a factor 100 smaller than the amount of HFO consumed. Therefore, an absolute deviation between the modeled MDL values and the real values leads to a larger relative deviation than for the HFO consumption. The second, more influential, factor is the fact that the HFO:MDL share is modeled as a fixed ratio of 99:1. In reality, however, this ratio is mainly determined by the (SECA) areas the vessel is sailing in during a certain time. Combining this variety and the fact that small absolute deviations leads to large relative deviations results in the high deviations shown in figure 4.15. In the end, the high deviation in modeled MDL consumption has no large impact on the total energy consumption, which is described in the next paragraph.

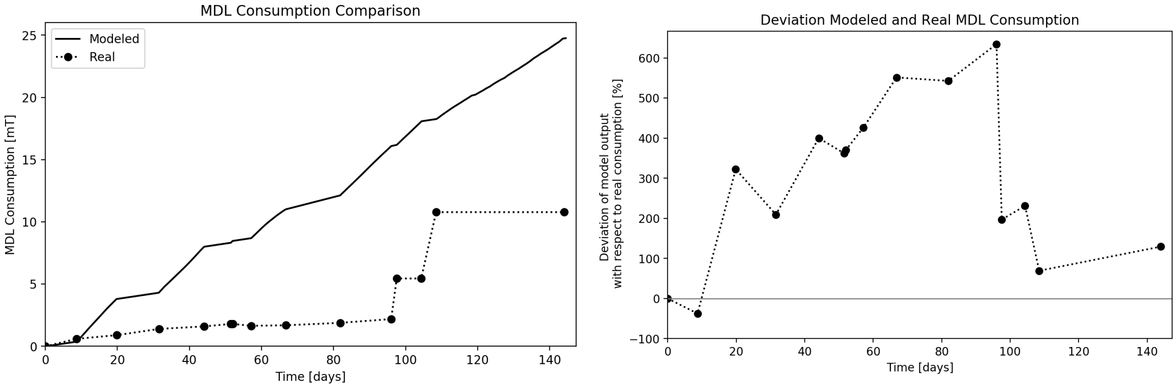


Figure 4.15: Comparison of modeled MDL consumption and real MDL consumption

In order to rule out the variation in fuel ratio used, the HFO and MDL consumptions are transformed to energy consumptions (using the lower heating values) and summed to a total energy consumption of the vessel. As described before, the modeled HFO consumption is slightly smaller than the real one and the modeled MDL consumption is larger than the real consumption. As can be seen in figure 4.16, the negative and positive drifts of the HFO and MDL deviations are ruled out when translating it to energy and considering it as one consumption. This means that the deviation is mainly based by an aberrant fuel ratio and that the used efficiency and power consumption values still hold. For this model, the fuel ratio of HFO:MDL = 99 : 1 is still considered a realistic assumption and therefore the model is valid for the calculation of the yearly fuel consumption.

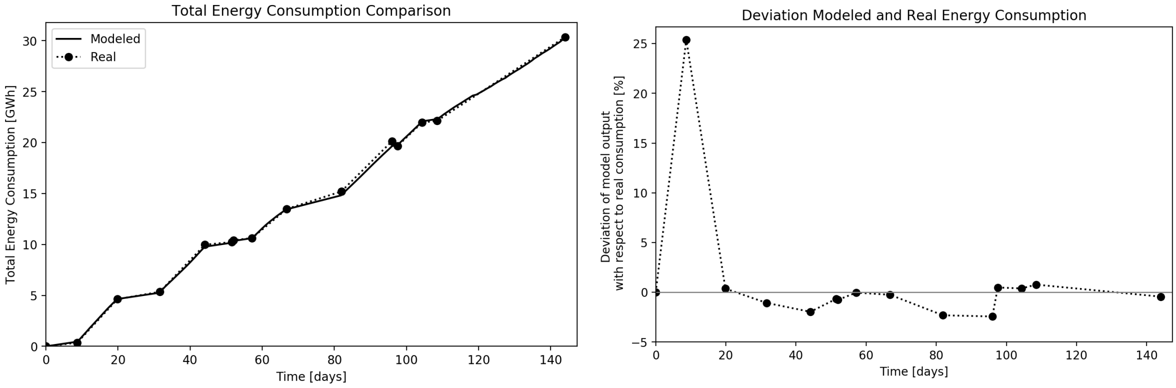


Figure 4.16: Comparison of modeled energy consumption and real energy consumption

Besides the energy consumption, the model has to be validated for the modeled distance sailed, which is an important variable for the $CO_2$ efficiency of the vessel. The modeled distance sailed is dependent on the engine power which is translated to a speed according to the speed-power curve in figure 4.8. The resulting distance sailed versus the time is shown in figure 4.17, as well as the real distance sailed according to the data. In the right graph in this figure, it can be seen that the deviation converges to near-zero in the second half of the operational profile. However, as opposed to the fuel consumption, the distance sailed cannot be compared over a time span of a full year. This is due to the fact that the distance sailed is an input for the transport work done which changes during the year due to different cargo loads of the vessel. For this reason, the real average distance sailed per hour - which is equal to the vessel's average speed during that hour - is compared with the modeled speed.

The deviation between the modeled speed and the real average speed per real data point is to be seen in the left graph of figure 4.17. It can be seen that most points are within the limits of +/- 3 knots. This deviation is substantial when considering a service speed of 12 knots. However, positive deviations can be evened out by negative deviations and therefore, it is important that the error in the model is equally distributed along the zero axis. In the right graph in figure 4.17, the absolute deviation is presented by means of a box plot and it can be seen that the median is exactly at a deviation of zero knots. Along this median, the deviations are equally distributed between the range of +/- 3 knots. This results that on average, the modeled distance sailed is equal to the real distance sailed and therefore the model is valid to approximate the real distance sailed by the vessel, which can be translated to the transport work carried out.

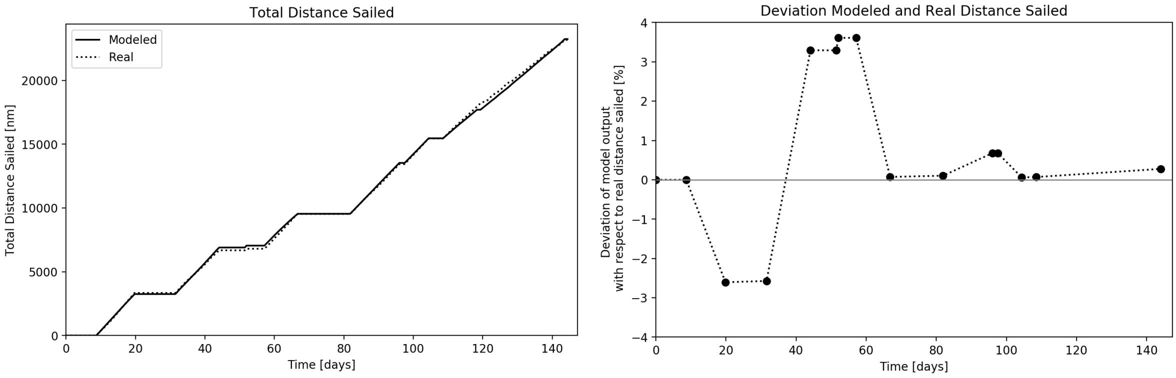


Figure 4.17: Comparison of modeled distance sailed and real distance sailed

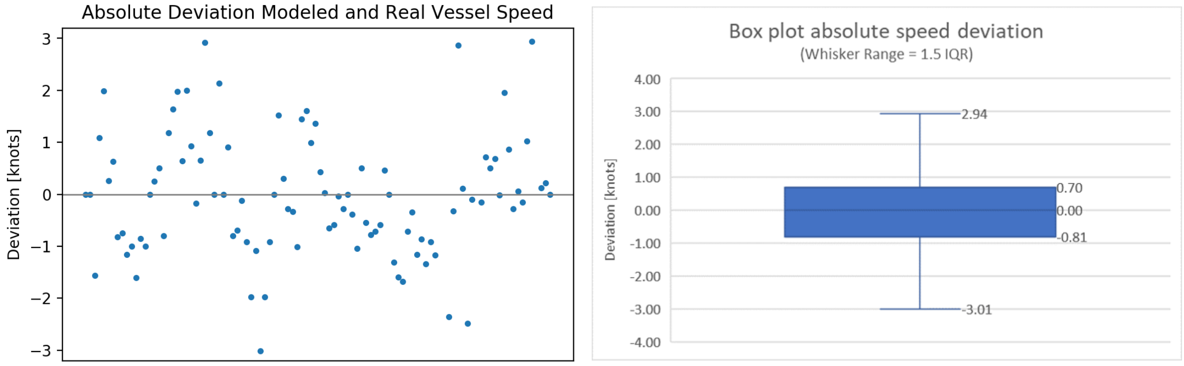


Figure 4.18: Absolute deviation between modeled and real vessel speed

## 4.3. Model input

In this section, all the input required to run the model for the case study is described and justifications are given. An important note is that the input described in this section are the base values which are used to create the baseline. Besides the baseline, there are several other scenarios to be modeled (see section 4.4) where certain input values are varied. The change of input values, however, will be described at the specific scenario description in section 4.4.

### 4.3.1. Vessel input

For the case study, a typical operational profile should be used as an input. As described in section 4.2.1, the operational profile of the case study vessel is highly variable and hard to predict. Therefore, it is chosen to consider the operational profile of 2017 of the vessel as representative for an average year of operation. This excludes the part where the vessel is in dry dock for a month. Also, as discussed in section 4.2.2, instead of a vessel speed and the DWT loaded on board, the main engine load of the vessel is used as an input. The main engine load is translated to a vessel speed according to the relation shown in figure 4.8. This results in the operational profile used as an input for the case study as shown in figure 4.19.

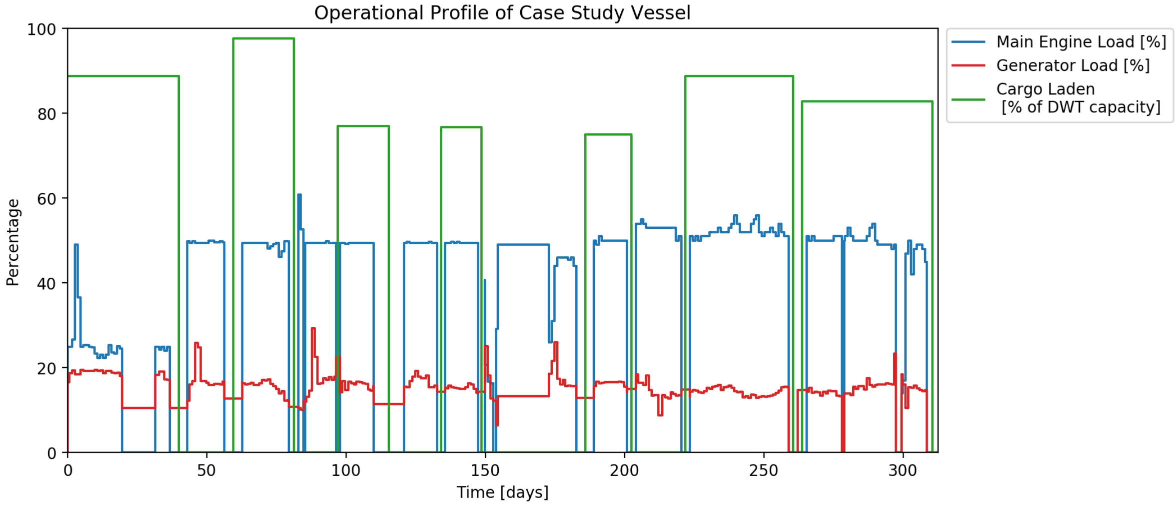


Figure 4.19: Operational profile of case study vessel as an input for the model

It is considered that this operational profile will be carried out for 95% of the time. This means that on average, the vessel is 18 days per year non-operational due to reasons such as maintenance, dry docking or other unexpected events. Including the port days within the operational profile, this translates to an average amount of 260 sailing days per year. Since the vessel has been built in 2012, the period of analysis is set to be 15 years. At the end of this period the vessel would be at the age of 22 years, at which time it is desired to be finished with investment projects since the end of the vessel's lifetime is approaching.

As described in section 4.2.3, the propulsive efficiency, auxiliary efficiency and power use in port are modeled to be as in table 4.5. Also. the last result from the data analysis is the fuel share of the case study vessel in 2017. The data shows that the ratio of energy consumed by burning HFO and MDL is approximately equal to HFO:MDL = 99:1. This difference between both fuels is easily to be explained, since the low sulphur and more expensive MDL is only used while sailing in SECA area's (see (IMO, 2018)). In the model this ratio is considered to be constant for the complete analysis period, when no fuel changing measures are implemented.

Table 4.5: Vessel input parameters for a case study on the vessel

| Input | Value | Unit |
|---|---|---|
| Analysis period | 15 | years |
| Operational time | 95 | [%] |
| Propulsive efficiency | 0.448 | [-] |
| Auxiliary efficiency | 0.311 | [-] |
| Power use in port | 878 | [kW] |
| Fuel ratio | 99:1 | [HFO:MDL] |

### 4.3.2. Measure input

In table 4.6, the measures and their properties taken as an input for this case study are presented. It appears that the values of their properties are very specific and exact, but in reality this is due to the fact that the numbers are based on the average of several sources. An extensive description of how each measure is modeled and sources for the values are described in the paragraphs below.

In this case study, the probability of reaching one of the three levels of fuel impact of a measure is modeled as an uniform distribution. In other words, there is an equal probability (1/3) that the implementation of a measure results in reaching minimum, average or maximum fuel saving impact. This decision has been made since the level of detail of the fuel saving impact in literature is insufficient in order to model it as, for instance, a normal distribution. With the information available in literature, it is not possible to conclude that it is more likely to reach the average fuel saving impact than the minimum and maximum. In case more results and studies on the measures become available, this probability distribution can easily be changed in the input sheet of the model.

Table 4.6: Measures to be analyzed during the case study

| Measure | Measure type | Fuel save min [%] | Fuel save avg [%] | Fuel save max [%] | CAPEX [$] | OPEX [$/yr] |
|---|---|---|---|---|---|---|
| Hull coating | Fuel saving | 1.50 | 3.05 | 4.60 | 231 750 | 46 350 |
| Propulsion improving devices | Fuel saving | 1.50 | 3.85 | 6.50 | 183 333 | 0 |
| Trim draft optimization software | Fuel saving | 0.83 | 1.92 | 3.25 | 43 333 | 0 |
| Hull air lubrication | Fuel saving | 2.67 | 8.83 | 15.00 | 1 050 000 | 10 000 |
| Wind assistance | Fuel saving | 2.00 | 7.50 | 15.00 | 994 500 | 86 800 |
| Auxiliary power by batteries | Fuel changing | - | - | - | 5 000 000 | 0 |
| Dual fuel engine | Fuel changing | - | - | - | 5 000 000 | 0 |

#### Hull coating

Anti fouling hull coating - in this report indicated as *hull coating* - is used to protect the steel hull from corrosion and to prevent marine growth from fouling the hull. As opposed to regular coating, anti fouling coatings have better prevention capabilities with respect to the fouling of marine growth to the hull due to the chemical composition of the coatings. Fouling to the hull could lead to great increases of the frictional resistance of a ship and therefore, preventing this could lead to savings in the fuel consumption.

Figure 4.20: Hull coating

Since the hull coating affects the frictional resistance of a vessel, the reduction potential is higher for full bodies ships such as the vessel in this case study. For the quantification of the fuel saving potential of this measure used in this case study, five representative references from literature are used, presented in table 4.7. Taking the average of those values as an input for this measure leads to a fuel saving percentage of [min; avg; max] = [1.50; 3.05; 4.60].

Typically, hull coating has to be applied to the vessel every five years and the costs are dependent on the size of the vessel. For the CAPEX of the hull coating, four representative references from literature are used and scaled to the case study vessel size, presented in table 4.7. In the determination and translation of these costs, only the difference between the price of regular coating and anti fouling coating is considered, since these are the real additional costs. Taking the average of those values as an input for this measure leads to a CAPEX of approximately 230 000 US$ every 5 years. However, since the feature of including re-investments in the model has not been developed yet, the measure is modeled as having one time the mentioned CAPEX when implementing and having an OPEX of one fifth of this CAPEX every year from implementation on. The values used for this measure as an input for the model are summarized in table 4.6.

Table 4.7: Sources used as a basis for the input variables of the hull coating measure

| Source | Fuel save min [%] | Fuel save avg [%] | Fuel save max [%] | CAPEX [$] | OPEX [$/yr] |
|---|---|---|---|---|---|
| (Hughes, 2016) | 1 | 2.5 | 4 | 267 000 | 53 400 |
| (Fathom, 2017) | 2 | 3 | 4 | 160 000 | 32 000 |
| (Bouman et al., 2017) | 1.5 | 3.25 | 5 | - | - |
| (Buhaug et al., 2009) | 1 | 3 | 5 | 250 000 | 50 000 |
| (Maddox Consulting, 2012) | 2 | 3.5 | 5 | 240 000 | 48 000 |
| Average: | 1.50 | 3.05 | 4.60 | 231 750 | 46 350 |

### Propulsion improving devices

Propulsion improving devices (PIDs) are different ducts, pre-swirl fins, fin on hull, rudders, caps, contra-rotating propeller or other modifications made to the hull or propeller in order to improve efficiency. Depending on the device, the main goal for these devices is to reduce the fuel consumption by improving the flow around the hull or propeller. The three main places to do modifications are in front of the propeller, behind the propeller or do modifications on the propeller or cap. Pre-swirl devices aim to improve the propeller inflow conditions, ducts may improve propulsion efficiency by improving the propeller inflow and post-swirl devices are used to recover parts of the rotational energy in the propeller slip stream (GloMEEP and DNV-GL, 2018).

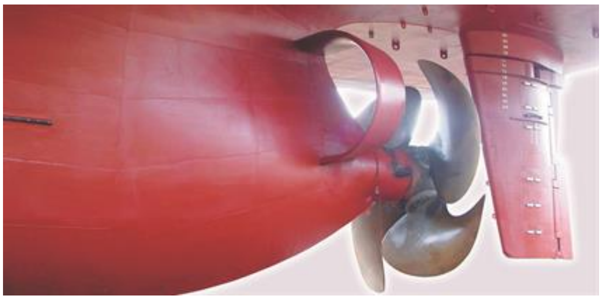


Figure 4.21: Propulsion improving device: duct (Babicz, 2015)

For every vessel, a different set of propulsion improving devices leads to the highest reduction potential, dependent on the vessel type, speed, design and other factors. For slow sailing bulk carriers in general, interesting PIDs are ducts, and post swirl devices (Babicz, 2015), but this varies per particular bulk carrier. Generally, a fuel consumption reduction of around 4% (Hochkirch and Bertram, 2010) is considered due to the implementation of PIDs and four additional representative references from literature are considered, as to be seen in table 4.8. Taking the average of those values as an input for this measure leads to a fuel saving percentage of [min; avg; max] = [1.50; 3.85; 6.50].

Due to the varying possible combination of PIDs, it is difficult to determine the CAPEX of this measure. Also, with limited information and spread in prices for the same measures throughout references, the costs are quite uncertain. However, there are three references used to estimate a price for PIDs for a bulk carrier which has an average of approximately 185 000 US$ (see table 4.8). For PIDs, it is considered that there are no substantial additional operational costs. The values used for this measure as an input for the model are summarized in table 4.6.

Table 4.8: Sources used as a basis for the input variables of the propulsion improving devices measure

| Source | Fuel save min [%] | Fuel save avg [%] | Fuel save max [%] | CAPEX [$] | OPEX [$/yr] |
|---|---|---|---|---|---|
| (Babicz, 2015) | 2 | 4 | 6 | - | - |
| (Svardal and Mewis, 2011) | - | - | - | 300 000 | 0 |
| (Hughes, 2016) | 2 | 3.5 | 5 | 100 000 | 0 |
| (Hochkirch and Bertram, 2010) | - | 4 | - | - | - |
| (Bouman et al., 2017) | 1.5 | 5 | 10 | - | - |
| (DNV-GL, 2016) | 0.5 | 2.75 | 5 | 150 000 | 0 |
| Average: | 1.5 | 3.85 | 6.5 | 183 333 | 0 |

### Trim draft optimization software

The trim and draft of a ship have an impact on its hull resistance and every vessel speed corresponds to one or multiple optimal combination of the trim and draft. Trim draft optimization software maps all these operational points by means of data collection and creates tables with the optimized operational points. By actively planning ballast conditions and cargo loading, the hull resistance can be minimized which leads to a fuel consumption reduction.

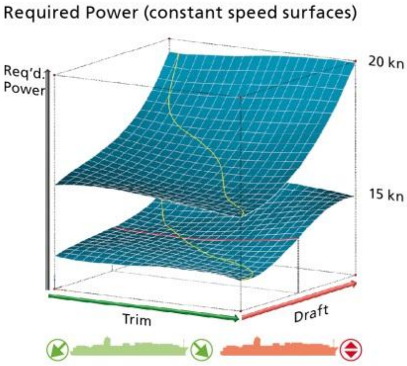


Figure 4.22: Trim draft optimization software output (GloMEEP and DNV-GL, 2018)

Although trim and draft optimization has the highest potential for ships where the wave friction dominates, it is still valuable for viscous friction dominating bulk carriers. Using four relevant references from literature, the average fuel savings percentage obtained by the implementation of trim draft optimization software on a bulk carrier is modeled to be [min; avg; max] = [0.83; 1.92; 3.25], as shown in table 4.9. Prices for trim draft optimization software are difficult to obtain from literature and suppliers, but are accounted for as a CAPAX of 43000 US$ (see table 4.9). When the software is purchased, there are no additional operational costs.

Table 4.9: Sources used as a basis for the input variables of the trim draft optimization software measure

| Source | Fuel save min [%] | Fuel save avg [%] | Fuel save max [%] | CAPEX [$] | OPEX [$/yr] |
|---|---|---|---|---|---|
| (Babicz, 2015) | - | - | 4 | - | - |
| (Hughes, 2016) | 0.5 | 1.25 | 2 | 25 000 | 0 |
| (Reichel et al., 2014) | 1 | 2 | 3 | 30 000 | 0 |
| (Maddox Consulting, 2012) | 1 | 2.5 | 4 | 75 000 | 0 |
| Average: | 0.83 | 1.92 | 3.25 | 43 333 | 0 |

### Hull air lubrication

Hull air lubrication is done by a system injecting air on the wetted flat part of the hull in order to reduce the hull resistance. The system creates an air layer between the flat bottom part of the vessel and the sea water and therefore results in reduced fuel consumption due to reduced resistance.

Figure 4.23: Hull air lubrication (Insight, 2017)

Hull air lubrication is best applicable for large, slow sailing flat bottomed vessels of which the frictional resistance dominates. This is the case for the bulk carrier in this case study and there are several relevant references presenting an indication for the possible fuel saving impact. In table 4.10, three references are presented which lead to an average expected fuel reduction impact percentage of [min; avg; max] = [2.67; 8.83; 15.00]. Due to the lack of research and application of this measures, the impact is very uncertain and therefore the spread is high.

As for other measures, credible values of the costs for the system are very limited available and the only sources are outdated. However, until more research is done, this is the information with which shipowners have to work with. Therefore, the CAPEX and OPEX (due to energy consumption of the system) of hull air lubrication is modeled as shown in tables 4.10 and 4.6.

Table 4.10: Sources used as a basis for the input variables of the hull air lubrication measure

| Source | Fuel save min [%] | Fuel save avg [%] | Fuel save max [%] | CAPEX [$] | OPEX [$/yr] |
|---|---|---|---|---|---|
| (Bouman et al., 2017) | 3 | 9 | 15 | - | - |
| (Buhaug et al., 2009) | 2 | 8.5 | 15 | 1 100 000 | 10 000 |
| (Wärtsilä, 2009) | 3 | 9 | 15 | 1 000 000 | 10 000 |
| Average: | 2.67 | 8.83 | 15.00 | 1 050 000 | 10 000 |

### Wind assistance

Wind assistance in shipping has the objective to recover thrust power from wind in order to reduce the main engine load while maintaining the same speed. Wind assistance on ships could be supplied by, for instance, kites or Flettner rotors. Flettner rotors are turning cylinders placed on the vessel which produces a thrust force according to the Magnus effect. Kites generate a pulling force on the ship which includes a force vector in the sailing direction of the ship. Both measures are still immature regarding the technical development and there is little uptake throughout the industry at this moment. However, the potential of this measure is high and worth exploring.

Figure 4.24: Wind assistance: Flettner rotors (McKenna, 2016)

Due to the low uptake throughout the industry, there is little literature and information available about the impact of wind assistance. Several theoretical studies has been carried out and a handful of practical testings, but the spread in the expected fuel reductions remain substantial. For the quantification of the fuel saving potential of this measure used in this case study, four representative references from literature are used, presented in table 4.11. Taking the average of those values as an input for this measure leads to a fuel saving percentage of [min; avg; max] = [2.0; 7.5; 15.0].

As for other measures, credible costs for the system are very limited available. However, until more research is done, this is the information with which shipowners have to work with. Therefore, the CAPEX and OPEX (due to energy consumption of the system) of wind assistance is modeled as shown in tables 4.11 and 4.6.

Table 4.11: Sources used as a basis for the input variables of the wind assistance measure

| Source | Fuel save min [%] | Fuel save avg [%] | Fuel save max [%] | CAPEX [$] | OPEX [$/yr] |
|---|---|---|---|---|---|
| (Bouman et al., 2017) | 3 | 11.5 | 20 | - | - |
| (Norsepower, 2018) | 2 | 5.5 | 9 | 1 000 000 | 100 000 |
| (Hughes, 2016) | 1 | 5.5 | 10 | 98 9000 | 73 600 |
| (Wärtsilä, 2009) | - | - | 21 | - | - |
| Average: | 2 | 7.5 | 15 | 994 500 | 86 800 |

### Auxiliary power by batteries

As opposed to the measures presented above, auxiliary power by batteries affects the type of fuel consumed, rather than decreasing it. Taking this measure means that the power grid in the vessel is adapted to be powered by both the diesel generators and a battery pack. This means that the auxiliary energy consumed could be partly generated by (green) electric sources which lead to a reduction in $CO_2$ emissions. The calculations and assumptions taken on the costs and impact of this measure are described below.

From the data analysis follows that the average load of the sum of the auxiliary engines is 15% and that the average sailing days per voyage equals 14 days (see figure 4.19. Considering the installed auxiliary power of 2340 [kW], the average auxiliary consumption per voyage can be calculated according to equation 4.4.

$$\text{Average auxiliary consumption per voyage} = 0.15 \cdot 2340 \cdot 14 \cdot 24 \equiv 118 \text{ [MWh]} \tag{4.4}$$

Considering the technological development of batteries at the moment of writing this report is not sufficient to supply the complete auxiliary energy demand by batteries, the assumption is made that this is done for 25% of the energy supply and 75% of the energy will still be supplied by the remaining diesel engines. Using several sources, the li-ion battery price is expected to be in the range of \$140/[kWh] in 2020 (Kittner et al., 2017; Union of Concerned Scientists, 2017) and with a fixed conversion cost of 1 million dollars, the price of this measure is estimated according to equation 4.5. Since the battery pack can replace at least one of the auxiliary diesel engines installed, it is assumed that there are no additional operational costs for maintaining this measure.

$$\text{CAPEX} = 0.25 \cdot 118000 \cdot 140 \cdot 1000000 \equiv 5\text{M US\$} \tag{4.5}$$

As opposed to fuel saving measures, this measure has no impact uncertainties regarding the fuel savings. Instead, the $CO_2$ reduction is decreased by using a fuel with a lower (deterministic) carbon content, which for green electricity is considered zero. The properties of this measure are summarized in table 4.13.

One last concern to take into account with the implementation of this measure is the additional space required on the vessel and the potential loss of revenue due to cargo capacity loss. A relevant case study on battery packs in the shipping industry shows that a realistic energy density for a battery pack on a ship could be 1680 kWh/TEU equivalent (GVT, 2018). For the size of the battery pack of this measure, the required space on the vessel would be approximately 18 TEU equivalent. Considering the large size of the case study vessel and the fact that it is never fully loaded with cargo (see figure 4.19), the costs of this space are neglected.

### Dual fuel engine

The last measure is investing in retrofitting the vessel from a diesel main engine to a dual fuel engine. By taking this measure, the fuel share for the main engine energy consumption is changed by burning an alternative fuel with a lower carbon content than HFO and MDL.

At the moment of writing this report, there are many different opinions, beliefs and studies done on the topic of what the next conventional low carbon fuel in the industry is going to be. All these studies and discussions have one aspect in common: it is very uncertain what the green shipping fuel of the future will be and many problems occur with every option. The focus of this case study is about the question if it is going to be necessary to change the fuel type in order to meet the regulations rather than about which fuel should be used. Therefore, the alternative fuel burnt in the dual fuel engine of this measure is modeled as an imaginable fuel rather than a specific one.

DNV-GL has published a paper (DNV-GL, 2018) in which the most plausible alternative fuels and their characteristics with respect to HFO are described. The price and tank to propeller (TTP) carbon emission factors of these fuels are presented in table 4.12. The values for the alternative fuel as used in this case study are described by the average of the fuels in the table; a fuel price of 662 [\$/mT] (assuming the density is equal to HFO) and a carbon content of 0.52 grams of $CO_2$ per gram of fuel burnt. For this measure, it is assumed that the dual fuel runs for 75% of the time on the alternative fuel and for the remaining 25% of the time on the conventional fuels HFO and MDL.

Table 4.12: Alternative fuels for the shipping industry

| | Relative to HFO[1] | | Absolute values | |
|---|---|---|---|---|
| Fuel | Price | $CO_2$ TTP | Price [\$/mT$_{eq}$] | gC/gFuel |
| HFO | 1.000 | 1.000 | 466 | 0.85 |
| LNG | 1.000 | 0.750 | 466 | 0.64 |
| LPG | 1.250 | 0.842 | 583 | 0.72 |
| Methanol | 1.500 | 0.474 | 699 | 0.40 |
| Bio-diesel | 1.857 | 0.000 | 865 | 0.00 |
| | | Average: | 662 | 0.52 |

[1] (DNV-GL, 2018)

Regarding the investment costs of this measure, there is just a small amount of resources to be found. According to (Stojcevski, 2016) and (Dolan and Andersson, 2016), the conversion costs to a methanol engine could be approximated by CAPEX = 350 \$/kW. For the case study vessel presented in this report, this would mean an investment of CAPEX = 4.3M US\$. A case study on the implementation of a LNG engine in a oil tanker representable for the bulk carrier in this report results in a total CAPEX of 5.8M US\$ (Dag, 2014). Considering these three references, the CAPEX for this measure is modeled to be 5 million dollars. The assumption is made that no additional operational costs are made with respect to the diesel engine. The model input values for the dual fuel engine are summarized in table 4.13.

Table 4.13: Key properties of the fuel changing measures

| Fuel changing measure | Carbon content [kg$_C$/kg$_{fuel}$] | Availability probability | CAPEX [\$] | OPEX [\$/yr] |
|---|---|---|---|---|
| Auxiliary power by batteries | 0 | 0.25 | 5 000 000 | 0 |
| Dual fuel engine | 0.52 | 0.75 | 5 000 000 | 0 |

### 4.3.3. Environment input

Besides the vessel specific input and the input of available technological measures, the environment the vessel operates in - now and in the future - has to be modeled. First of all, there is an economical environment consisting of, among other things, fuel prices and discount rates. Also, there is a political environmental of which the most important element for this case study is IMO's upcoming $CO_2$ regulations. The way these environmental elements are modeled in this case study is described in the paragraphs below.

The operational costs of a vessel consist of approximately 50% of fuel expenses (Stratiotis, 2018) and therefore, change in fuel prices have a great impact on the costs for shipowners. At the same time, however, fuel prices are very difficult to predict. To avoid speculation about these fuel prices in the baseline of the case study, the fuel prices are kept constant during the simulation period as the last known value (prices of July, 2018). In one of the case study scenarios, the fuel prices will be varied in order to study the effect on the results (see section 4.4). In figure 4.25, eight months of historical prices of HFO, MDL and electricity is presented and the values for which it will be kept constant during the simulation period (see also table 4.14).

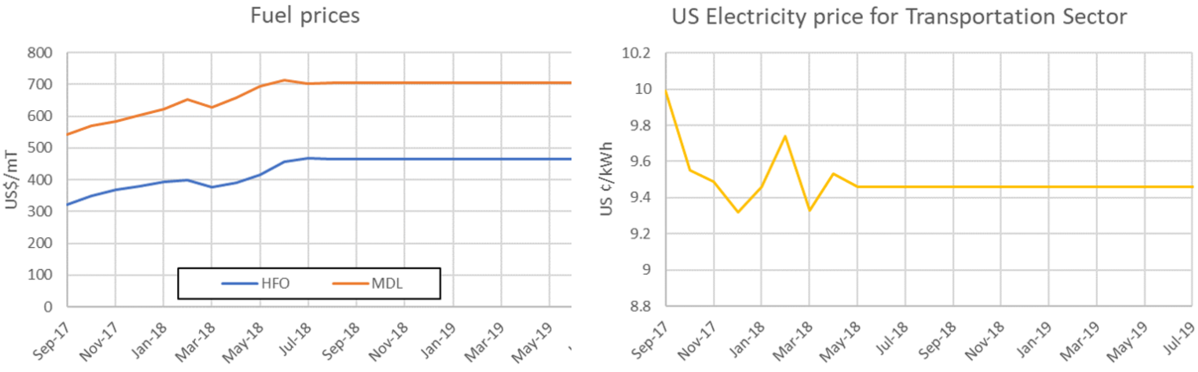


Figure 4.25: Historical fuel prices of HFO and MDL (SHIP & BUNKER, 2018) and electricity (Hankey, 2018). To avoid speculation, the fuel prices in the model are kept constant as their values in July, 2018

The discount rate used by companies differs per sector, company size and economical environment. For the value used in this study, discount rate of similar companies are used as a reference. Although the majority of shipping companies do not make their discount rate public (KPMG, 2011), there are still some reference values to be found. The shipping company A.P. Møller-Mærsk Group, for instance, used a discount rate of 6% in their financial analysis of the first half of 2018 (A.P. Møller - Maersk A/S, 2018). The German container shipping company Hapag-Lloyd used a discount rate of 7.9% for their financial analysis of 2017 (Hapag-Lloyd, 2018). As Hapag-Lloyd did for 2017, many companies use their historical weighted average costs of capital (WACC) and use it as their discount rate to evaluate investment projects of the future (Ross, 2018). According to a database of NYU Stern School of Business including the average WACC of various company sectors in the United States in 2018 (NYU Stern, 2018), the average WACC for the marine and transportation sectors is 7.2%. With these reference values in mind, an assumption has been made to use a discount rate of 7% for the case study in this report.

In section 1.1.2, IMO's climate agreement for the shipping sector and upcoming reduction targets are described. An important aspect of these targets is that the $CO_2$ efficiency of ships have to decline with 40% by 2030 with respect to the efficiency at 2008. The upcoming policy and regulations which will lead from these targets are at this moment neither published nor decided by IMO and therefore an assumption has to be made for the way a policy is taken as an input for the model.

To create an expected policy for the $CO_2$ efficiency, the same method is used as IMO's EEDI regulational framework, in which the sustainability of ships in the design phase is regulated. This framework was based on EEDI data of many at that time already existing ships, through which a line was fitted resulting in the baseline (IMO, 2013; IRCLASS, 2013). In IMO's second GHG study (Buhaug et al., 2009), the Energy Efficiency Operational Indicator (EEOI) of various ship types and sizes for the year 2007 are presented. The data of 2007 is assumed to be representative for 2008 (the baseline year), since the world fleet does not change drastically within one year. The data points of bulk cariers are plotted and a line is fitted through the data points resulting in the baseline to be used in this case study as to be seen in figure 4.26. From this baseline, the regulations of 40% reduction in 2030 and 70% reduction in 2050 can be calculated. In this case study, only the 2030 line is relevant since the case study vessel is expected to be out of service in 2050. Taking a look at these lines at the DWT of the case study vessel, it can be seen that the EEOI limit in 2030 for this vessel is equal to EEOI = 4.37 [$gCO_2$/ton-nm].

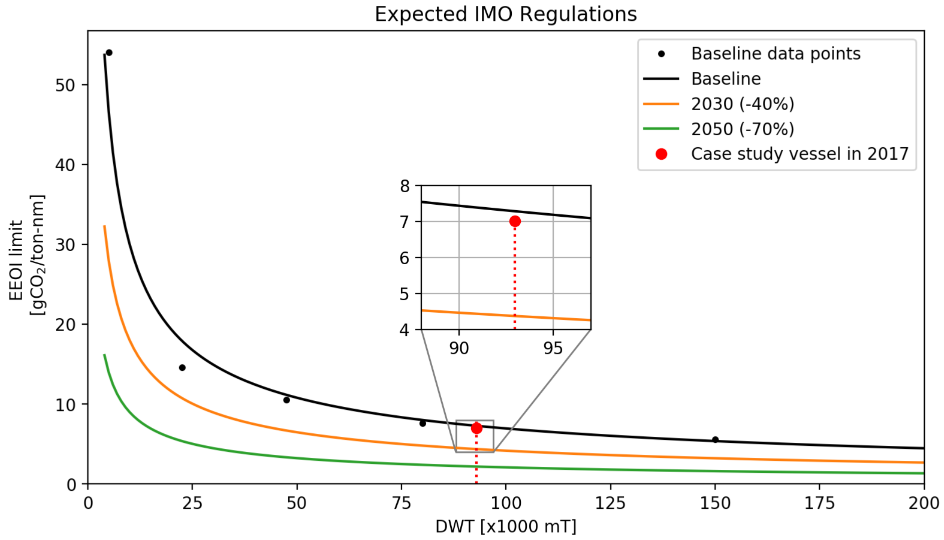


Figure 4.26: Expected EEOI limits by IMO regulations. Black points in graph represent IMO's data points (Buhaug et al., 2009) which form the basis of the baseline fit.

One of the assumptions taken in the baseline scenario is that a vessel will be not allowed to sail when it does not meet the regulations of 2030. This would mean that the costs of not meeting the regulations equals the potential loss of revenue of the vessel. For the case study vessel, the revenue is based on a charter rate per day. According to the most recent charter rates (as of August, 2018), this potential loss of revenue is modeled as a charter rate of 14000 US$ per day (Simpson Spence Young, 2018), see figure 4.27.

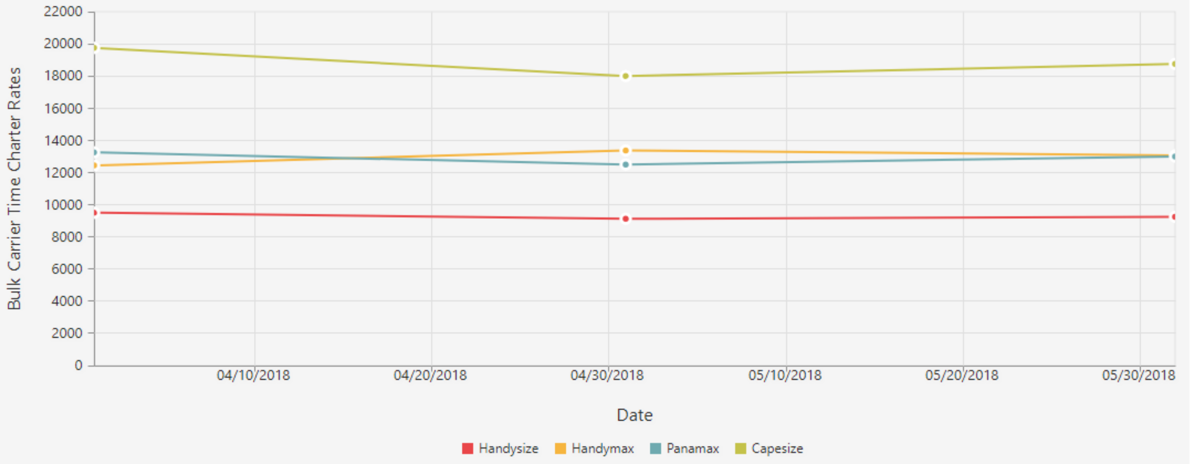


Figure 4.27: Bulk carrier time charter rates (Simpson Spence Young, 2018)

The environmental input used for the baseline scenario in this case study can be summarized as shown in table 4.14.

Table 4.14: Environment input for the case study

| Input | Value | Unit |
|---|---|---|
| HFO price | 466 | [\$/mT] |
| MDL price | 706 | [\$/mT] |
| Electricity price | 9.46 | [¢/kWh] |
| Alternative fuel price | 622 | [\$/mT] |
| Discount rate | 7 | [%] |
| EEOI limit 2030 | 4.37 | [$gCO_2$/ton·nm] |
| Charter rate | 14 000 | [US\$/day] |

## 4.4. Scenarios

In section 4.3, the standard model input values for this case study are described. These input values are the foundation of the baseline scenario; the scenario which is assumed to be the most likely situation based on the information available at the moment of running and analyzing it. However, the assumption that it is the most likely situation today does not mean that it describes the situation of tomorrow properly. For this reason, different scenarios are created in order to compare the results with different input values and the results of the baseline scenario. Analyzing these different scenarios gain insight in the rate of impact of certain variables and could clarify which variables are more important to consider than others.

### High fuel price scenario

Earlier work in this field implies that models in the maritime environment are likely to be sensitive to fuel prices (Kana and Harrison, 2017; Rehn et al., 2016). This makes sense when relating this to the model presented in this study since a major part of the costs and savings are related to the fuel consumption of the vessel and thus the fuel price. For this reason, the second case study scenario is related to the fuel prices. According to the World Energy Outlook of 2016 by the International Energy Agency, oil prices are expected to rise from this moment on (IEA and OECD, 2016), see figure 4.28.

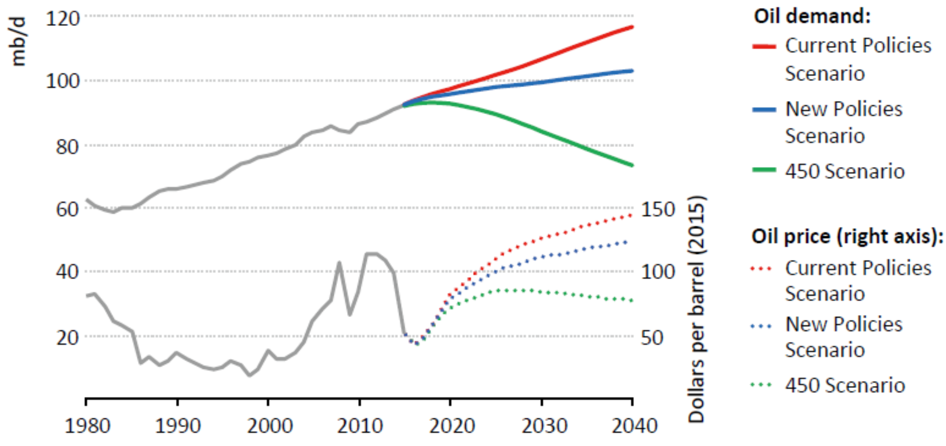


Figure 4.28: Projections of world oil demand and price by the International Energy Agency (IEA and OECD, 2016)

Since HFO and MDL are residual and distillate products of oil, it is assumed that the prices of those fuels increase linearly with the oil price. Note that in reality this assumption is not necessarily true, since the oil prices are affected by many other economical and political influences. However, for the purpose of exploring the effects of high fuel prices, this assumption is valid. The oil prices from the 'Current Policies Scenario' from the graph in figure 4.28 is taken, because it reflects on the scenario of the governmental policies practiced at the time of the study (2016). If the fuel prices are increased with the same incremental rate as the oil prices, the HFO and MDL fuel prices for the high fuel price scenario are as shown in table 4.15.

In this scenario, it is assumed that only the HFO and MDL prices are rising over time. Although it is inevitable that prices for electricity and alternative fuels also will change over time, they are kept constant in this scenario as to be the baseline values in order to create a difference in the vessel's current fuel and its potential future fuel. This is done in order to explore the effect of fuel prices on the output of the model and decision making of the ship owners.

Table 4.15: Fuel price projections for the high fuel price scenario. Projected oil prices in third column are based on (IEA and OECD, 2016).

| Year | Sim. year | Oil price [US$/barrel] | 2018 factor | HFO price [US$/mT] | MDL price [US$/mT] | Elec. price [¢/kWh] | Alt. Fuel Price [$/mT] |
|---|---|---|---|---|---|---|---|
| 2018 | 0 | 53 | 1.00 | 466 | 706 | 9.46 | 662 |
| 2019 | 1 | 68 | 1.28 | 598 | 906 | 9.46 | 662 |
| 2020 | 2 | 83 | 1.57 | 730 | 1106 | 9.46 | 662 |
| 2021 | 3 | 88 | 1.66 | 774 | 1172 | 9.46 | 662 |
| 2022 | 4 | 94 | 1.77 | 826 | 1252 | 9.46 | 662 |
| 2023 | 5 | 99 | 1.87 | 870 | 1319 | 9.46 | 662 |
| 2024 | 6 | 105 | 1.98 | 923 | 1399 | 9.46 | 662 |
| 2025 | 7 | 110 | 2.08 | 967 | 1465 | 9.46 | 662 |
| 2026 | 8 | 113 | 2.13 | 994 | 1505 | 9.46 | 662 |
| 2027 | 9 | 116 | 2.19 | 1020 | 1545 | 9.46 | 662 |
| 2028 | 10 | 119 | 2.25 | 1046 | 1585 | 9.46 | 662 |
| 2029 | 11 | 122 | 2.30 | 1073 | 1625 | 9.46 | 662 |
| 2030 | 12 | 125 | 2.36 | 1099 | 1665 | 9.46 | 662 |
| 2031 | 13 | 127 | 2.40 | 1117 | 1692 | 9.46 | 662 |
| 2032 | 14 | 129 | 2.43 | 1134 | 1718 | 9.46 | 662 |
| 2033 | 15 | 131 | 2.47 | 1152 | 1745 | 9.46 | 662 |

## Carbon pricing scenario

In the baseline scenario, the assumption is made that in case the vessel does not meet the 2030 $CO_2$ efficiency regulations, it is not allowed to sail and therefore the costs are modelled as a potential loss of revenue of the charter rate per day. However, at the time of the execution of this study, IMO merely adopted the vision and not yet a concrete policy (IMO, 2018a). Therefore, it could be possible that another policy than the one assumed in the baseline scenario will be created by the IMO. The carbon pricing scenario is studied in order to explore the impact on the decision making of the ship owner due to another regulation policy by IMO.

When regulations go into force in 2030, the amount of $CO_2$ emitted by the vessel will be limited dependent on its transport work. Putting a price on the $CO_2$ emissions could be organized in at least two different ways. First of all, the amount of $CO_2$ emitted within the regulation limits could be 'for free' and only the amount of $CO_2$ emitted exceeding these limits is priced. The second option is to charge nothing at all when the regulations are met, but charge all $CO_2$ emitted when not, also the part within the limits. First runs of the model show that only pricing the limit-exceeding part of the $CO_2$ emissions results in relatively low regulation costs which does not affect the results and decision making in any way. For this reason, the carbon pricing scenario will be based on the assumption that when the regulations are not met, a carbon price have to be paid for every ton of $CO_2$ emitted by the vessel and when the vessel does meet the regulations, no fees will be charged.

In order to model this policy, a price has to be set on $CO_2$ emissions. $CO_2$ prices are highly dynamic (Seifert et al., 2008) and as difficult to predict as other economical variables such as stock prices and fuel prices. For instance, carbon offset prices in the USA during 2017 were on an average of 15.8 US$/t$CO_2$ (Liu and Cui, 2017) and the *European $CO_2$ Emission Allowance* has a rate of $21/t$CO_2$ as per September 2018 (Markets Insider, 2018). However, these are the most recent carbon prices and as said before, they are highly dynamic and according to a recent report, European carbon prices are expected to increase to a price of $55/t$CO_2$ by 2030 (Lewis, 2018). Since the IMO regulation is going into force in 2030, that price is used in the model as the price for every ton of $CO_2$ emitted when not meeting the regulations.

### Dry dock schedule

Initially, it is assumed in the baseline scenario that any measure can be implemented at any moment in time. However, according to SOLAS regulations (IMO, 1974), vessels like the case study vessel must go into dry dock for inspection and maintenance at least every 5 years. Dry docking is an expensive activity for ship owners due to direct costs such as dock rent and indirect costs in the form of lost revenues (Hansen, 2013). For this reason, the amount of dry dockings of a vessel are opted to be minimized by the ship owner and the implementation of $CO_2$ reducing measures are likely to be done during an already schedule dry dock.

First runs of the model show that including a dry dock schedule in the model has a substantial impact on the financial and emission results of the vessel. For this reason, all the scenarios described above (i.e. baseline-, high fuel price- and carbon pricing scenario) are carried out with both the docking schedule excluded and included. When the dry docking schedule is included, the measures which require a dry dock to be implemented are forced to be implemented at one of the scheduled dry docking years. For the case study vessel, which went into dry dock in 2017 for the last time, these are scheduled for 2022 (simulation year 4), 2027 (year 9) and 2032 (year 14).

A summary of the case study scenarios is presented in table 4.17.

### Speed reduction

For the scenarios where the regulation costs type is *out of service*, there will be calculated what the required speed reduction is in order to still meet the regulations in case this is not possible with only the implementation of measures. While the economics of slow steaming are very complex with affecting factors such as freight rates, bunker costs and interest rates (Liang, 2014), it is assumed that reducing speed is the least favorable measure and the last resort to meet regulations.

The speed reduction option is not applicable to the carbon price scenario, where $CO_2$ offsetting is allowed, since it is assumed that a speed reduction is undesired - or the last resort - and therefore the shipowner rather pays for carbon offsets if necessary. This difference in policy is due to the fact that the carbon price scenario includes a variable regulation cost depending on the emissions, as opposed to the binary costs in the baseline and high fuel price scenario.

### Measure sets

The measures which are to be tested are listed in table 4.6. Due to limitations of the model considering computational power, the maximum number of measures analyzed per run is $N = 6$. For this reason, measure sets are created which consists of combinations of efficiency improving measures and fuel changing measures.
In table 4.16, five measure sets are defined which are analyzed for each scenario (see table 4.17). Measure set A tests if it could be feasible to only improve the efficiency without changing to an alternative fuel for either the auxiliary engine or the main engine. Measure set B goes a step further and tests - besides the efficiency improving measures - for a fully electrical auxiliary power line, including batteries on board. If more radical $CO_2$ cut downs are required, measure set C test for a complete exchange to a dual fuel engine, changing the share of fuels burnt. In this measure set for this case study, one alternative fuel type is considered, since the objective of the case study is more about finding out if and when it would be required for the shipowner to exchange the ship's engine, rather than speculating about which alternative fuel type is the most promising for the future. Measure set D does not take efficiency improving measures into accounts and only considers the rather 'radical' options of changing the fuel type of both the auxiliary power line and the main engine. For measure set E, the investment risk for ship owners is considered and therefore this set only takes financially safe measures into account. In order to test this, each measure is analyzed individually in the environment of the scenario. The measure is forced to be implemented in the first year and upcoming regulations are neglected. The result for each measure is the costs savings with respect to not implementing the measure and, if applicable, the payback period. For measure set E, only the measures are considered which have a payback period equal or smaller than 15 years in the worst case scenario of minimal impact on the efficiency.

Table 4.16: Measure sets used for each case study scenario presented in table 4.17

| Measure | Set A | Set B | Set C | Set D | Set E |
|---|---|---|---|---|---|
| Hull Coating | 1 | 1 | 1 | | Only if safe investment |
| Propulsion Improving Devices | 1 | 1 | 1 | | Only if safe investment |
| Trim Draft Optimization Software | 1 | 1 | 1 | | Only if safe investment |
| Hull Air Lubrication | 1 | 1 | 1 | | Only if safe investment |
| Wind Assistance | 1 | 1 | 1 | | Only if safe investment |
| Auxiliary Power by Batteries | | 1 | | 1 | Only if safe investment |
| Dual Fuel Engine | | | 1 | 1 | Only if safe investment |

Table 4.17: Case study scenarios

| | **a. Docking schedule excluded** | **b. Docking schedule included** |
|---|---|---|
| **1. Baseline** | Fuel price: as in table 4.14<br>Regulation cost type: out of service*<br>Speed reduction: if required | Fuel price: as in table 4.14<br>Regulation cost type: out of service*<br>Speed reduction: if required |
| **2. High fuel price** | Fuel price: as in table 4.15<br>Regulation cost type: out of service*<br>Speed reduction: if required | Fuel price: as in table 4.15<br>Regulation cost type: out of service*<br>Speed reduction: if required |
| **3. Carbon pricing** | Fuel price: as in table 4.14<br>Regulation cost type: $55/tCO_2$<br>Speed reduction: not applicable | Fuel price: as in table 4.14<br>Regulation cost type: $55/tCO_2$<br>Speed reduction: not applicable |

*Out of service means a loss of potential revenue in terms of chartering day rate ($14 000/day)

# 5

# Case study results

In this chapter, the results of the case study as described in chapter 4 are presented. First of all, in section 5.1, the included $CO_2$ reducing measures are analyzed on an individual basis after which the results of the case study scenarios are described in section 5.2. Lastly, the overall conclusion of the case study on the vessel are described in section 5.3.

## 5.1. Analysis of individual measures

In order to gain insight in the financial attractiveness of individual measure investments and their expected impact on the $CO_2$ efficiency of the vessel, analyses are made on the individual $CO_2$ reducing measures in the environment of the specific scenario. This means that for each measure an analysis is made in which it is forced to be implemented in the first year and with the assumption that there will be no regulations going into force in 2030. Besides the financial attractiveness and expected $CO_2$ impact, it provides more insight in the reason why certain measures are selected in the MDP process, described in section 5.2, and others are not. At last, these individual results will be the basis of the measure selection for measure set E, in which only safe investments are considered.

### 5.1.1. Scenario 1 and 3 - baseline and carbon pricing

First of all, the individual measures are analyzed in the environment of the baseline and carbon pricing scenarios. For this analysis, these two scenarios provide an equal environment, since the difference between both is the difference in pricing not meeting the regulations. For this analysis, regulations are neglected and therefore both scenarios are the same for this analysis. In figure 5.1, two types of results are presented: expected costs saving lines per measure and the expected improvement of the $CO_2$ efficiency of the vessel. Not only the expected values are presented in these results, but also the minimum and maximum ranges of the measures, which could be interpreted as best- and worst case scenarios.

Taking a look at the cost saving graphs of the hull coating and hull air lubrication measures, it can be seen that according to the expected value theory, the measures are expected to be profitable after a payback period of four or five years. However, in the worst case when the measures have the minimum expected impact on the vessel's efficiency, both measures are expected to have a longer payback period than the 15 remaining years of the vessel. For the wind assistance measure this effect is even more substantial; in the worst case event, the operational costs are higher than the cost savings and the annual total costs will be higher than the situation where wind assistance is not implemented. However, for all these three measures there is also a optimistic probability with relatively high cost savings. Since the MDP theory works with expected values, these measures will be selected to implement in the baseline and carbon pricing scenarios, but it is important to realize the risk involved in these measures.

As to be seen in the graphs of propulsion improving devices and trim draft optimization software, these measures both have an expected payback period of less than a year and from that moment start on making a profit. Also, in the worst case scenario when the measures obtain a minimum impact on the vessel's efficiency, the payback periods are within four and two years respectively, which make them a financially attractive investment. Opposing to these are the measures of exchanging the auxiliary and main engine systems. Investing in batteries for the auxiliary power results in a annual cost saving, but not sufficiently large to earn back the investment within 15 years. For an engine refit, the costs per year increase due to the higher fuel price and therefore the loss grows with every operational year.

Looking to the last graph of figure 5.1, the expected improvement of the vessel's $CO_2$ efficiency by implementing the measures are shown. It can be seen that, as for the costs, the probability ranges differ per measure and also the rate of impact. For instance, retrofitting a dual fuel engine is financially the worst option of the presented measures, but also results in the highest and most certain carbon emission decrease. The relation between the costs and $CO_2$ efficiency impact of the measures will become important when regulation comes into force and measure costs will be weighted against costs of not meeting the regulations.

According to the approach described in section 4.4, the measures selected for measure set E are only the measures which have a positive cost saving after 15 years in the worst case scenario of minimal impact on the efficiency. Taking a look to the graphs in figure 5.1, this is only applicable to the propulsion improving devices and the trim draft optimization software. Therefore, measure set E only consists of these two measures.

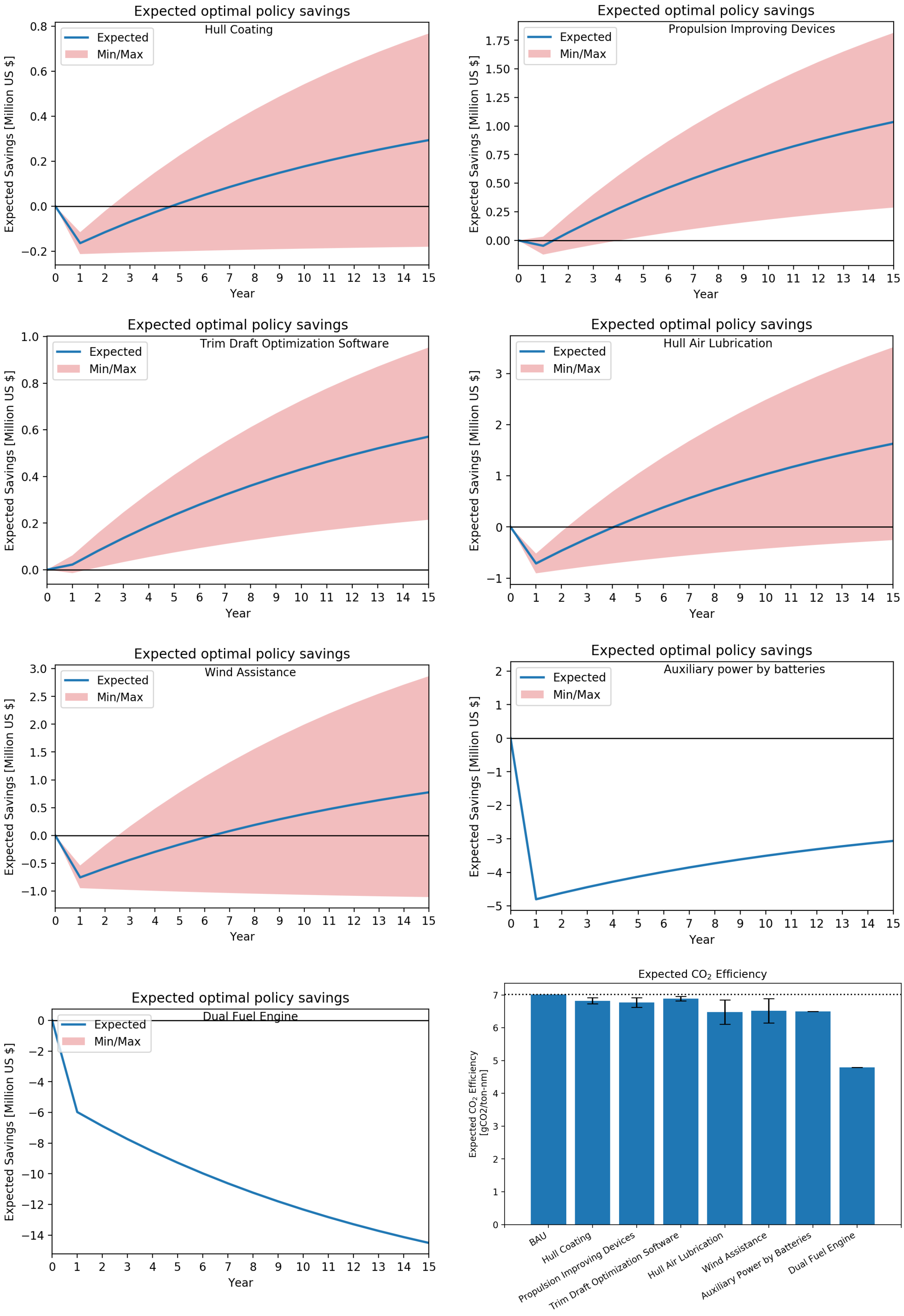


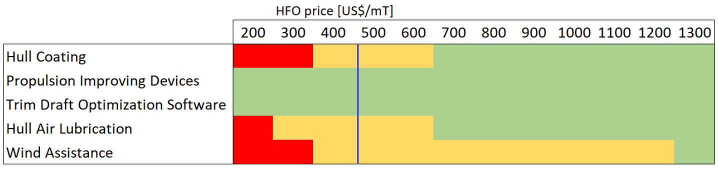
Figure 5.1: Analysis of the implementation of individual measures in the baseline and carbon pricing scenarios

### 5.1.2. Scenario 2 - High fuel price

The most important variable at the foundation of the individual measure analyses is the fuel price. When the fuel prices change, the results as presented in the previous section (figure 5.1) will change as well. The payback period of the fuel changing measures are dependent on - as the name implies - the fuel saved after the implementation and therefore the costs saved with respect to keep the vessel in its original state. Therefore, when the fuel prices increase, the amount of money saved per ton of diesel increases and the investment in fuel saving devices become more interesting or more profitable.

For the fuel changing measures, the fuel prices are affecting the profitability in a slightly different way. For these measures, the spread between the conventional fuel and the alternative fuel is important. If the alternative fuel is more expensive than the conventional fuel (as is the case in scenarios 1 and 3), the costs per ton of fuel burnt increases and the measure is not profitable. However, when the alternative fuel is cheaper than the conventional fuel, the effect is reversed and the amount of money saved will increase per ton of fuel burnt. The effect on the varying fuel prices in this scenario on the results of the individual measure analyses is to be seen in the graphs in appendix B. As expected, it can be seen that the fuel saving measures are making higher cost savings due to the high fuel price and the fuel changing measures as well, but in this case due to the greater spread in fuel prices (conventional fuels versus alternative fuels).

More interesting than these individual scenario results are the limits where certain measures change from non profitable to profitable. These limits give the shipowner insights in the way the measures would perform in the current or future economical environments. First of all, these boundaries are explored for the fuel saving devices. In figure 5.2, a color diagram is shown for the fuel saving devices acting in certain fuel price environments on the case study vessel. For this analysis, the small amount of MDL consumption is ignored and assumed to be HFO and the price for HFO is varied. Besides the fuel price where a certain measure is (non) profitable, the color diagram also indicates the uncertainty spread of the measure in orange; the fuel price where the measure is expected to be profitable, but is not profitable in worst case scenario.



HFO price [US$/mT]

| | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 | 1100 | 1200 | 1300 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hull Coating | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Propulsion Improving Devices | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Trim Draft Optimization Software | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Hull Air Lubrication | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 | 🟩 |
| Wind Assistance | 🟥 | 🟥 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟨 | 🟩 |

Figure 5.2: Fuel price sensitivity of efficiency improving measures. The colors indicate the financial profitability of the implementation of a measure and have the following meanings: green - profitable at any impact scenario; yellow - expected value is profitable, but worst case impact is not profitable; red - not profitable; blue line - fuel price of baseline scenario

As described before, the profitability of the fuel changing measures are dependent on the spread between the conventional and alternative fuel prices. For the dual fuel engine, the HFO price is set out versus the alternative fuel price and for every combination a profitability analysis has been done. The results of this is to be found in figure 5.3 and it could be seen that for this measure in the case study vessel a fuel price spread of approximately 200 \$/mT is required. For the auxiliary power by batteries measure, this analysis has been done slightly different. Since the electricity prices are not expect to increase or decrease substantially until 2040 (IEA and OECD, 2016), the electricity price has been kept constant. Instead, the battery price (i.e. investment costs of the measure) is set out versus the HFO price, since the battery price is expected to decrease over time (Union of Concerned Scientists, 2017). In figure 5.4, the results of this analysis is presented in a color diagram and could function as a rule of thumb for the shipowner.

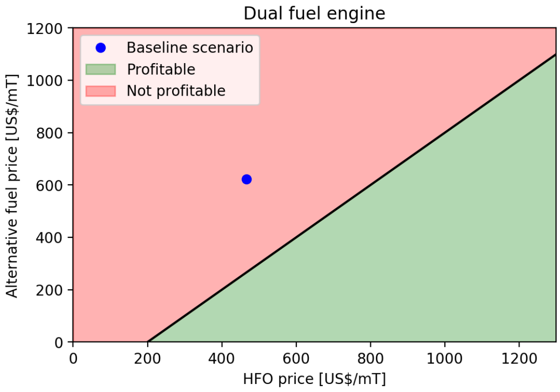


Figure 5.3: HFO versus alternative fuel price sensitivity of dual fuel engine

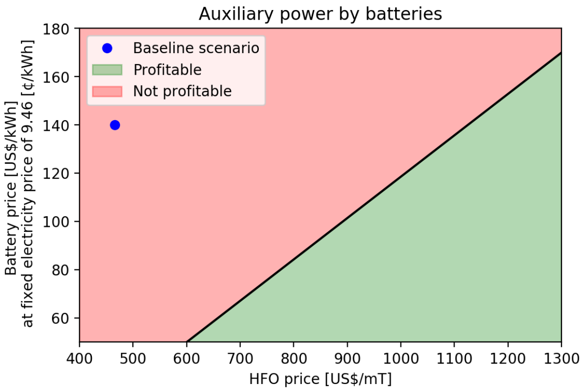


Figure 5.4: HFO versus battery price sensitivity of auxiliary power by batteries

## 5.2. Analysis of scenarios

In this section, the results of the three scenarios described in section 4.4 are presented. An analysis of the baseline scenario results are described in section 5.2.1 and the results of the high fuel price scenario is presented in section 5.2.2. In section 5.2.3 the results of the carbon price scenario are described after which the impact of considering a docking schedule in the model is described in section 5.2.4.

### 5.2.1. Baseline scenario

If only fuel saving measures are considered, referred to as measure set A in this report, the resulting policy for the model in the baseline scenario is presented in figure 5.5. It can be seen that the optimal policy states that all five fuel saving measures should be implemented in year 1 - or as soon as possible. This outcome is in line with the analysis of the individual measures described in section 5.1.1, in which was concluded that all fuel saving measures result in positive expected cost savings. A logical result from following this optimal policy is the states accessed presented in figure 5.6; all fuel saving measures are implemented from year 1 on.

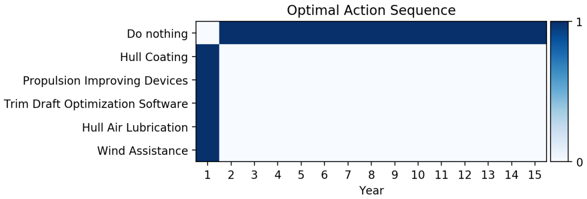


Figure 5.5: Optimal policy resulting from the model for measure set A in scenario 1a

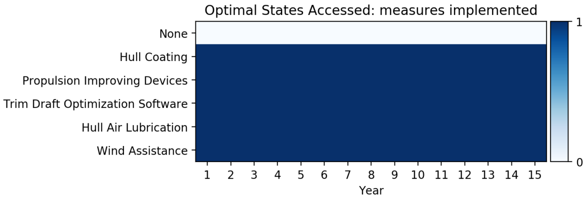


Figure 5.6: States accessed when following optimal policy for measure set A in scenario 1a

Following the optimal policy as presented in figure 5.5, the $CO_2$ efficiency of the case study vessel will be improved. The $CO_2$ efficiency per year is presented in figure 5.7. In this figure, the current performance of the vessel is indicated as the business as usual (BAU) line and also the regulation limits are included in the figure. It can be seen that, from year 1, on the expected $CO_2$ efficiency is improved due to the implementation of the fuel saving measures. However, the improvement is insufficient to meet the regulations in 2030 (year 12) and therefore, the vessel has to reduce its speed by 25% in order to avoid being out of service. Additionally, the total accumulated $CO_2$ emissions by the vessel following the optimal policy, including the speed reduction, is shown in figure 5.8. In this figure, it can be seen that in year 15 the total $CO_2$ emissions are reduced by 120 000 [mT].

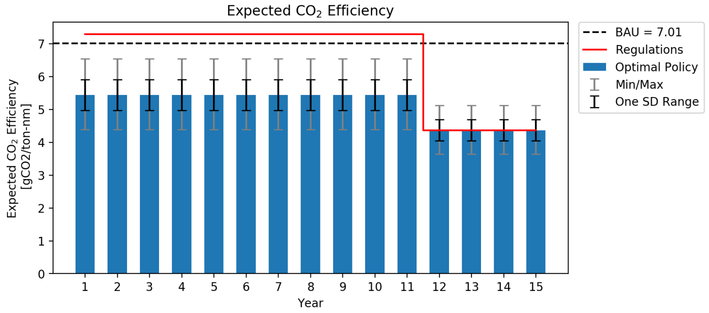


Figure 5.7: Expected CO$_2$ efficiency during the analysis period for measure set A in scenario 1a

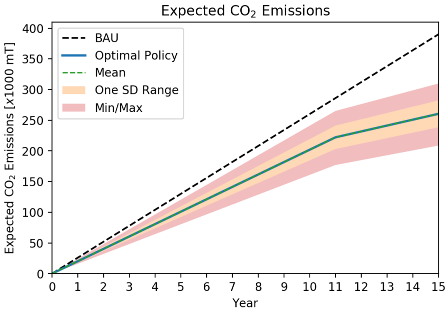


Figure 5.8: Expected CO$_2$ emissions during the analysis period for measure set A in scenario 1a

In figure 5.9, the expected costs of following the optimal policy is shown together with the BAU line. Figure 5.10 shows the difference between the BAU line and optimal policy line which therefore represents the expected cost savings of following the optimal policy with respect to the BAU line. In the figures it can be seen that after additional costs in year 1 - due to the investment in measures - the expected cost saving line crosses the break even point around year 4 after which positive cost savings are expected. Important to notice is that the costs of the BAU line increase tremendously in year 12, which is a result of not meeting the regulations going into force in that year. For this reason, the cost savings in figure 5.10 also increase rapidly from year 12 on, since the regulations are expected to be met when following the optimal policy and apply a speed reduction.

The optimal policy for measure set A the expected output as a result of following this in the baseline scenario can be summarized as shown in table 5.1.

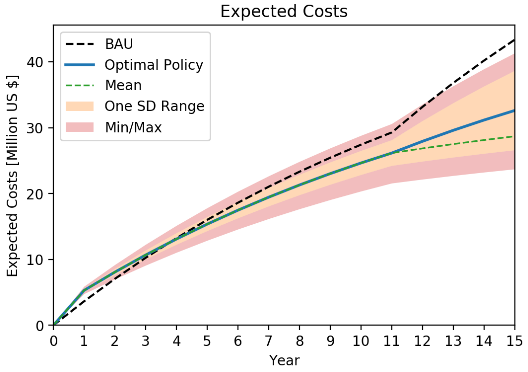


Figure 5.9: Expected costs during the analysis period for measure set A in scenario 1a

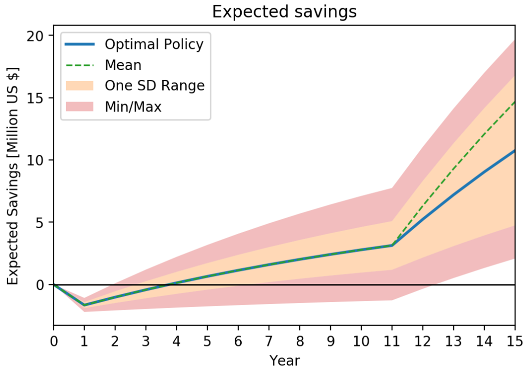


Figure 5.10: Expected savings when following optimal policy for measure set A in scenario 1a

As seen in the optimal policy for measure set A (figure 5.5), the optimal policy contains certain actions; definitely implement all fuel saving measures since they are all expected to save costs within the coming 15 years. When analyzing the optimal policies for measure set B and C, however, policy uncertainty come into play for the implementation of electric auxiliary power or a dual fuel engine. As can be seen in the optimal policy of measure set B in figure 5.11, the probability to implement the auxiliary power by batteries measure in year 11 is 50%, as well as the states accessed in figure 5.12. In the environment of year 1, this measure is financially not profitable to implement (see section 5.1.1), but after the introduction of regulation costs in year 12, it becomes a more favorable option than doing nothing which results in a vessel that is out of service. The resulting action probability of 50% is based on two underlying questions: (1) *are the regulations already met by only implementing the fuel saving measures?* and (2) *in case the regulations are not already met, is it possible to meet them by implementing this measure?*. If the regulations are already met by the implementation of the fuel saving measures - which is a (minor) possibility in the best case scenario - it makes no sense to make a costly and loss making investment in another measure. Also, when the regulations are not met yet, but the implementation of the auxiliary power by batteries measure will also not be sufficient, it again makes no sense to make the investment. The corresponding results with policy uncertainty are calculated according to the expected value theory described in section 3.6 and to be found in table 5.1.

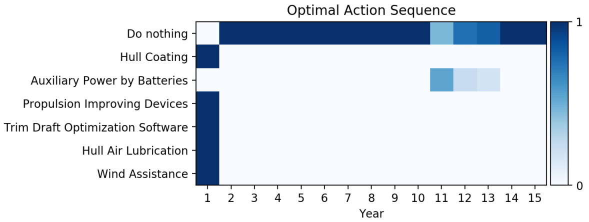


Figure 5.11: Optimal policy resulting from the model for measure set B in scenario 1a

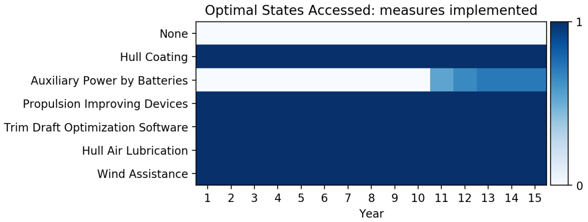


Figure 5.12: States accessed when following optimal policy for measure set B in scenario 1a

Back in section 5.1.1, the conclusion is drawn that the auxiliary power by batteries and dual fuel engine measures are financially not profitable and should not be implemented if not enforced by regulations. However, when taking the regulations into account in this scenario, the results of measure set D (only considering those fuel changing measures), is that both measures should be implemented in year 11, just before the regulations go into force (see figure 5.13). On the one hand, these are very costly investments which only are profitable under the pressure of regulation. On the other hand, the impact on the $CO_2$ efficiency is substantially and regulations are - considering the factors taken into account in this study - certainly met by taking these measures. Because of this, the expected accumulated cost savings are not large, but it is certainly not necessary to reduce the vessel's speed, which is assumed to be a considerable advantage (see table 5.1).

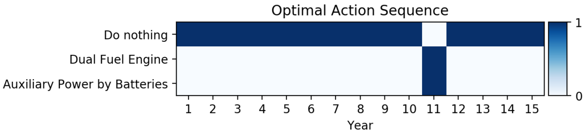


Figure 5.13: Optimal policy resulting from the model for measure set D in scenario 1a

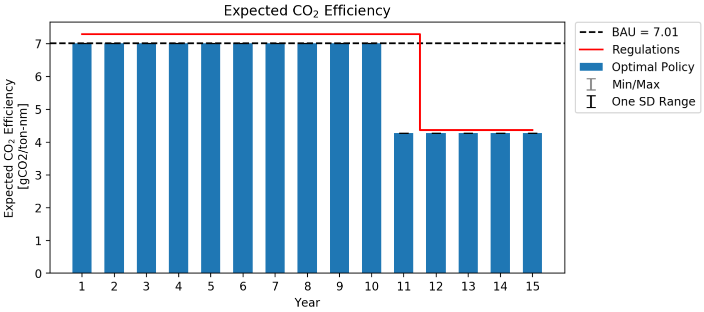


Figure 5.14: Expected $CO_2$ efficiency during the analysis period for measure set D in scenario 1a

Measure set E is analyzed in this case study to explore the possibilities of only making low risk investments. When looking to the results of this measure set in table 5.1, it can be seen that besides the implementation of the two financially profitable measures, the vessel also has to reduce its speed by 46% in order to meet the upcoming regulations. Such a large speed reduction (6 knots versus 12 knots) is considered unrealistic and would result in an impossible situation of carrying out proper operations with the vessel. The conclusion drawn from this result is that it is inevitable to do - with the current knowledge in literature - more risky investments as a shipowner in order to cut down $CO_2$ emissions to meet the regulations.

In summary, the results of the different measure sets conclude on one common policy for this scenario. Firstly, either all fuel saving measures or only the two financially profitable fuel saving measures should be implemented as soon as possible. Thereafter, the true impacts of the taken measures can be monitored before a second decision has to be made ahead of year 11; is it required to take a fuel changing measure in year

11 and if so, which one - or combination - is the most favorable at that moment in time? For this decision, the age of the vessel should also be taken into account; is it really a smart decision to do a big retrofit on a vessel with an age of 18 years? Although, exact mathematical numbers behind the model might conclude this, other risks and constraints of the problem should also be taken into account. More about the interpretation of the results is described in chapter 6. Lastly, also part of the decision is the choice between the fuel changing measures or possible speed reduction; speed reduction could be a more favorable measure rather than an expensive technical measure at the near end of the vessel's lifetime.

Table 5.1: Model results of the five measure sets in the baseline scenario excluding the dry docking schedule. The upper part of the table represents the optimal policy with the optimal moments of implementation of each measure per measure set and the lower part shows the expected output when following that policy.

| Scenario 1a - baseline | Set A | Set B | Set C | Set D | Set E |
|---|---|---|---|---|---|
| Hull coating | ASAP | ASAP | ASAP | - | - |
| Propulsion improving devices | ASAP | ASAP | ASAP | - | ASAP |
| Trim draft optimization software | ASAP | ASAP | ASAP | - | ASAP |
| Hull air lubrication | ASAP | ASAP | ASAP | - | - |
| Wind assistance | ASAP | ASAP | ASAP | - | - |
| Auxiliary power by batteries | - | year 11* | - | year 11 | - |
| Dual fuel engine | - | - | year 11* | year 11 | - |
| Expected required speed reduction [%] | 25.4 | 15.4 | 0 | 0 | 46.2 |
| Expected $CO_2$ efficiency in year 15 [$gCO_2$/ton-nm] | 4.37 | 4.32 | 3.84 | 4.28 | 4.36 |
| Expected accumulated $CO_2$ reduction [x1000 mT] | 120 | 115 | 117 | 51 | 98 |
| Expected accumulated cost savings [million $] | 10.2 | 8.0 | 7.8 | 1.3 | 10.6 |
| Break-even year of investment combination | 4 | 4 | 4 | 15 | 2 |

*Action has a probability aspect of being optimal or not, depending on the true impact of formerly implemented measures.

The optimal policy resulting from the baseline scenario can be simplified and visualized as shown in figure 5.15.

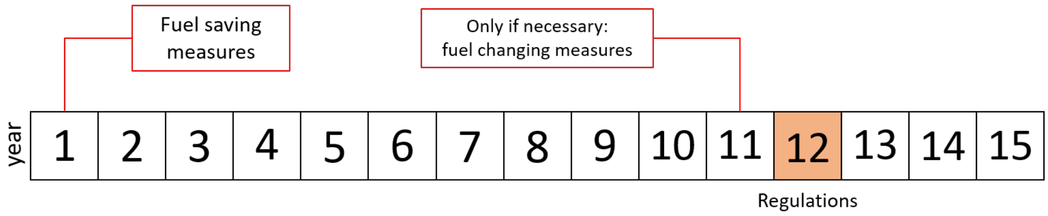


Figure 5.15: Simplified visualization of the policy resulting from the baseline scenario (excluding the dry docking schedule)

### 5.2.2. High fuel price scenario

In table 5.2, the results for the five measure sets in the high fuel price scenario are presented. In comparison with the results for the baseline scenario, there are both similarities and differences in the optimal policies and corresponding results to be noticed.

First of all, the optimal implementation moments for the fuel saving measures are the same for both scenarios; implement them as soon as possible. This is a logical outcome according to the fact that in both scenarios the fuel saving measures are financially profitable and therefore have to be implemented as soon as possible in order to maximize the profits (see section 5.1). Differences in the optimal policy with respect to the one of the baseline scenario come into play at the fuel changing measures. It can be seen in the results that the optimal moments to implement these are many years earlier than in the baseline scenario. This is basically the result of the spread between the prices of the conventional fuels - HFO and MDL - and of the alternative fuel and electricity. In this scenario it is modeled that the conventional fuel prices rise according to the increase of oil price and the price for the alternative fuel and electricity remain constant as the baseline value. According to this, in year 2 alternative fuel and electricity becomes cheaper per kWh than HFO and the result is that it is expected to pay off to implement the fuel changing measures in that year already rather than to wait until the moment the regulations go into force.

Considering the results following the optimal policies presented in table 5.2, there are some important differences to be noticed with respect to the baseline scenario. It can be seen that the expected accumulated cost savings of the five policies are higher than the baseline scenario. This is mainly the result of the higher fuel prices which means that with every ton of fuel decrease a higher cost savings is obtained. Also, applicable for measures sets B, C and D, the fuel changing measures are implemented years earlier which means a greater decrease of total HFO and MDL consumption. Another result of implementing the fuel changing measures in an early stage is that the expected accumulated $CO_2$ reduction is higher over the 15 years of analysis, which is favorable for the environment.

In summary, this scenario shows that the moment of implementation of the fuel changing measures are strongly dependent on the difference in fuel price between the conventional fuels and the alternative fuels rather than the moment of regulations going into force. This is an additional conclusion to the one already made in section 5.1.2, in which the fuel price and spread dependency is described. The general effect on the results is that the expected accumulated $CO_2$ reduction and cost savings increase which is favorable. However, the fuel price is a factor which cannot be influenced by the shipowner and is solely dependent on the world's economical situation.

Table 5.2: Model results of the five measure sets in the high fuel price scenario excluding the dry docking schedule. The upper part of the table represents the optimal policy with the optimal moments of implementation of each measure per measure set and the lower part shows the expected output when following that policy.

| Scenario 2a - high fuel price | Set A | Set B | Set C | Set D | Set E |
|---|---|---|---|---|---|
| Hull coating | ASAP | ASAP | ASAP | - | ASAP |
| Propulsion improving devices | ASAP | ASAP | ASAP | - | ASAP |
| Trim draft optimization software | ASAP | ASAP | ASAP | - | ASAP |
| Hull air lubrication | ASAP | ASAP | ASAP | - | ASAP |
| Wind assistance | ASAP | ASAP | ASAP | - | - |
| Auxiliary power by batteries | - | year 2* | - | ASAP | - |
| Dual fuel engine | - | - | year 2* | ASAP | Year 2 |
| Expected required speed reduction [%] | 25.4 | 12.8 | 0 | 0 | 0 |
| Expected $CO_2$ efficiency in year 15 [$gCO_2$/ton-nm] | 4.37 | 4.35 | 3.81 | 4.28 | 4.11 |
| Expected accumulated $CO_2$ reduction [x1000 mT] | 120 | 131 | 172 | 152 | 154 |
| Expected accumulated cost savings [million $] | 21.9 | 16.1 | 24.3 | 15.1 | 21.4 |
| Break-even year of investment combination | 3 | 6 | 5 | 10 | 6 |

*Action has a probability aspect of being optimal or not, depending on the true impact of formerly implemented measures.

The effects of the high fuel prices with respect to the baseline scenario is visualized in figure 5.16.

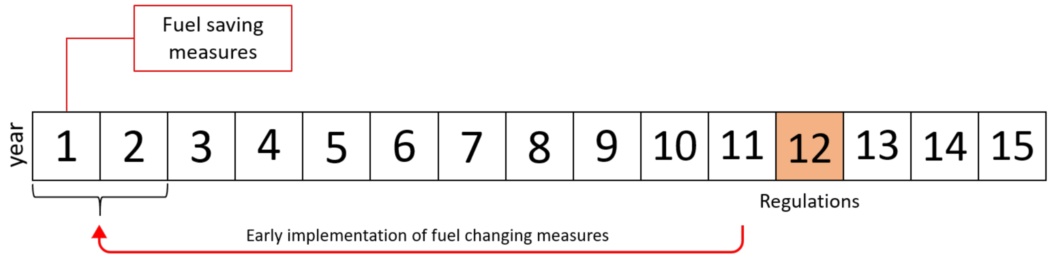


Figure 5.16: Effect of high fuel prices on the moment of implementation of measures with respect to the baseline scenario

### 5.2.3. Carbon price scenario

The results of the carbon price scenario presented in table 5.3 give an insight in the possible effects of the upcoming regulation policy - or better said: the lack of effects. As to be seen in the results, only the financially profitable measures as described in section 5.1.1 should be implemented. This is even the case when the expected regulation requirements of 2030 are not met by only investing in profitable measures. For the ship owner it is less costly to pay the carbon price rather then to invest in more expensive measures. The carbon price of 55 $/tCO_2$ is simply not high enough to stimulate the investment in more expensive measures.

The result of this lack of action is that - for this vessel - IMO's decarbonization targets will not be met. As to be seen in table 5.3, the expected $CO_2$ efficiency is higher than the regulation limits in any case and therefore the expected accumulated $CO_2$ reduction during the 15 years is limited. The conclusion is that a regulatory framework with a carbon price of 55 $/tCO_2$ is insufficient to reach the environmental targets set by IMO.

The question arising from this conclusion is which carbon price would be sufficient in order to stimulate the ship owner to invest in the fuel changing measures. The answer to this question includes not only the carbon price, but also the prices of the conventional and alternative fuels. In figure 5.17, this analysis is given for the investment profitability of a dual fuel engine in this scenario. In this figure, it can be seen that the higher the price of the alternative fuel with respect to HFO, the higher the carbon price should be in order to stimulate the investment. When the alternative fuel becomes cheaper than HFO, no carbon price is necessary anymore to stimulate this investment. In this scenario of which the results are presented in table 5.3, the combination of fuel price spread and carbon price is in the red area of the analysis in figure 5.17.

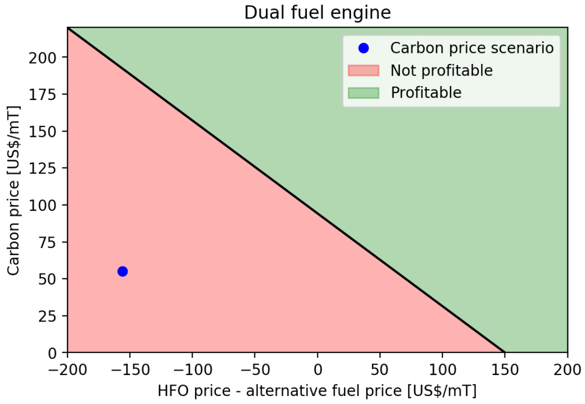


Figure 5.17: Spread between HFO and alternative fuel price versus carbon price sensitivity of dual fuel engine

Table 5.3: Model results of the five measure sets in the carbon price scenario excluding the dry docking schedule. The upper part of the table represents the optimal policy with the optimal moments of implementation of each measure per measure set and the lower part shows the expected output when following that policy.

| Scenario 3a - carbon price | Set A | Set B | Set C | Set D | Set E |
|---|---|---|---|---|---|
| Hull coating | ASAP | ASAP | ASAP | - | - |
| Propulsion improving devices | ASAP | ASAP | ASAP | - | ASAP |
| Trim draft optimization software | ASAP | ASAP | ASAP | - | ASAP |
| Hull air lubrication | ASAP | ASAP | ASAP | - | - |
| Wind assistance | ASAP | ASAP | ASAP | - | - |
| Auxiliary power by batteries | - | never | - | never | - |
| Dual fuel engine | - | - | never | never | - |
| Expected required speed reduction [%] | 0 | 0 | 0 | 0 | 0 |
| Expected $CO_2$ efficiency in year 15 [$gCO_2$/ton-nm] | 5.44 | 5.44 | 5.44 | 7.01 | 6.65 |
| Expected accumulated $CO_2$ reduction [x1000 mT] | 87 | 87 | 87 | 0 | 20 |
| Expected accumulated cost savings [million $] | 4.8 | 4.8 | 4.8 | 0 | 1.7 |
| Break-even year of investment combination | 4 | 4 | 4 | - | 2 |

The effect of the carbon price scenario with respect to the baseline scenario is shown in figure 5.18 in the previous section.

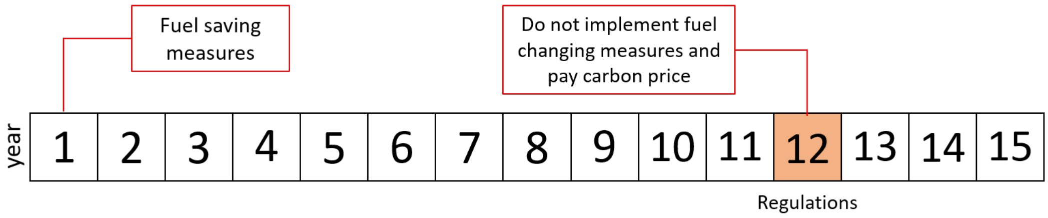


Figure 5.18: Effect of carbon price regulatory framework on the moment of implementation of measures with respect to the baseline scenario

### 5.2.4. Impact of docking schedule

The results of the baseline scenario including the docking schedule is to be found in figure 5.4. The two other scenarios including the docking schedule (high fuel price and carbon price) are to be found in appendix C. In the resulting policies, there are two effects to be seen which are caused by the consideration of the docking schedule: delayed implementation of measures and early implementation of measures (with respect to the scenarios ignoring the docking schedule).

When considering the docking schedule, measures implemented in year 1, 2 or 3 in the optimal policy are delayed to the next scheduled dry docking in year 4. This is the case for the fuel saving measures with an exception for trim draft optimization software. This is due to the fact that for the implementation of this measure the vessel does not necessarily need to be dry docked, as opposed to the other fuel saving measures. A result of the delayed implementation, the resulting accumulated $CO_2$ reduction and cost savings are expected to be lower, since the measures are implemented for a shorter amount of time.

Early implementation occurs for the measures taken in year 10 or 11. These are the measures which are initially not profitable (as described in section 5.1.1), but are required in order to meet the regulations going into force in year 12. In order to meet the regulations, it is desired to implement these measures during the last schedule dry dock before year 12, rather then delay it till the next dry dock. The result of the early implementation of these measures is that the accumulated cost savings are expected to be lower, since these are non-profitable measures which are implemented for a greater amount of time. On the positive side, however, the resulting accumulated $CO_2$ reduction is expected to be greater, since the measures are reducing the $CO_2$ emissions for a longer period of time as well.

In summary, the consideration of the dry dock schedule does have a substantial effect on the moment of implementation of the measures and the results leading from that. Figure 5.19 illustrates the effect of considering the dry dock schedule on the resulting optimal policy. In general, a delayed implementation of the fuel saving measures leads to both reduced expected cost savings and $CO_2$ reduction. An early implementation of the fuel changing measures leads to reduced expected cost savings, but also to increase expected $CO_2$ reduction. It should be noted that this is the conclusion for these measures in the environments of the analyzed scenarios; it is possible that for other scenarios (i.e. other oil price projections) these conclusions are not applicable.

Table 5.4: Model results of the five measure sets in the baseline scenario including the dry docking schedule. The upper part of the table represents the optimal policy with the optimal moments of implementation of each measure per measure set and the lower part shows the expected output when following that policy.

| Scenario 1b - baseline | Set A | Set B | Set C | Set D | Set E |
|---|---|---|---|---|---|
| Hull coating | year 4 | year 4 | year 4 | - | - |
| Propulsion improving devices | year 4 | year 4 | year 4 | - | year 4 |
| Trim draft optimization software | ASAP | ASAP | ASAP | - | ASAP |
| Hull air lubrication | year 4 | year 4 | year 4 | - | - |
| Wind assistance | year 4 | year 4 | year 4 | - | - |
| Auxiliary power by batteries | - | year 9* | - | year 9 | - |
| Dual fuel engine | - | - | year 9* | year 9 | - |
| Expected required speed reduction [%] | 25.4 | 16.5 | 0 | 0 | 46.2 |
| Expected $CO_2$ efficiency in year 15 [$gCO_2$/ton-nm] | 4.37 | 4.37 | 3.84 | 4.28 | 4.36 |
| Expected accumulated $CO_2$ reduction [x1000 mT] | 103 | 101 | 113 | 71 | 95 |
| Expected accumulated cost savings [million $] | 8.8 | 7.1 | 5.4 | 0.1 | 10.3 |
| Break-even year of investment combination | 7 | 10 | 12 | 15 | 1 |

*Action has a probability aspect of being optimal or not, depending on the true impact of formerly implemented measures.

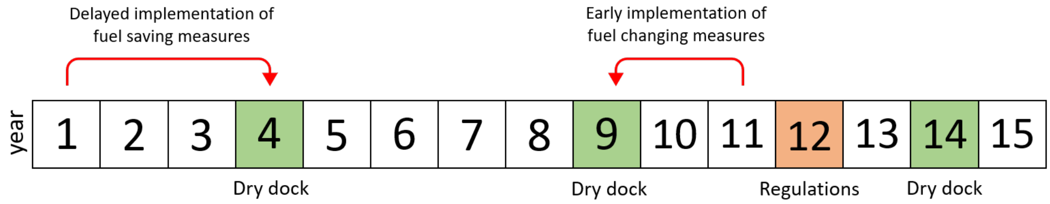


Figure 5.19: Effect of considering the dry dock schedule on the moment of implementation of measures with respect to the baseline scenario

## 5.3. Conclusion case study

By the analysis of the several scenarios, there are several conclusions drawn from the results. Considering the baseline scenario, the actions to be taken by the shipowner 'today' are a further research on the possibility and effects of the fuel saving measures. Trim draft optimization software and propulsion improving devices are expected to be financially profitable in the current environment and are therefore promising to reduce the $CO_2$ emissions of the vessel in a profitable way. Hull coating, hull air lubrication and wind assistance are promising as well, but the risks involved with these measures are substantial; the possibility exist that the payback periods of these measures are longer than 15 years. Further research should be carried out in order to reduce the risk involved with the investment in those measures. After the possible implementation of certain fuel saving measures, the true impacts on the fuel consumption should be monitored by the shipowner. This maps the new environmental performance of the vessel and gives insight in the steps still to be taken ahead of the regulations of 2030. If fuel saving measures are not implemented or the ones implemented are insufficient in order to meet the upcoming regulations, new decisions have to be made ahead of 2030. These decisions will involve the options of taking fuel changing measures or reduce the sailing speed. The optimal policy for this will be dependent on many factors, including the new environmental performance of the vessel, the state of the art of the fuel changing measures, the economical conditions with respect to investing and speed reduction and the development of the exact policy on the upcoming regulations by the IMO.

The results of the high fuel price scenario lead to a couple of conclusions. The policy for the implementation of the fuel saving measures does not change; due to the high fuel prices the measures has only became more interesting due to the increased expected cost savings. On the other hand, the policy regarding the fuel changing measures does change. Due to the fuel price spread between the conventional fuels on the one side and the alternative fuel and electricity price on the other side, the fuel changing measures become financially profitable without the enforcement by the regulations. For this reason, the decision to implement these measures are moved forward to year 1 of 2. The effects of the high fuel prices with respect to the baseline scenario is visualized in figure 5.16 in the previous section.

The carbon price scenario leads to the conclusion that an expected carbon price of 55 $\$/tCO_2$ in 2030 would not stimulate the shipowner to invest in the fuel changing measures. Therefore, only the profitable fuel saving measures are taken in year 1 - similar to the baseline scenario - and further actions will not be taken. Instead, the shipowner would pay for the tons of carbon emitted since that is the less costly option. The effect of the carbon price scenario with respect to the baseline scenario is shown in figure 5.18 in the previous section.

Considering the dry dock schedule in the model leads to two major changes in the decision making. First of all, the fuel saving measures which were initially planned to implement as soon as possible, are now delayed until the next scheduled dry dock in year 4. Due to this delayed implementation, resulting total cost savings and accumulated $CO_2$ reductions are decreased a little bit. On the other hand, however, fuel changing measures initially scheduled for year 11 are now implemented during the last scheduled dry dock prior to 2030, in year 9. This early implementation has also a negative effect on the total cost savings, but affects the accumulated $CO_2$ reductions positively. The effect of including the dry dock schedule with respect to is shown in figure 5.18 in the previous section.

Now, the baseline scenario is the scenario which acts as the starting point of the policy made by the shipowner. Also, it is expected that the shipowner does take the dry dock schedule into account, since it would have a major impact on the costs and operations neglecting it. This means that the baseline scenario including the dry dock schedule - of which the results are presented in table 5.4 - is the most likely scenario used by the shipowner. The most favorable measure set would be the one where no speed reduction is required and which has the highest expected accumulated cost savings. Measure set C - including the fuel saving devices and the dual fuel engine - is for this reason the measure set to choose for this vessel. Following the optimal policy presented in figure 5.20, results in expected cost savings of 12% and a $CO_2$ reduction of 29%, as shown in figure 5.21. The $CO_2$ efficiency is expected to be reduced by 45% in year 15 while maintaining the operational speed as business as usual.

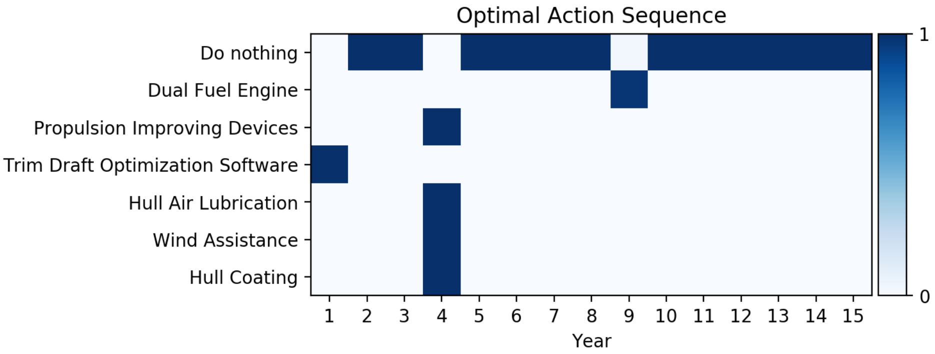


Figure 5.20: Optimal policy resulting from the model for the most likely combination for the vessel in this case study (measure set C in scenario 1b)

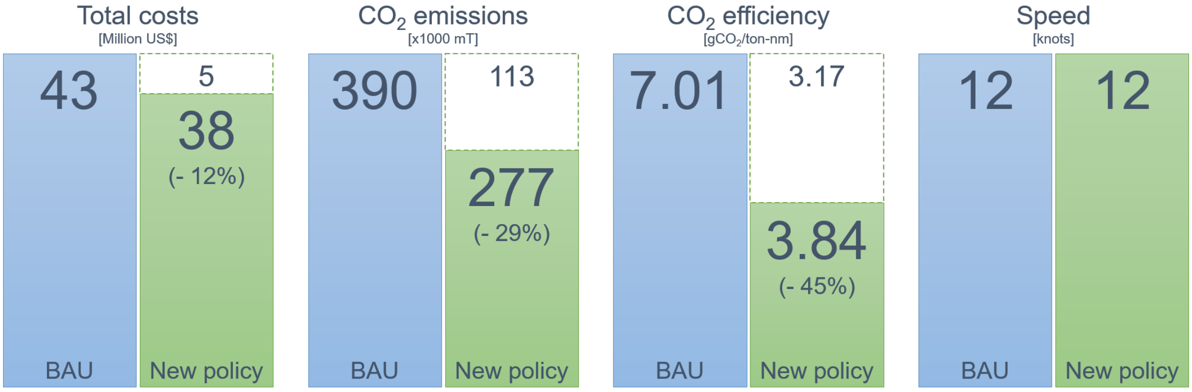


Figure 5.21: Expected results by following the optimal policy in figure 5.20 for the case study vessel

# 6

# Discussion

Following the results of the case study, there are several points to discuss about the model. A selection of these points of discussion leads to recommended future work to be carried out on the model, which is described in chapter 8

### Model validity

While for every model applies that the quality of the output is directly determined by the quality of the input (*garbage in, garbage out*), it goes a step further for this model; the validity of the model is completely dependent on the input. The basis of the model - Markov Decision Processes - is a method which determines the optimal policy by calculating all possible alternatives based on the input values. In other words, the better the vessel and its performance is described in the vessel input, the more valuable the results from the tool will be.

### Intended use of results

While the tool creates an optimal policy regarding the implementation of $CO_2$ reducing measures, the results are meant to function as supporting information during the decision process, rather than function as the decision itself. The shipowner is still the one responsible for making the decisions and should choose whether to follow the results of the tool or not. For instance, when the expected cost savings of a certain measure are positive, the measure is selected by the tool without considering the risks involved in the investment. In the end, the shipowner should analyze this risk and make the decision whether it is worth taking or not.

### Intended use of tool

In this report, the tool has been applied carrying out a case study regarding the policy making of an owner of a bulk carrier. While the objective of this study has been fulfilled by the development of a tool focused on the shipowner, the possibilities are not limited to that objective. For instance, the tool could be used by regulatory policy makers to test the $CO_2$ reducing flexibility of shipowners; what are realistic reduction targets set for the shipping industry? Another application of the tool could be the analysis and comparison of a range of ship segments in order to identify those measures which have a broad potential; measures with a broad potential would have the priority of research funding in order to stimulate the uptake and $CO_2$ reduction in the shipping industry.

### Uncertainties

The model presented in this report is able to deal with uncertainties regarding the impact on the $CO_2$ emissions of the vessel. While this is one of the major uncertainties involved in the decision making, there are other types of uncertainties which are not included in the model. For example, uncertainties regarding fuel prices, development of investment costs of measures and charter rates are not yet taken into account in the model. For this reason, the results of the tool do not cover all uncertain aspects involved and should be interpreted with care.

### Regulatory framework

As shown in the results of the case study, the regulatory framework is an input with a substantial effect on the results. In the case study, a realistic assumption is made for the limits set by the regulations and two scenarios are considered regarding the possible price for exceeding those limits. Due to the lack of information provided by IMO on the translation of the emission targets to a regulatory framework, this is one of the limited amount of ways to take the upcoming regulation into account. However, the value of the results would be improved tremendously if more details of the regulatory framework would be known, since a big uncertainty would be eliminated. In accordance with the previous paragraph, the regulatory framework could also be stochastically modeled, which is elaborated on in chapter 8.

### Slow steaming

The expected cost savings of the measure sets where speed reduction is applied consist for a substantial part of fuel savings due to the reduction of speed. While this reduction of fuel costs is valid in these scenarios, the potential costs of slow steaming are not accounted for in the model. For the case study presented in this report, slow steaming might affect the charter day rate of the vessel due to a loss of value in comparison with competitive charter bulkers. For vessel sailing a fixed schedule, the costs of slow steaming might result from a decrease in annual voyages made and thus a decrease in cargo shipped. A method which could account for the costs of slow steaming is described in chapter 8.

### Added value with respect to similar studies

Although other studies and tools do handle with uncertainties, the results are mainly calculated on world fleet level due to which results and risks for individual shipowners are unknown. This tool does present the results and risks for the individual, which - hopefully - results in a more proactive attitude with respect to mitigating $CO_2$ emissions in the shipping industry. An important additional insight with respect to other studies and tools is given by the incorporation of a regulatory framework in the analysis; where certain measures might not be profitable in the environment of today, the same measures could become profitable when regulations go into force. This additional insight is especially the result of creating a time line in which the optimal actions taken by the shipowner are presented, a feature which is barely used in similar studies. The last main aspect of the added value lies within the possibility of analyzing a specific vessel. Due to this, the results are vessel focused and more reliable than the results of tools making use of predefined general operational profiles and vessel performance specifics.

# 7

# Conclusion

The case study presented in this report has shown the application of the developed tool in a real situation. It has proven that the tool is suitable to deal with the problem regarding the uncertainty of shipowners in their decision making on the implementation of $CO_2$ reducing measures to their vessel. This has been reached by meeting the requirements presented in the research objective in section 1.4 and repeated below. In the next paragraph, these requirements are revisited and an elaboration is included on how these are met in the model.

The tool should:

- be based on a framework which could be applied to the most relevant ship segments of the world's merchant fleet; container vessel, oil tankers and bulk carriers;
- be based on input data which is generally available to shipowners;
- be able to analyze both individual measures and sets of combined measures;
- deal with uncertainties regarding the impact of $CO_2$ reducing measures and upcoming regulations;
- determine the best moment of implementing measures in order to minimize total costs;
- determine the expected and extreme values of the impact on the ship's $CO_2$ efficiency and the accumulated $CO_2$ reduction in accordance with the output of the other modalities included in MEO;
- determine the expected and extreme values of the accumulated costs and savings with respect to the business as usual in accordance with the output of the other modalities included in MEO;
- determine the expected payback time of individual measures and the break-even year of combined investments.

Bulk carriers, oil tankers and container vessel do not substantially differentiate with respect to their main objective - the transport of cargo - and energy consuming systems supporting that objective. By successfully carrying out a case study on a bulk carrier, it can be concluded that the tool can be applied on the three most relevant ship segments as defined in this report. Regarding the input of the tool, it has been set up requiring three different kinds; environment input, measure input and vessel input. The environment input and measure input can be obtained from publicly available information in research papers and other reports, as shown in this report. More important is the input of the vessel and systems specifics. As proven in the case study, all the required data could be obtained by an analysis of the daily reports of the vessel. These daily reports are - partly by regulation - already a standard for shipping companies and therefore generally available to use to obtain the input required for the tool.

Due to the dynamic character of the model setup, it is possible to analyze any measure or set of measures which include a range of possible fuel saving impacts and project this on the financial and environmental performance of one specific ship. Since Markov Decision Processes are at the base of the tool, it is suitable to optimize for optimal cost savings and a time line is created which states the best moment of implanting the measures to be analyzed. With this optimal policy, the expected impact on the ship's $CO_2$ efficiency and the obtained $CO_2$ reduction can be calculated. This can also be done for the total costs and the savings with respect to the business as usual. With the costs savings, the payback time of both individual measures and sets of measures can be determined as well.

The key conclusion from the case study is that by the implementation of a dual fuel engine in combination with fuel saving measures such as propulsion improving devices, trim draft optimization software, hull air lubrication, wind assistance and anti fouling hull coating, the $CO_2$ efficiency of the vessel could be reduced by 45%. This is sufficient to be compliant with the expected carbon emission regulations of 2030 and leads to a total $CO_2$ reduction of 29% over 15 years. Without having to reduce the speed of the vessel, this results in expected cost savings of 12% over 15 years.

By meeting the requirements for the tool, it is proven to be a valuable extension to TNO's MEO tool and the thesis objective as written below is fulfilled.

*Develop an extension of TNO's Multi-level Energy Optimization tool supporting shipowners in the decision making process regarding the pathway of implementing $CO_2$ reducing measures in sea-going vessels in the face of uncertainty, using Markov Decision Processes.*

With the fulfillment of the thesis objective, the presented tool provides a solution for the knowledge gap as described in the research objective. The tool forms a bridge between the literature and general tools on the one side and the implementation by shipowners on the other side by linking the literature to one specific vessel and dealing with the challenges and uncertainties involved in the decision making process.

# 8

# Future work

In this chapter, recommendations for future work regarding this study are described.

## Increase possible number of measures to be included

Due to the exponential state space expansion with the addition of every measure to be analyzed, approximately 14 gigabytes of memory is required for the analysis of six measures. To avoid the use of measure sets and to get the results for all measures at once, it would be valuable to improve the handling of the memory required to run the model. This could be done modeling the tool as a Bayesian network; the actions taken in one epoch affect to possible actions to take in the next epoch and therefore the state space to be calculated by the model. Table 8.1 shows an example of a decision path of the implementation of two measures, where measures 1 and 2 are implemented in epoch $n$ and $n+1$ respectively. It shows a large reduction in the possible actions to take throughout time, which means a huge decrease in calculations to be carried out by the MDP.

Table 8.1: Example of a two measure implementation analysis. Actions possible to take are dependent on actions taken before

| Epoch $n$ | Epoch $n+1$ | Epoch $n+2$ | … | Epoch $N$ |
|---|---|---|---|---|
| Do nothing | Do nothing | **Do nothing** | … | **Do nothing** |
| **Measure 1** | ~~Measure 1~~ | ~~Measure~~ | … | ~~Measure 1~~ |
| Measure 2 | **Measure 2** | ~~Measure 2~~ | … | ~~Measure 2~~ |
| Both | ~~Both~~ | ~~Both~~ | … | ~~Both~~ |

## Include slow steaming as a measure

As described in section 4.4, speed reduction is modeled as being the last resort to meet the regulation limits when this is not achieved by the implementation of measures. However, slow steaming could be an operational measure which is financially more interesting than investing in big retrofit measures such as a dual fuel engine. Therefore, it is recommended to improve the model by adding the possibility of speed reduction as a measure. This could be done by the discretization of the speed reduction and include this as a measure. For two possibilities of speed reduction and one technical measure, the state space and actions would be defined as in equations 8.1 and 8.2 respectively. It can be seen that the state space and number of (combined) actions to be taken grow tremendously ($12^N$ and $5^N$), but this could be dealt with using Bayesian networking, as described in the previous paragraph.

$$\mathbf{S} = \begin{pmatrix} \text{Not implemented; 0 knots reduction} \\ \text{Not implemented; 1 knots reduction} \\ \text{Not implemented; 2 knots reduction} \\ \text{Minimum impact; 0 knots reduction} \\ \text{Minimum impact; 1 knots reduction} \\ \text{Minimum impact; 2 knots reduction} \\ \text{Average impact; 0 knots reduction} \\ \text{Average impact; 1 knots reduction} \\ \text{Average impact; 2 knots reduction} \\ \text{Maximum impact; 0 knots reduction} \\ \text{Maximum impact; 1 knots reduction} \\ \text{Maximum impact; 2 knots reduction} \end{pmatrix} \quad (8.1) \qquad \mathbf{A} = \begin{pmatrix} \text{Do not implement measure} \\ \text{Implement measure} \\ \text{Apply 0 knots speed reduction} \\ \text{Apply 1 knots speed reduction} \\ \text{Apply 2 knots speed reduction} \end{pmatrix} \quad (8.2)$$

The financial benefits of slow steaming would be accounted for in the decreased fuel costs in the reward function. For the costs of slow steaming, it is advised to add a slow steaming cost element to the reward function, as shown in equation 8.3. This slow steaming costs would be dependent on the freight rate, bunker costs, ship costs, cargo cost, interest rate and environmental cost (Liang, 2014).

$$R(s,a,E) = C(s,E)_{\text{fuel}} + C(a)_{\text{investment}} + C(s)_{\text{operational}} + C(s,E)_{\text{regulation}} + C(s,E)_{\text{slow steaming}} \tag{8.3}$$

### Combined impact of measures

In the model presented in this report, the fuel saving impact of multiple measures are modeled as the sum of the individual measures, as described in section 3.6 and shown in equation 8.4.

$$\text{Fuel savings}_{\text{total}}[\%] = \text{Fuel savings}_{\text{M1}} + \text{Fuel savings}_{\text{M2}} + \cdots + \text{Fuel savings}_{\text{M}N} \tag{8.4}$$

However, it is very likely that certain measures affect each others impact and the total fuel savings are less than the sum of the savings of the individual measures. For this reason it is advised to include a possibility to account for the effect of combined implemented measures. This could, for instance, be done by means of a combined reduction matrix in which factors are included to account for the impact decrease of combined measures. An example of such a matrix is given in equation 8.5. However, in order to use this in the model, more research has to be carried out on the individual impacts of measures and the possible effects of combining certain measures.

$$\text{Reduction factor matrix} = \begin{array}{c} \\ M1 \\ M2 \\ M3 \\ M4 \end{array} \begin{array}{c} \begin{array}{cccc} M1 & M2 & M3 & M4 \end{array} \\ \begin{pmatrix} 1 & - & 0.8 & - \\ - & 1 & - & 0.9 \\ 0.8 & - & 1 & - \\ - & 0.9 & - & 1 \end{pmatrix} \end{array} \tag{8.5}$$

### Include more uncertainties

The model presented in this report deals with uncertainties regarding the true impact of $CO_2$ reducing measures. However, these are not the only uncertainties involved in the decisions making process (as described in chapter 6) and therefore it would be valuable to add more stochastic variables in the model. Examples of these uncertainties are given by (Kana et al., 2015) and include fuel prices, fuel supply chain risks, regulatory framework and measure capital costs. Other variables which could be modeled stochastically are capital costs and impact rate of measures due to technical development (measure maturity) and the degradation of the propulsive and auxiliary efficiency of the vessel.

When multiple uncertainties are included in the model, the problem becomes too complex to approximate the probability range according to the method described in section 3.6. Therefore, an alternative method should be used to analyze the problem with respect to the probabilities involved. A method to do this is combining the MDP method with a Monte Carlo approach, as presented by (Kana and Harrison, 2017). With this approach, a large number of simulations are run to make an analysis of the MDP output range and the standard deviation and extreme output limits can be identified.

### Apply MDP method to other modalities in MEO

In this study, it is shown that Markov Decision Processes is a valuable method for analyzing the cost efficient decarbonization of vessels. Therefore, it is advised to expand this method to the road, rail and inland waterway modalities in MEO. Considering the most relevant uncertainties of each modality, a probabilistic analysis can be made on the optimal policies of the different modality sizes and segments. Have the method applied to all modalities, an comparative analysis between them can be carried out and it could support studies on the overall pathway to national or global decarbonization in the transport sector.

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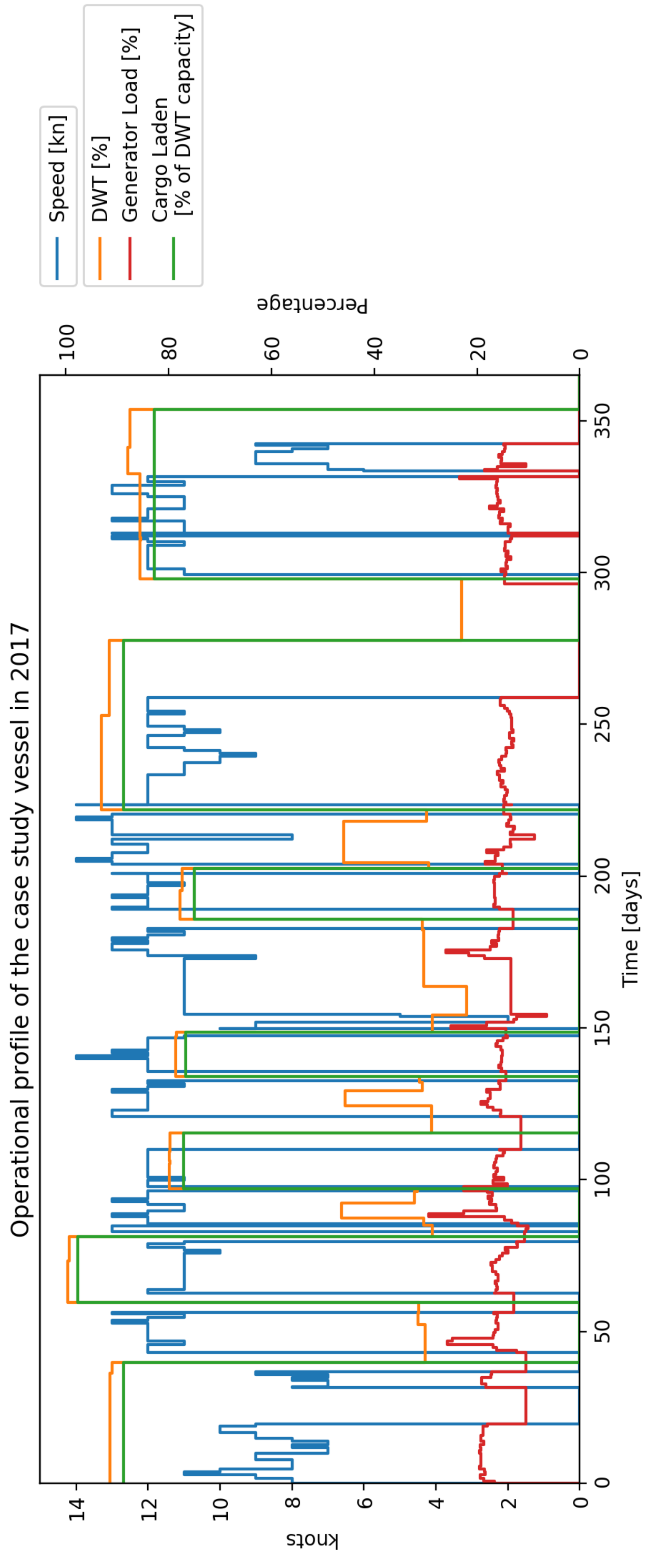
# A

# Operational profile


Operational profile of the case study vessel in 2017
Speed [kn]
DWT [%]
Generator Load [%]
Cargo Laden
[% of DWT capacity]
knots
0
2
4
6
8
10
12
14
Percentage
0
20
40
60
80
100
Time [days]
0
50
100
150
200
250
300
350

# B

# Analysis of individual measures - high fuel price

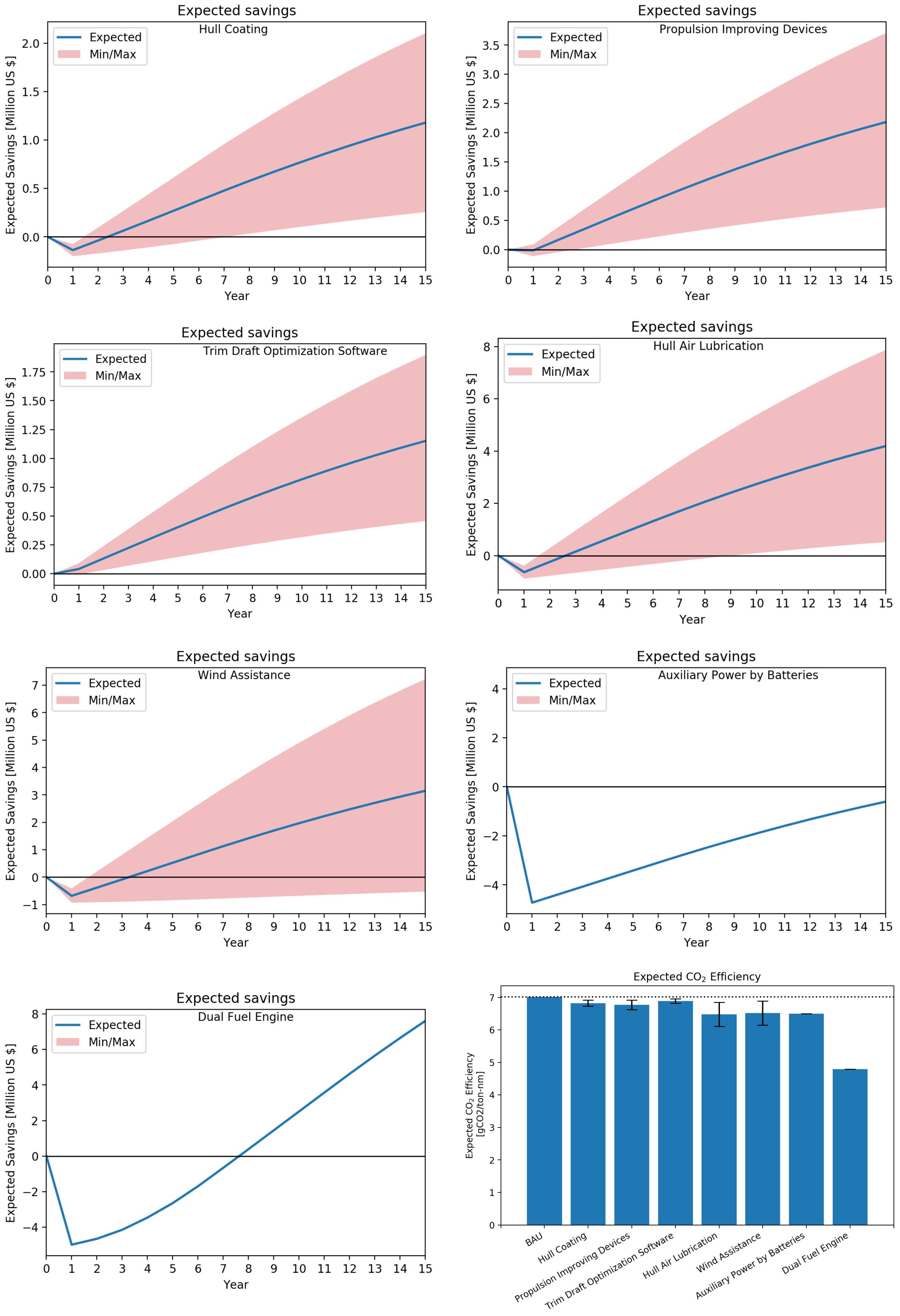


Figure B.1: Analysis of the implementation of individual measures in the high fuel price scenario

# C

# Results of scenarios including docking schedule

Table C.1: Model results of the five measure sets in the high fuel price scenario including the dry docking schedule. The upper part of the table represents the optimal policy with the optimal moments of implementation of each measure per measure set and the lower part shows the expected output when following that policy.

| Scenario 2b - high fuel price | Set A | Set B | Set C | Set D | Set E |
|---|---|---|---|---|---|
| Hull coating | year 4 | year 4 | year 4 | - | year 4 |
| Propulsion improving devices | year 4 | year 4 | year 4 | - | year 4 |
| Trim draft optimization software | ASAP | ASAP | ASAP | - | ASAP |
| Hull air lubrication | year 4 | year 4 | year 4 | - | year 4 |
| Wind assistance | year 4 | year 4 | year 4 | - | - |
| Auxiliary power by batteries | - | year 9* | - | year 4 | - |
| Dual fuel engine | - | - | year 4 | year 4 | year 4 |
| Expected required speed reduction [%] | 25.4 | 16.5 | 0 | 0 | 0 |
| Expected $CO_2$ efficiency in year 15 [g$CO_2$/ton-nm] | 4.37 | 4.30 | 3.80 | 4.28 | 4.11 |
| Expected accumulated $CO_2$ reduction [x1000 mT] | 103 | 108 | 144 | 121 | 130 |
| Expected accumulated cost savings [million $] | 19.6 | 17.1 | 22.0 | 15.4 | 19.6 |
| Break-even year of investment combination | 5 | 5 | 7 | 10 | 7 |

*Action has a probability aspect of being optimal or not, depending on the true impact of formerly implemented measures.

Table C.2: Model results of the five measure sets in the carbon price scenario including the dry docking schedule. The upper part of the table represents the optimal policy with the optimal moments of implementation of each measure per measure set and the lower part shows the expected output when following that policy.

| Scenario 3b - carbon price | Set A | Set B | Set C | Set D | Set E |
|---|---|---|---|---|---|
| Hull coating | year 4 | year 4 | year 4 | - | - |
| Propulsion improving devices | year 4 | year 4 | year 4 | - | year 4 |
| Trim draft optimization software | ASAP | ASAP | ASAP | - | ASAP |
| Hull air lubrication | year 4 | year 4 | year 4 | - | - |
| Wind assistance | year 4 | year 4 | year 4 | - | - |
| Auxiliary power by batteries | - | never | - | never | - |
| Dual fuel engine | - | - | never | never | - |
| Expected required speed reduction [%] | 0 | 0 | 0 | 0 | 0 |
| Expected $CO_2$ efficiency in year 15 [$gCO_2$/ton-nm] | 5.44 | 5.44 | 5.44 | 7.01 | 6.65 |
| Expected accumulated $CO_2$ reduction [x1000 mT] | 71 | 71 | 71 | 0 | 17 |
| Expected accumulated cost savings [million $] | 3.5 | 3.5 | 3.5 | 0 | 1.4 |
| Break-even year of investment combination | 7 | 7 | 7 | - | 1 |